INVESTIGATION INTO STRUCTURAL BEHAVIOUR OF INSULATION OF THE PRESTRESSED CONCRETE PRESSURE VESSELS OF WYLFA NUCLEAR POWER STATION

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ABSTRACT

In the design and development of insulation for the pressure vessels of gas-cooled reactors, difficulties arise in the simulation of dynamic loading conditions in the laboratory, and of their definition for the purpose of analysis. Experience at Wylfa has shown that under some conditions, and particularly where highly turbulent flow occurs, the stresses induced in the studs retaining insulation cover plates may be sufficiently high to cause fatigue failure. This paper outlines the course of events related to this situation, presents stress data obtained by measurement under reactor conditions and draws tentative conclusions from the currently available data.

1. INTRODUCTION

In the development of prestressed concrete pressure vessels for gas-cooled nuclear reactors, thermal insulation has emerged as a feature requiring particular attention. The design of insulation in this application involves the resolution of a three-cornered conflict between the requirements of thermal performance, the accommodation of thermal expansion and structural integrity in the reactor environment. Of these, the third raises difficulties in regard to the specification of the dynamic loadings to which the insulation will be subjected, which cannot be readily simulated in the laboratory. It is nevertheless most important in a reactor design to predict the stress levels likely to arise in the cover plates and fixing studs, to ensure a satisfactory fatigue life.

In Great Britain, stainless steel insulation is used for the pressure vessels of many reactors. In its simplest form, a pack of insulation is held against the liner by a corner plate carried on a stud, Fig.1, the diameter of the stud being a minimum consistent with adequate strength, to limit heat transfer. This arrangement gives freedom for thermal expansion at the cover plate and insulation foils without the induction of high thermal stresses.

The cover plates however experience dynamic loading as a result of pressure variation in the coolant arising both from noise generated by the circulators and also from turbulence in the gas flow. The effect of this excitation is to generate fluctuating stresses in cover plates and studs. Whilst there is now no evidence to believe that the stress levels in cover plates are important, experience at Wylfa has shown that those in the studs may under some circumstances such as to cause fatigue failure. In some locations it has been necessary to change multi-studded cover plates, Fig.2, and to accept high strain conditions in order to mitigate the high cycle fatigue problem.

At first sight the problem might appear to be susceptible to theoretical analysis. However, neither the excitation nor the resistance to motion resulting from interaction of cover plates and insulation, and from the radiation of energy into the coolant can be quantified with sufficient precision as to make such analysis worth while. The alternative approach is to attach strain gauges to representative components and hence to obtain direct strain measurements, in the laboratory where possible, and in the reactor where no other choice exists.

Events at Wylfa during 1970 have led to the need for such investigations both in the laboratory and in the reactor, which will form the pattern for further work that will be carried out in connection with AGRs, in which potentially more severe environmental conditions exist.

This paper briefly describes the narrative of events at Wylfa and of the various investigations which have been carried out, and gives some of the more significant results which have been obtained by direct measurement in the reactor.

2. NARRATIVE OF EVENTS

The importance of the influence of circulator noise on reactor components was appreciated during the commissioning of Hinkley Point A in 1963, ref [1]. In the following year, the studs and cover plates of typical panels of insulation of the design proposed for Wylfa were subjected to acoustic tests in atmospheric air. Studs and cover plates were strain gauged, and tests were carried out with narrow band excitation at frequencies close to the circulator blade passing frequency of 512 hz chosen to give local resonances. These tests indicated that maximum stress levels of about 1,200 psi (85 kg/cm^2) in the cover plates, allowing for spatial variation, and allowing for the stress concentration at the stud hole, and 500 psi (35 kg/cm^2) in the studs when extrapolated to the expected sound pressure level of 159 db. These stresses, which like all those which follow in this paper, are root mean square values. No attempt was made to measure the effects of gas flow partly because of the difficulties in simulating the correct con ditions and partly because it was felt that the magnitude of acoustic pressure variations went well beyond the range of pressure variations due to turbulence.

As part of the instrumented unfuelled engineering runs in 1969, strain gauges were fitted to the cover plates of insulation close to the circulator inlets, that is in the region of the highest noise levels. These indicated stress levels not exceeding 50 psi.

On completion of the fuelled engineering runs in February 1970, extensive damage was found to insulation in the inlet bowl of No. 2 circulator. In particular, three cover plates had become detached, as a result of what was found to be a fatigue failure in the studs. Similar damage was not observed in the other three circulator bowls. It was therefore suspected that the damage had arisen during the three weeks when No. 2 circulator had been out of operation as a result of a seal failure. Pairs of strain gauges were applied to replacement studs to measure stresses in the longitudinal direction in the affected area, their cables being led away over the cover plates of the new insulation. Additionally, pressure transducers were fitted in the same area to determine sound pressure levels.

In the subsequent tests in May 1970, sound pressure levels in the region of 154 to 158 db were measured in No. 2 circulator bowl under normal operation, a typical spectrum being as indicated in Fig.3. The approximate mass flow through the circulator was 6,500 lb/sec. (2,950 kg/sec), the gas density 1.75 lb/ft^3 (28.0 kg/m^3), and the velocity in the region of the circulator inlet 50 ft/sec (15.2 m/sec). Under these conditions stresses in studs were found not to exceed 100 psi (7.1 kg/cm^2). When No. 2 circulator was shut down, a quite different situation arose. An increase occurred in sound pressure level to around 163 db and the spectrum, Fig.4, showed great activity in the region of 20 to 50 hz. Stress levels in the studs were high, and were sensitive to both the flow through the other circulators and also to the inlet guide vane settings of No. 2 circulator. As a result of limitations arbitrarily placed on the measured stresses it was not possible to simulate the conditions under which the damage had arisen, the test being discontinued when stud stresses of 1,700 psi (120 kg/cm^2) were measured.

The low frequencies dominating both sound pressure and strain spectra were consistent with those of vortex shedding from the inlet spokes of the circulator as a result of reverse flow. As operation of the reactor with one circulator shut down is an accepted condition, it was necessary to devise a suitable design of cover plate attachment to withstand this excitation. The solution which was subjected to acoustic and electro-mechanical tests in the laboratory, was a four-studded arrangement as shown in Fig.2. This design has the disadvantages of increased heat conductance and of high temperature induced stresses. This latter feature was the subject of tests to ensure adequate resistance to high strain fatigue.

In repeat tests in the reactor in September 1970, the measured stresses were found not to exceed 200 psi (14.2 kg/cm^2) when the circulator was shut down. Surprisingly stresses of up to 435 psi (30.8 kg/cm^2) were measured in some studs during normal operation, possibly as a result of response of the rigid cover plate-stud structure with the blade-passing frequency. No clear pattern of stresses was detected, and it is felt that the numerical data obtained during these tests would not of general interest.

As a result of experience during the first series of tests, some concern was felt for the insulation in the gas outlet region above the core, Fig.5, where as flowing from the shielding labyrinth impinges at about 50 to 55 ft/sec (15.2 to 18.8 m/sec) on the vessel insulation. Consequently strain gauges were fitted to a number of studs in this region, and pressure transducers were placed in neighbouring positions. Measurements were obtained during the second series of tests which were found to be of great interest. These are presented in the following section.

3. RESULTS OF TESTS IN REACTOR OUTLET REGION

Five stud positions were selected for instrumenting. These lay on a vertical section of the vessel, at a position where high turbulence might be expected from vortices shed from support structures in the gas passage. Ideally more studs should have been instrumented but this would have increased the extent of rebuilding of the insulation. The studs concerned, at positions indicated in Fig.5, were of ½ inch (12.7 mm) diameter and of carbon steel. The cover plates were of ¼ inch (6.4 mm) mild steel, and measured approximately 1 ft/6in by 2 ft (0.46 by 0.61 m). Micromear strain gauges mounted on stainless steel shims were cemented to the studs at two positions 90° apart, and arranged to measure longitudinal stresses. The gauge positions were as close as possible to the threads at the outer end of the stud, since this is the most vulnerable part on account of the stress concentration effect of the threads. The nominal insulation pack thickness is 2⅛ inches (54 mm).

Details of the relevant reactor conditions and of the readings obtained are given in Table I. Unfortunately the sound pressure transducers failed early in the test, as did two of the ten strain gauges. One gauge on each of the top two studs failed, although one of these gave some useful indications.

Fig.6 shows a typical strain spectrum. This again exhibits a large amount of activity in the region of 7 to 40 hz.

The most convenient parameter against which to plot stresses is the dynamic head of the gas, or rather $\frac{M^2}{\rho}$, where M is the reactor mass flow and ρ the gas density, which may be obtained directly from measured data without requiring assumptions to be made about gas flow patterns.

Longitudinal stresses in the studs may arise from excitation in the bending or push-pull mode. With signals from only two strain gauges it is not possible to determine the extent to which each node is present. To obtain a pessimsitic estimate of the maximum stress in a stud, it must be assumed that the measured stresses result from bending. The maximum stress is then obtained as the root of the sum of the squares of the two measured values. In Table I the individual stresses have been combined in this manner.

When the individual and combined stresses are plotted against dynamic head they appear to indicate a unique relationship. Fig.7 gives a typical plot of combined stresses for the central stud. It will be seen that the points obtained at high density and low mass flow lie close to those for low density and high mass flow. No obvious explanation is available for this. The apparent relationship was used to extrapolate to the stresses expected at the dynamic head arising under normal reactor outlet conditions when the correct outlet gas temperature obtains. This indicated that the margin against fatigue failure was adequate but not generous.

4. CONCLUSIONS

The object of this paper is to present data obtained under reactor conditions on dynamic stresses arising in the studs used to attach cover plates for pressure vessel insulation. In detail, the conclusions to be drawn from this information depend on the interests of the reader. The following general conclusions are however suggested.

4.1 The stresses arising in insulation studs under operating conditions in uranium-magnox reactors resulting from circulator noise and gas turbulence are not negligible. In particular, where single stud fixings are used and where considerable turbulence exists, stress levels may be such as to cause concern about fatigue failure.

4.2 Some of the evidence from Wylfa indicates a relationship between stress levels and the dynamic head of the gas.

4.3 Stresses in the retaining studs for insulation for other reactor types, and notably AGR, should be investigated by laboratory tests and possibly mathematical models, and also by direct measurement in the reactor during commissioning.

4.4 Further investigations are also required into the fatigue strength of studs, and also into the fatigue aspects of multi-studded cover plates, especially at high reactor outlet temperatures.

5. ACKNOWLEDGEMENT

The author is grateful to the Central Electricity Board of the United Kingdom for permission to publish the information given in this paper.

REFERENCE

[1] RIZK, W. and SEYMOUR, D.F., "Investigations into failure of gas circulators and circuit components at Hinkley Point Nuclear Power Station". I.Mech.E. Pro. 1964-65 Vol 179 Par I No. 21.

TABLE I.
RESULTS OF STRAIN GAUGE READINGS.

	4-9-70									5-9-70				
DATE AND TIME	0017	1025	1210	1442	1620	1811	1827	2132	2320	0155	0215	1600	1650	1750
INLET PRESSURE-(p.s.i.a.)	208	298	304	323	346	353	357	375	406	397	397	425	425	425
INLET TEMPERATURE- °C	195	250	255	253	261	263	264	257	256	251	251	245	246	249
I.G.V. SETTINGS.	-3°	-3°	+10°	+10°	-3°	+10°	-3°	-3°	-3°	(1.) -3°	[illegible]	+2°	(1.) -2°	[illegible]
GAUGE 81- TOTAL (mV.)														
NOISE (mV.)														
r.m.s. STRESS (p.s.i.)														
GAUGE 82- TOTAL	37	48	47	52	55	48	60	60	60	42	46	66	50	50
NOISE	30	31	34	37	32	26·5	28	30	32	36	36	36	39	38
STRESS	140	238	212	237	291	260	345	338	330	140	186	360	203	211
GAUGES 81 & 82-COMBINED STRESS														
GAUGE 83 - TOTAL	30			41										
NOISE	30			38										
STRESS	0			100										
GAUGE 84 - TOTAL	42	60	56	60	50	60	75	75	78	50	55	90	60	55
NOISE	29	30	33	37	32	25	27	30	31	35	35	35	40	37
STRESS	198	338	294	307	477	354	455	446	465	232	278	539	291	275
GAUGES 83 & 84- COMBINED STRESS	198			323										
GAUGE 85 - TOTAL	41	60	56	60	65	60	70	75	85	50	53	85	55	55
NOISE	29	32	33	37	32	26	27	32	36	35	36	36	40	38
STRESS	189	330	294	307	368	352	420	440	501	232	252	501	241	258
GAUGE 86 - TOTAL	42	60	55	60	70	55	70	75	80	50	50	81	52	52
NOISE	29	30	32	36	30	26	26	32	36	30	35	36	36	38
STRESS	198	338	291	312	411	315	423	440	464	232	232	472	244	239
GAUGES 85 & 86- COMBINED STRESS	274	482	414	437	552	473	598	622	684	328	348	687	342	345
GAUGE 87 - TOTAL	29	35	36	39	36	30	34	36	42	36		41	38	38
NOISE	30	32	34	37	30	27	27	32	36	35		36	38	38
STRESS	0	92	80	80	129	85	134	107	141			128		
GAUGE 88 - TOTAL	30	35	36	39	36	30	33	36	40	36		39	37	38
NOISE	30	32	33	37	30	27	26	30	34	34		35	36	36
STRESS	0	92	93	80	129	85	131	129	137	77		112		79
GAUGES 87 & 88-COMBINED STRESS	0	130	123	113	183	120	187	167	197	77		170	0	79
GAUGE 89 - TOTAL	33	39	39	42	40	35	38	42	48	39		47	40	42
NOISE	31	33	32·5	38	32	27·5	28	32	37	36		37	40	32
STRESS	74	135	140	116	156	141	169	177	199	98		188		116
GAUGE 90 - TOTAL	31	37	37	41	38	33	38	40	45	36		45	38	40
NOISE	30	32	32	37	30	26·5	27	32	35	35		35	36	36
STRESS	0	121	121	115	152	128	173	156	184			184	79	113
GAUGES 89 & 90- COMBINED STRESS	74	181	185	163	218	191	244	236	271	98		263	79	162
MASS FLOW M (lb./sec)	14,800	19,000	18,000	19,200	21,600	20,700	22,200	23,600	25,500	(2.) 19,200	(2.) 20,300	26,500	(2.) 20,200	(2.) 21,100
DENSITY ρ lb./ft³	1·04	1·31	1·32	1·41	1·45	1·52	1·53	1·63	1·76	1·75	1·75	1·88	1·88	1·87
$\frac{M^2}{\rho}$ $\left(\frac{lb.\,ft^3}{sec^2} \times 10^{-6}\right)$	211	276	246	262	313	282	322	342	370	210	236	374	217	238
PRESSURE TRANSDUCER No. 107-READING.					460			400						
LEVEL (db.)					153			152						
PRESSURE TRANSDUCER No. 108-READING.				200	250									
LEVEL (db.)					149									

NOTES
(1.) No. 2. CIRCULATOR SHUT DOWN.
(2.) MASS FLOW ESTIMATE TAKES INTO ACCOUNT BACK FLOW THROUGH No. 2 CIRCULATOR.

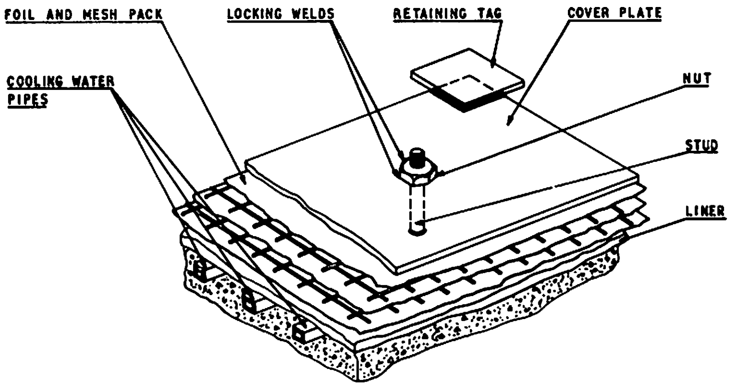


FIG. 1 - TYPICAL INSULATION COVER PLATE RETAINED BY SINGLE STUD

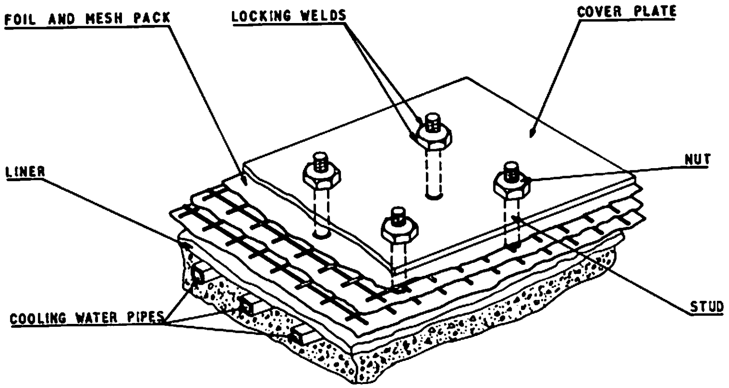


FIG. 2 - TYPICAL INSULATION COVER PLATE RETAINED BY FOUR STUDS

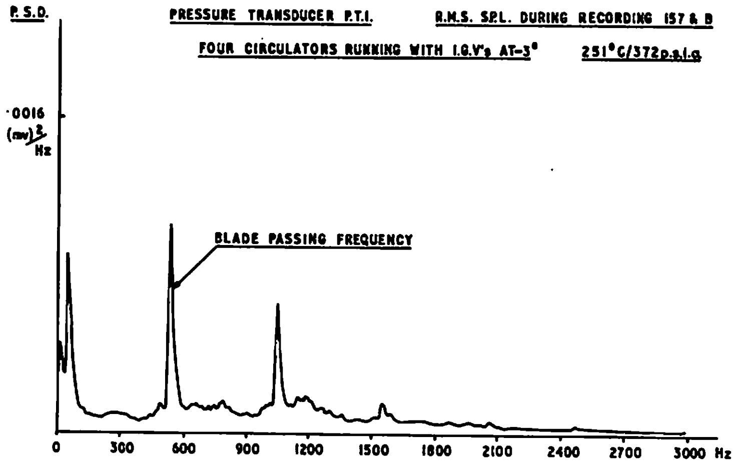


FIG. 3 - SOUND PRESSURE SPECTRUM IN CIRCULATOR INLET UNDER NORMAL OPERATIONS

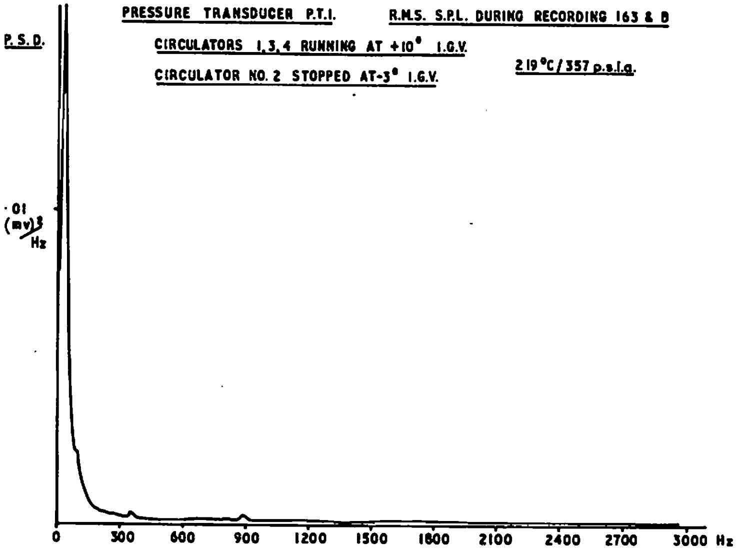
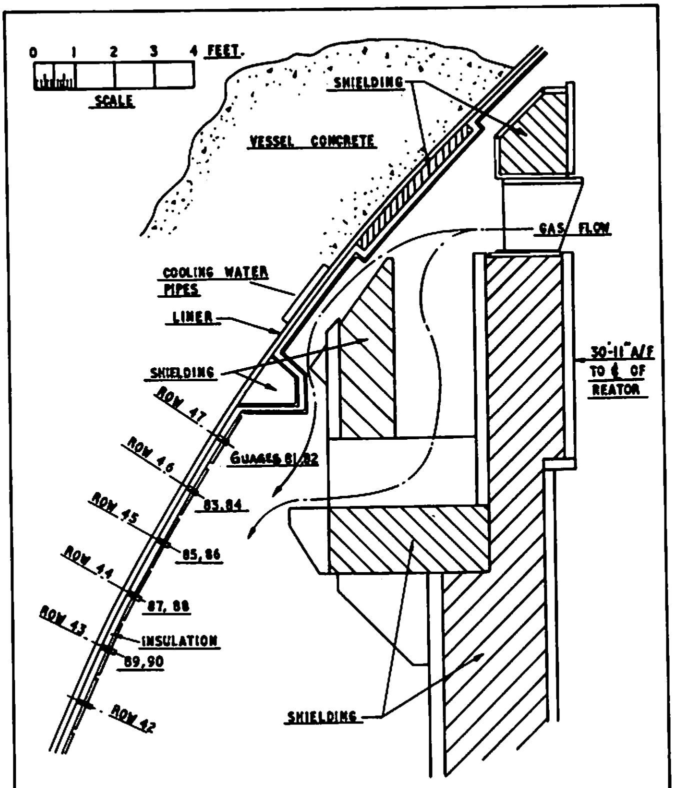
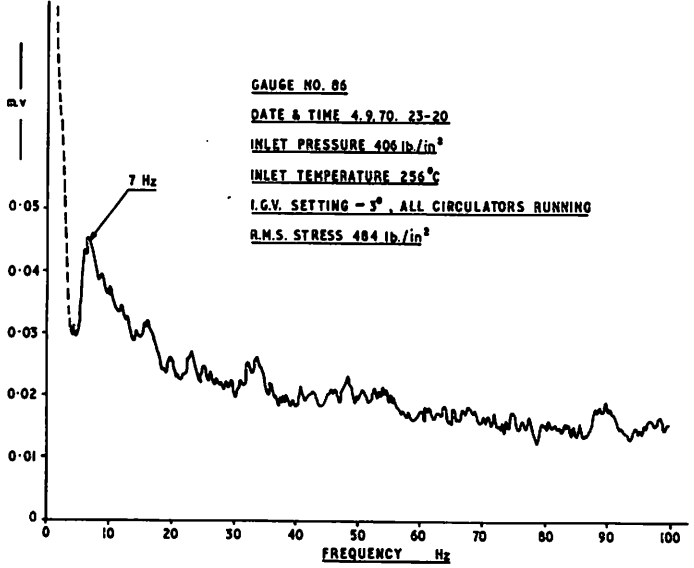


FIG. 4 - SOUND PRESSURE SPECTRUM IN CIRCULATOR INLET WITH CIRCULATOR OUT OF OPERATION



GEOMETRY OF REACTOR GAS OUTLET REGION.

FIG.No. 5.



GAUGE NO. 86

DATE & TIME 4.9.70. 23-20

INLET PRESSURE 406 lb./in²

INLET TEMPERATURE 256°C

I.G.V. SETTING – 3°, ALL CIRCULATORS RUNNING

R.M.S. STRESS 484 lb./in²

FIG. 6 – TYPICAL STRAIN SPECTRUM FOR STUD IN GAS OUTLET REGION

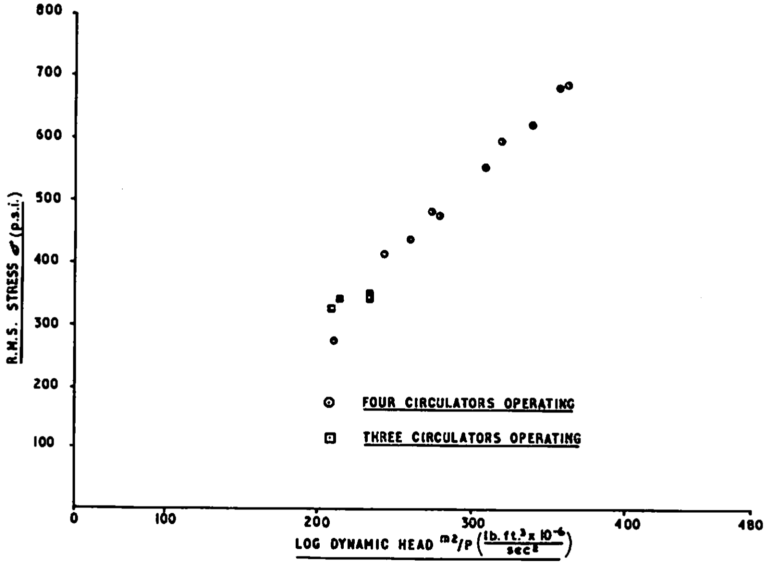


FIG.-7 – PLOT OF COMBINED STRESSES FOR CENTRE STUD IN GAS OUTLET REGION AGAINST LOG DYNAMIC HEAD

DISCUSSION

Q

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The four-studded cover plate must lead to a very much more rigid structure. How does this affect the design of the cover-plate itself and the studs with regard to the temperature movements ?

A

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The four-studded cover plate design is indeed more rigid than with a single stud. Since the liner temperature is around 50°C and the cover plate temperature 250°C at reactor inlet, the studs are subjected to bending stress cycles going well into yield. It is therefore necessary to carry out high strain fatigue tests to ensure that the studs can accept the high strain and high cycle loadings without premature failure.