Transactions of the 14th International Conference on Structural Mechanics in Reactor Technology (SMiRT 14), Lyon, France, August 17-22, 1997 J09/6

Structural analysis of the core shroud of Tarapur Atomic Power Station (TAPS) reactor under accident conditions

Khatua G.M.[1], Bhasin V.[1], Mukhopadhyay D.[1], Gupta S.K.[2], Kushwaha H.S.[1]
(1) Bhabha Atomic Research Centre, India
(2) Nuclear Power Corporation, India

ABSTRACT : This paper presents the structural analysis of the Core Shroud of Tarapur Atomic Power Station Boiling Water Reactor (TAPS-BWR), India. The structural analysis has been done under postulated accidents like Main Steam Line Break (MSLB), Recirculation Line Break (RLB) and Safe Shutdown Eartquake (SSE). However, in the original design, theses accident loads were not considered. The analysis has been done for healthy shroud with out crack. From the analysis, it is concluded that adequate safety margins are available under all accident conditions.

1.0 INTRODUCTION

The twin nuclear reactors (660.9 MWth) at Tarapur Atomic Power Station (TAPS), India, belong to the class of early generation Boiling Water Reactors (BWR). They are dual cycle reactors with two recirculation loops. At present they are working on single primary loop with a reduced power (500 MWth). The secondary loop with associated recirculation line does not contribute to power generation but is there to provide recirculation flow.

Over the last few years, the Core Shroud of some of the BWRs, operating abroad, have developed cracks at different weld locations. Intergranular Stress Corrosion (IGSC) is recognized as the primary cause for Core Shroud weld cracking. It was also found that most of the cracks are circumferential and associated with heat affected zone. The main objectives of these analyses are to assess the integrity of the Core Shroud, ability of the reactor shut down and impairment of core cooling, during postulated accident conditions such as Safe Shutdown Earthquake (SSE), Main Steam Line Break (MSLB) and Recirculation Line Break (RLB).

The analysis presented in this paper has been done for the core shroud without crack, since, although, the reactor is operating for quite a long time (since November, 1969), due to reduced power, the age of the reactor in terms of full power year is not so large. Also, only the central channels are loaded with fuel and outer channels are reducing fluence reaching the Core Shroud. Besides, visual inspection conducted till now, does not indicate the presence of any cracks. The structural design of this Core Shroud takes into account normal operating loads. The accident loads arising from postulated events like MSLB, RLB and SSE were not considered during the design stage. However, in the second phase of the work, the cracks of different sizes and locations will be postulated and similar analysis would be carried out.

The thermal hydraulic analysis for RLB and MSLB has been done using the computer code RELAP4/MOD6. Subsequently, hydraulic loads have been calculated using these results. The postulated MSLB event leads to a large upward load on Core Shroud whereas, RLB results in downward load on the Shroud. Dynamic structural analysis of Core Shroud following RLB and MSLB have been done using Dynamic Load Factor (DLF) method. The structural assessment has been based on American Society of Mechanical Engineers Boiling and Pressure Vessel (ASME B&PV) code Sec. III NB&NG. The postulated accident loads have been treated as Level D service loads.

2.0 DESCRIPTION OF THE REACTOR AND CORE SHROUD

The TAPS-BWR has 368 fuel channels out of which 284 channels contain 6 by 6 fuel assemblies. The remaining channels are plugged. The reactor channels are enclosed in a core shroud which separates the core from the downcomer. It also helps to maintain fuel alignment such that control rod can be inserted.

The Core Shroud (shown in Fig.1) is composed of two cylindrical vessels and three rings. The two vessels are main shroud shell (ID=124 in. and t=1 in.) and shroud lower shell (ID=112 in. and t=1 in.). The three rings are shroud bottom ring, core support ring and shroud flange. Shroud bottom ring connects main shroud shell with the shroud lower shell and supports bottom core support plate and its associated stiffening grid. Core support ring connects shroud lower shell to conical skirt. The conical skirt is welded to reactor pressure vessel and provide rigid support to the Core Shroud assembly. The upper end of main shroud shell is covered with torispherical dished head. Torispherical shroud head is perforated in the crown region. The Drier-Separator assembly is connected to it. The steam at low quality enters Drier-Separator assembly through perforations in torispherical shroud head. Finally after moisture separation and drying, steam of required quality goes to Turbine through main steam lines. The saturated water goes to the downcomer annulus between main shroud shell and reactor pressure vessel. In the downcomer, it gets mixed with the incoming feed water and ultimately fed to the inlet of the core through recirculation pump.

The bottom core support plate is a perforated plate, which in turn is connected to shroud bottom ring. At the top, another grid, called top grid, is located. The weight of fuel assemblies is transferred finally to reactor pressure vessel bottom head. In general, both top grid and bottom core support plate along with bottom stiffener grid help in maintaining alignment of fuel assemblies during normal and accident conditions. Two pairs of core spray pipes are connected to main shroud shell. These pipes are part of Emergency Core Cooling system (ECCS) (shown in Fig. 1). These pipes deliver cold water to core spray ring spargers during ECCS injection. The upper end of main shroud shell is connected to reactor pressure vessel through 6 thermal stabilizers. The thermal stabilizers are equally spaced along the circumference. The thermal stabilizer comprises of pin and lugs with a hole. It provides lateral support to Core Shroud and permits axial thermal expansion of main shroud shell due to clearance between pin and lug hole.

The entire shroud assembly except the conical skirt is made up of Austenitic Stainless Steel - AISI Type 304 (18% Cr, 8% Ni). Conical Skirt is made up of INCONEL-600 (72% Ni, 15% Cr, 8% Fe).

The reactor operates at 1000 psig. The core flow is 27.2 E+6 lbs/hr. with an inlet enthalpy of 525.0 Btu/lb. The design pressure of RPV is 1200 psi and design temperature 600 deg.F.

3.0 METHODOLOGY

Each accident analysis has been divided into two parts

3.1 CALCULATION OF THERMAL HYDRAULIC, STRUCTURAL AND SIESMIC LOADS

For the calculation of thermal-hydraulic loads acting on the Core Shroud, a detailed analysis has been carried out for each postulated accident scenario using the thermal-hydraulic code RELAP4/MOD6. However, it is assumed that the thermo-mechanical equilibrium exists between two phases of the coolant during the transient. The accident sequences considered for Recirculation Line Break (RLB) is (i) An instantaneous double ended guillotine rupture is postulated at the discharge side of the recirculation pump in one of the two loops. (ii) The reactor trips on high drywell pressure. (iii) The turbine stop valve closes on low main steam line pressure with some delay and PSIV closes at low reactor pressure. The closing of stop valve or PSIV separates the reactor from the turbine generator. For Main Steam Line Break (MSLB) the scenario is (i) An instantaneous double ended guillotine rupture is postulated in one of the two main steam lines before PSIV. (ii) When the steam flow rate is more than 140% of the normal flow in that line, the PSIV starts closing. At 10% closure of PSIV, the reactor scrams. On closure of PSIV, the reactor is separated from the turbine generator. The feed flow rate increases to its upper bound.

In order to calculate the loads on the shroud wall due to the pressure differentials and due to drag, the downcomer and the core have been divided into a number control volumes. Separate volumes have been considered for the lower plenum, where the liquid is subcooled and for the upper plenum where moisture separator and dryers are present. Since either the PSIV or the stop valve closes following the transient and thus the reactor core is separated from the turbine generator, this part of the reactor has been modeled as non-conduction heat exchanger where a part of the heat is removed. The Core Heat Slab model has been used in the core. RELAP4 heat transfer model has been used in the core region. The Moody's model has been used for the critical flow. For pumps, centrifugal model with four quadrant curves have been used [1]. The mass, energy and momentum equations in the differential form are as follows

$$A\frac{\delta\rho}{\delta t} = -\frac{\delta W}{\delta X} \qquad (1)$$

$$A\frac{\delta(\rho e)}{\delta t} = -\frac{\delta}{\delta X}\{W(h+\frac{v^2}{2}+\phi)\} + q_w\frac{\delta A_w}{\delta X} \qquad (2)$$

$$A\frac{\delta(\rho v)}{\delta t} = -\frac{\delta(v\,W)}{\delta X} - A\frac{\delta P}{\delta X} - \rho g A\frac{\delta Z}{\delta X} - \frac{\delta F_k}{\delta X} \qquad (3)$$

3.1.1 Loads due to mslb and rlb

The total load on the Core Shroud due to LOCA has been calculated by adding the forces due to pressure differential across the shroud and the drag forces on the shroud wall. The drag force on the shroud has been calculated from the frictional pressure drop due to drag.

The transients following the RLB and MSLB have been analyzed for first 20 s, since the maximum differential pressure is confined within this time period. The Fig.3 and Fig.4 show the differential pressure across the shroud wall at two different locations following MSLB and RLB. Since the liquid in the downcomer and the lower plenum of the vessel is slightly subcooled, the flow following RLB is much higher and hence the differential pressure is also higher. But for MSLB, the fluid in the steam line is saturated steam, the flow is less and the pressure differential is also less. Flow reversal takes place following the RLB. Therefore the direction of force changes, but for MSLB, it remains in the same direction.

3.1.2 Safe shutdown earthquake loads

In order to account for postulated SSE loads, the horizontal and vertical siesmic loads have been considered in the analysis.

3.2 STRUCTURAL ANALYSIS

Dynamic analysis of Core Shroud assembly following MSLB/RLB has been done using DLF method. DLF vs. frequency spectra has been obtained for the given load time histories.

DLF = Ymax/Yst (4)

The Dynamic response for Single Degree of Freedom (SDOF) system is obtained by the solution of Duhamel's Integral.

$$Y(t)=e^{-\xi\omega t}\{\ (\ \frac{Y'i+\xi\omega Yi}{\omega_d}\ )\sin\omega_d t+Yi\cos\omega_d t\ \}+Yst\frac{\omega^2}{\omega_d}\int_0^t f(\tau)e^{-\xi\omega(t-\tau)}\sin\omega_d(t-\tau)d\tau \tag{5}$$

For MSLB/RLB time histories, the DLF vs. frequency spectra were evaluated by computer program DLFSPEC [5]. The damping ratio taken is 2% of critical damping ratio.

The added damping due to light water has been neglected. The DLF vs. frequency for MSLB/RLB load time histories at some important locations are shown in Fig.4 and Fig.5.

3.2.1 Finite element modeling of the core shroud

All the components of the Core Shroud assembly along with their important geometrical dimensions have been modeled by 3D finite element modeling (Fig.2). For the perforated torispherical head and bottom core support plate, equivalent solid plate approach, with modified elastic and plastic constants (Young's Modulus, Poison's ratio and Yield Stress) has been followed [6]. The Finite Element Model is shown in Fig.5. The connection of Conical Skirt to RPV was modeled as rigid support. Therefore, the lower end of the Conical Skirt is totally tied. The top end of the Main shroud Shell is connected to RPV through thermal stabilizers. It provides transverse support and partial axial support to the Core Shroud.

3.2.2 Calculation of hydrodynamic added mass

The Core Shroud components are submerged in water. During transient loads the vibration of submerged components experience impulsive pressure reactions of surrounding fluid, which is manifested in terms of Hydro Dynamic Added Mass. In order to have realistic natural frequencies of the components, the Hydrodynamic Added Mass for all the components of the Core Shroud has been calculated as $M_h = M_c + C_m M_d$.

3.2.3 Evaluation of the natural frequencies of the core shroud components

In order to asses the Dynamic Amplification during MSLB/RLB, the natural frequencies of the Core Shroud components have been evaluated. For RLB/MSLB, it has been seen that after about frequency of 25 Hz, the DLF values saturate. Therefore first 75 modes were considered which cover frequencies upto 31 Hz.

3.2.4 Stress/instability analysis and results for rlb, mslb and sse

According to TAPS design calculation report, rules of ASME B&PV Code Sec.I and ASME B&PV Code Sec.VIII were followed. Currently, the design rules of nuclear assessment is available in ASME B&PV Code Sec.III. This analysis is based on ASME B&PV Code Sec.III NB and Sec.III NG. However the results presented here is for the Sec.III NB only. The allowable stress considered is the minimum of Sec.I, SecIII and Sec.VIII Division 1. The postulated loads are classified as Level D service loads due to their low probability. The analysis is based on differential pressure/drag force vs. time histories, corresponding DLF vs. frequency spectra and mode shapes/natural frequencies of Core Shroud Components. The results at locations of interest are shown in the table 1 and table 2.

Table 1 Stress Intensity near Weld Locations for MSLB and RLB Loads .

Location (Welds and others, see Fig.1)	Memb.Stress (Ksi)		Stress Limit (ksi)	Bending Stress (Ksi)		Pm (or Pl) + Pb Stress(Ksi)		Stress Limit (Ksi)
	MSLB	RLB		MSLB	RLB	MSLB	RLB	
H-10	4.4 (Pl)	8.9 (Pl)	72.0	6.6 (Q)	12.4 (Q)	4.4	8.9	72.0
H-9	9.8 (Pl)	19.0 (Pl)	57.24	2.2 (Q)	4.3 (Q)	9.8	19.0	57.24
H-8	9.5 (Pl)	18.6 (Pl)	57.24	1.2 (Q)	2.4 (Q)	9.5	18.6	57.24
H-6	7.7 (Pl)	14.3 (Pl)	57.24	1.7 (Q)	0.3 (Q)	7.7	14.3	57.24
H-5	8.3 (Pl)	9.8 (Pl)	57.24	3.5 (Q)	4.3 (Q)	8.3	9.8	57.24
H-4B	6.0 (Pl)	12.9 (Pl)	57.24	1.3 (Q)	2.1 (Q)	6.0	12.9	57.24
H-4A	6.4 (Pl)	12.4 (Pl)	57.24	0.2 (Q)	1.0 (Q)	6.4	12.4	57.24
H-3	6.4 (Pl)	12.9 (Pl)	57.24	2.4 (Q)	4.1 (Q)	6.4	12.9	57.24
H-1	2.9 (Pl)	3.5 (Pl)	57.24	9.1 (Q)	20.1 (Q)	2.9	3.5	57.24
Knuckle Region of Shroud	10.7 (Pl)	18.0)Pl)	57.24	9.3 (Q)	16.0 (Q)	10.7	18.0	57.24
Opening of Core Spray Lines	16.4 (Pl)	33.4 (Pl)	57.24	0.3 (Q)	0.4 (Q)	16.4	33.4	57.24

Table 2 Stress Intensity near Welds and other than Weld Locations for SSE Loads.

Location (Welds and others, see Fig.1)	Memb. Stress (Ksi)	Bending Stress (Ksi)	Total Pm (or Pl) , (Ksi)	Stress Limit (Ksi)	Pm (or Pl) +Pb (Ksi)	Stress Limit (Ksi)
H-10	0.7 (Pm)	2.6 (Pm)	3.3	48.0	3.3	72.00
H9	1.0 (Pm)	2.8 (Pm)	3.8	38.16	3.8	57.24
H8	0.4 (Pm)	4.7 (Pm)	5.1	38.16	5.1	57.24
H-6	1.2 (Pm)	3.3 (Pm)	4.5	38.16	4.5	57.24
H-5	0.5 (Pm)	2.5 (Pm)	3.0	38.16	3.0	57.24
H-4B	0.4 (Pm)	0.9 (Pm)	1.3	38.16	1.3	57.24
H-4A	0.2 (Pm)	0.8 (Pm)	1.0	38.16	1.0	57.24
H-3	0.1 (Pm)	2.5 (Pm)	2.6	38.16	2.6	57.24
H-1	0.5 (Pm)	6.2 (Pm)	6.7	38.16	7.7	57.24
Knuckle Region of the Shroud	6.1 (Pm)	2.9 (Pb)	6.1	38.16	9.0	57.24
Opening of Core Spray Lines	3.6 (Pl)	0.6 (Q)	3.6	57.24	4.2	57.24

4.0 DISCUSSION AND CONCLUSION

The need of this study arose, following the cracking of Core Shroud of BWR located outside India. The transient loads due to MSLB, RLB and SSE were not considered in the original design of the TAPS reactor. Hence, healthy core shroud with these postulated accidents has been analyzed as a first step towards assessment of structural safety. The loads following MSLB is tensile where as loads following RLB is compressive in nature. The maximum loads, including the drag, are 7.63 E+5 lbs for MSLB and 9.06 E+5 lbs for RLB. The MSLB loads will be particularly important for Core Shroud with crack. The analysis has been done based on both ASME B&PV Code Sec.III NB & NG, the results presented here is for the Sec.III NB. In order to be conservative, the allowable stress considered is the minimum of Sec.I, SecIII and Sec.VIII.

From the stress analysis it is concluded that the actual stress intensities are well below the stress limits either for RLB or for MSLB or for SSE. From instability analysis, it was concluded that, for MSLB event there is a margin of 3.8 on load to cause plastic buckling of knuckle region of the Torispherical Shroud Head as compared to minimum requirement of 2.0. This postulated buckling is localized in nature. For RLB event there is a margin of 2.2 on load to cause plastic collapse of knuckle region as compared to minimum requirement of 1.1.

5.0 NOMENCLATURES

A	Flow area	v	Fluid velocity
A_w	Wall area for heat transfer	W	Mass flow rate
C_m	Coefficient of added mass	X	Path length co-ordinate
e	Total fluid specific energy	Yi	Initial displacement
	$(u + \frac{v^2}{2} + \phi)$	Y'i	Initial velocity
F_k	Frictional force	Ymax	Maximum response at any time in output response history
F(t)	Load time history		
f(t)	Load time history, normalized w.r.t. P_0, such that $F(t) = P_o.f(t)$	Yst	Static response of SDOF system for max. load in load time history
$f(\tau)$	Value of f(t) at $t = \tau$	Y(t)	Dynamic response of SDOF system
g	Gravitational acceleration constant	Z	Elevation Co-ordinate value
h	Fluid enthalpy $(h = u + \frac{P}{\rho})$	ϕ	Gravity potential function $(g = \frac{\delta\varphi}{\delta Z})$
M_c	Mass of fluid contained in the component	ζ	Damping ratio
M_d	Mass of fluid displaced by the component	ρ	Fluid density
M_h	Hydrodynamic added mass	τ	Time constant
P_b	Bending stress	ω	Undamped natural frequency of SDOF system
Pl	Primary local membrane stress		
P_m	Membrane stress	ω_d	Damped natural frequency of SDOF system
P_o	Maximum load in a load time history		
Q	Secondary bending stress		
q_w	Wall heat flux		
t	Time coordinate		
u	Fluid specific internal energy		

6.0 REFERENCES

1. RELAP4/MOD5: A computer program for transient thermal-hydraulic analysis of nuclear reactors and related systems. User's manual, Volume 1, RELAP4/MOD5 description. K.R. Katsma et al., Idaho National Engineering Laboratory. Report No. ANCR-NUREG-1355, September 1976

2. RELAP4/MOD6: A computer program for transient thermal-hydraulic analysis of nuclear reactors and related systems. User's manual, S.R. Fischer et al., Idaho National Engineering Laboratory. Report No. CDAP TR003, January 1976

3. American Society of Mechanical Engineers, Boiling and Pressure Vessel Code, Sec.I, Sec III-NB &NG and Sec.VIII Div.1, 1992

4. Fritz R.J., The effects of liquids on the dynamic motions of immersed solids, Journal of Engg. for Industry, Feb., 1972, pp 167-173

5. Bhasin V. and Kushwaha H.S., DLSPEC: Program for evaluating DLF spectra, Reactor Engineering Dvision, Bhabha Atomic Reseach Center, Mumbai 40085, India.

6. O' Donnell W.J., and Langer B.F., Design of Perforated Plates, Journal of Engg. for Industry, Vol. 84, 1962, p-307.

7. Slot T., and O' Donnell W.J., Effective elastic constants for thick perforated plates with square and triangular penetration patterns, Journal of Engg. for Industry, Vol. 93, 1971, p-395.

8. Porowski J.S., and O'Donnell W. J., Plastic Strength of Perforated Plates with Square Penetration Patterns, Journal of Pressure Vessel Technology, Vol.97, 1975, p-145.

9. COSMOS/M (ver.1.71, 1995) Finite Element Computer Program, Structural Research and Analysis Corporation, Santa Monica, California 90405.

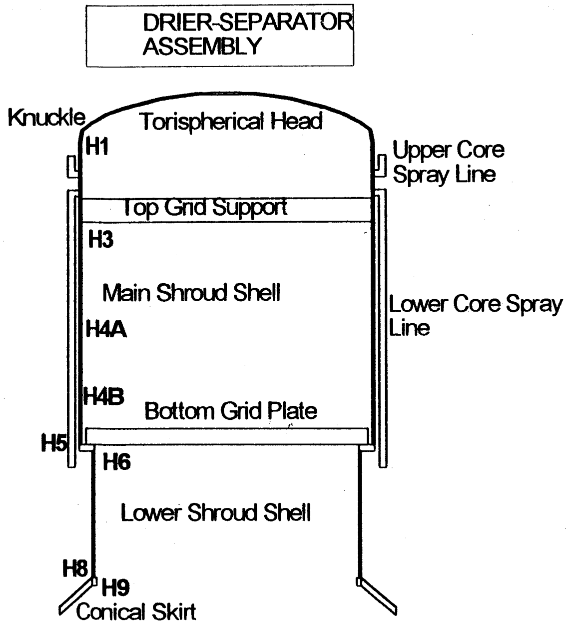

Fig.1 Schematic View of TAPS Core Shroud indicating main components & Weld Locations

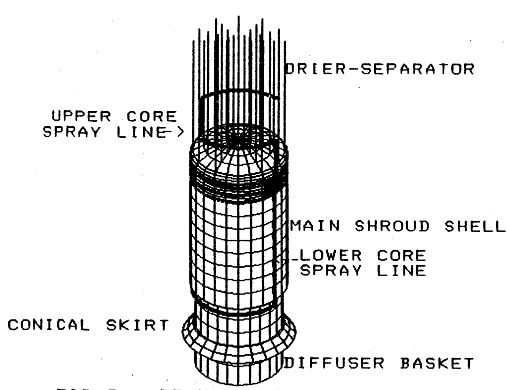

FIG.2 : FE MESH OF CORE SHROUD

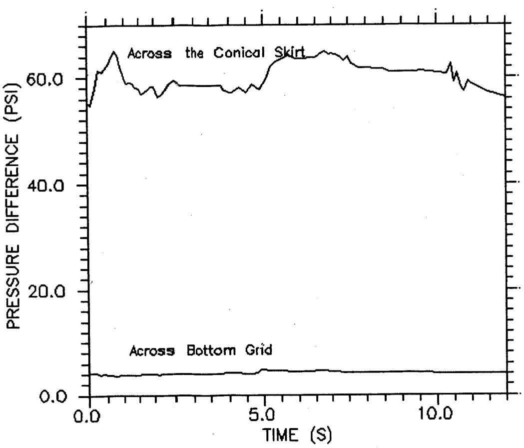

Fig.3 DIFFERENTIAL PRESSURE AT TWO DIFFERENT LOCATIONS FOR MSLB

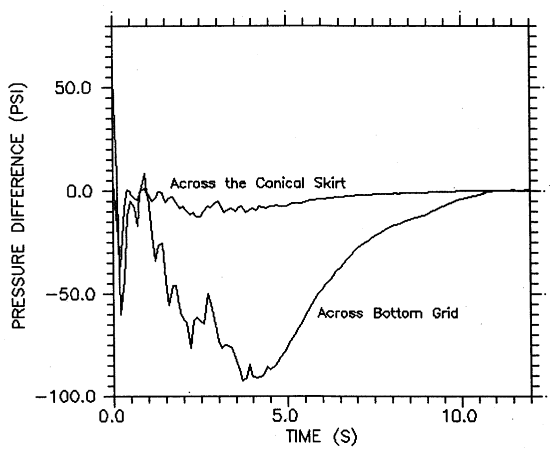

Fig.4 DIFFERENTIAL PRESSURE AT TWO DIFFERENT LOCATIONS FOR MSLB

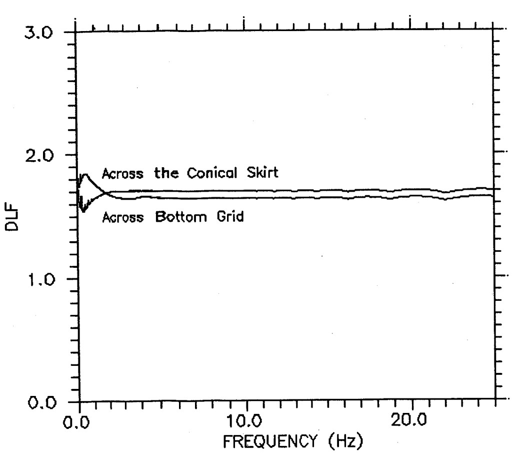

Fig.6 DLF–FREQUENCY RESPONSE FOR DIFFERENTIAL PRESSURE AT TWO DIFFERENT LOCATIONS FOR MSLB

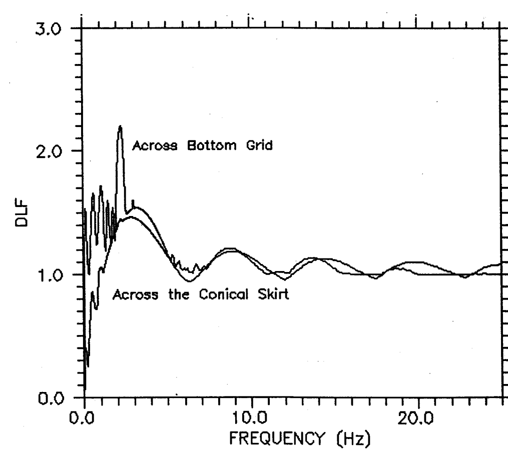

Fig.5 DLF–FREQUENCY RESPONSE FOR DIFFERENTIAL PRESSURE AT TWO LOCATIONS FOR RLB