Vibration analysis of a Pool Type LMFBR.
Fluid-structures Coupled Modes
and Response to Flow Excitations

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Summary

A comprehensive analysis in several steps was made in order to estimate the flow induced vibrations of SUPERPHENIX reactor internal structures. This analysis includes calculation and full-scale tests in air, fluid-structure modal calculation and limited verification by tests. In both cases, the calculation used a substructuration procedure. Excitation sources were estimated using reduced scale models. These sources were then introduced in the modal model of the complete fluid-coupled assembly in order to calculate the response in terms of displacements and stresses.

The stress responses due to these sources revealed to be below the fatigue stress limits. Their maximum were localized at the points where strain gages were implemented for the control of the reactor behaviour during operation.

1. Description of the Problem

The internal structures of SUPERPHENIX reactor mainly consist of several thin concentric axisymmetrical vessels. 12 couples of crossings are fixed on the two main internal vessels named "conical redan" and "toroïdal redan" /1/. Sodium fills the internal volumes and the thin spaces separating the vessels (see figures 2, 3 and 4).

The main excitation sources consist of pressure fluctuations generated by the turbulent flow in the hot collector (core outflow) and in the cold collector (heat exchangers outflow).

A full-scale calculation and test program (see figure 1) has been developed and accomplished in order to analyse the flow induced vibrations of these reactor internals:

a) a calculation of the main natural modes of the structure has been made in air, and compared to full-scale test data.

b) fluid has been introduced into the 3 D modeling of vessels and the fluid structure coupled modes are obtained. Calculation procedure use substructuration technics, substructures being described by axisymmetric F.E. models.
We note that the presence of sodium strongly couples the substructures and reduces the resonance frequencies by a factor of ten.

c) excitation sources, predicted on the base of an hydroelastic mock-up are applied to the modal model giving a prediction of vibratory levels.

2. In Air Calculation and Tests

A first step concerned the achievement of a model of the structures in air. A substructuration procedure was used, involving a two-dimensional axisymmetrical finite element calculation of substructures modes (AQUAMODE code) /2/ and then a stiffness assembly (TRISTANA code) /3/.

Results of these calculations show that the three-dimensional effects due to the presence of crossings is localized in particular frequency zones of the main assemblies natural frequencies. Lowest resonances were about 1.7 Hz, and concerned the "conical redan" assembly with an axisymmetrical type mode shape (n=3) and a weak coupling of pump crossings. For this conical assembly and up to 8 Hz, only pumps crossings coupling appears in two frequency zones respectively about 4,5 Hz and 6.3 Hz /1, 4 and 5/.

The lowest resonant frequency of the "toroïdal redan" assembly was at 4.05 Hz, with almost a pure axisymmetrical shape (n=6). Again, pumps crossings have the major coupling effects in two frequency zones around 5.5 and 8 Hz (See table I).

Such results were verified by a full-scale test procedures conducted on site. The comparison showed a 10% confidence in natural frequencies as well for the main vessels behaviour, as for the coupling effect of crossings. Damping rates appeared to be high for such welded structures: 1 to 2%.

3. Calculation of the Fluid Coupled Modes

The structural model so qualified was modified in order to introduce the representation of the fluid. Liquid finite elements was used for the thin layers separating the vessels, and the hot collector fluid was represented by an equivalent added mass. The liquid free surface was modelized by a zero pressure condition (gravity effect is neglected).

It should be noticed that the equivalent added masses due to the presence of the fluid are very high compared to structural and fluid masses. A sensibility analysis showed that their effect was reduced comparatively to the inertial effect of the thin fluid layers, modelized by finite elements.

A finite element calculation was conducted on each substructure, note that these substructures include coupled axisymmetrical shells and sodium sheets (see figure 3).

An assembly procedure was then realized using the modal basis of substructures resulting from the axisymmetric finite element calculation. As for the calculation in air, it used a stiffness type clamped relation between structural nodes at the connections. The 3 D coupling between shells and crossings, and between the crossings themselves, was neglected.

Results of the "in sodium" calculation exhibit first natural frequencies reduced by a factor of 7 compared to those "in air". 74 modes were founded with resonance frequencies lower than 1.5 Hz. The first modes involve uniquely the conical redan assembly, with a weak coupling of crossings. Only the 7th mode begins to influence the "toroïdal redan assembly", and the 15th corresponds to a major effect of crossings.

4. Estimation of the Sources

The characterization of the pressure fluctuation sources induced at the walls of the internal structures has been estimated from experimental measurements on hydraulic mock-ups of reactor internals. At the CEA/DEMT, tests have led to the estimation of pressure efforts induced by the turbulent flow in the hot collector on the conical redan vessels and their associated crossings. Other tests were related to the measure of pressure fluctuation at the outlet of the heat exchangers on the cold collector /6 and 7/. Similar tests have been realized by EdF/LNH.

The pressure fluctuations power spectral densities showed to have very low cut-off frequencies respectively 0.016 Hz and 0.04 Hz for the hot and cold collector. In addition, in the frequency range of the first modes of the fluid-coupled structures, the excitation of the cold collector was more than an order of magnitude higher than the one of the hot collector (see figure 5).

5. Calculation of the Response of the Structures

The results were expressed in terms of a majorant of the standard deviation $\overline{\delta}(S,O)$, taking pessimistic correlation lengths and angles. Subsequently, two damping rates were taken uniformly on all the modes: 1 and 2%.

Results showed that the cold collector source effect was dominant on the maximum response in displacement, localized at the upper end of the conical redan vessel. This result is interesting, taking into account the fact that this source do not excite directly this vessel. The transmission effect is due to fluid coupling and 3 D coupling by the crossings.

An extensive analysis was realized in order to find the maximum stress localization. Four such localizations were found at the bend of vessels, as shown in figure 4.

References

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/2/ JEANPIERRE, F., BRABANT, F., LEPAREUX, M., "Système CEASEMT - Programme AQUAMODE", Rapport EMT/SMTS/VIBR/80/18 (1980).

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Figure 1 - Procedure for the analysis of the flow induced vibrations of SUPERPHENIX internal structures.

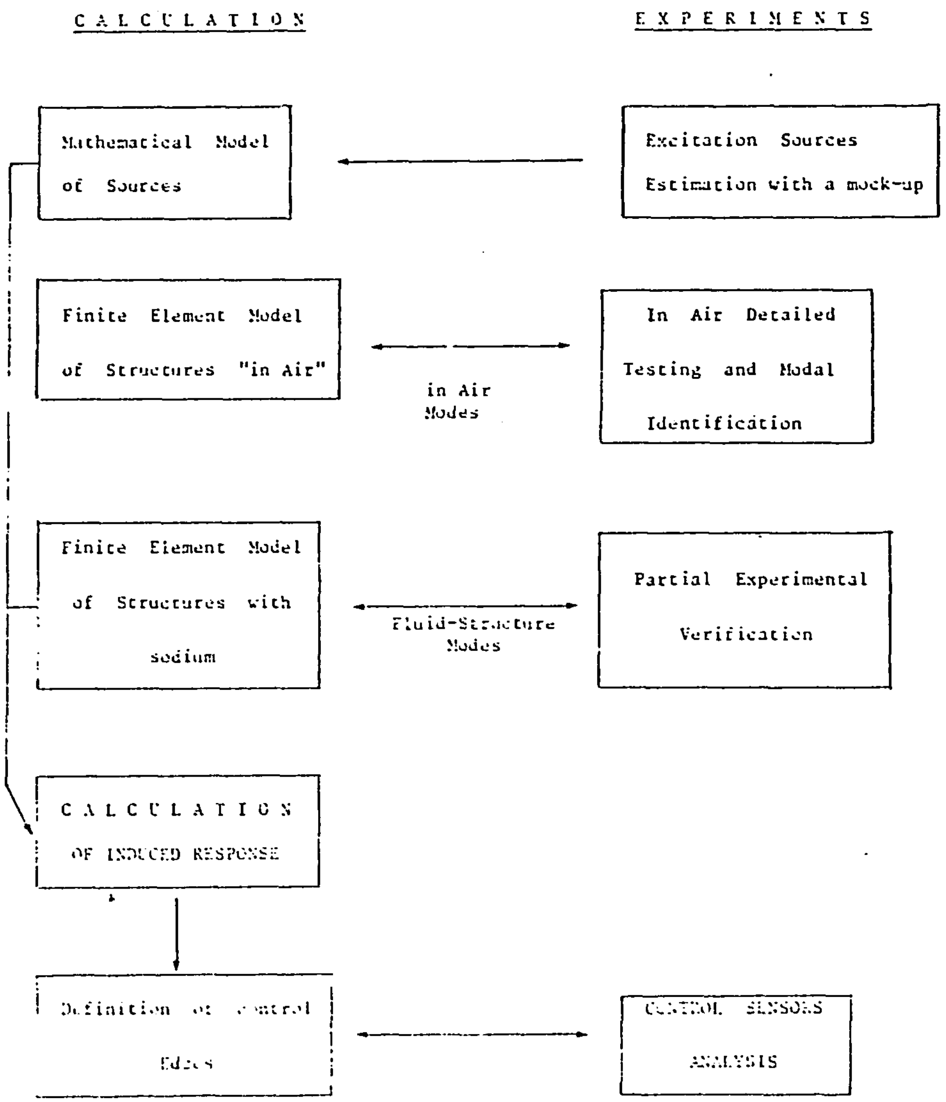


Table I - Eigen modes in air of internal structures
Comparison between calculation and tests

1 - Conical redan vessels

n	Calculation	Tests
3.1	1.7	1.58 - 1.74
2.1	2.24 - 2.43	1.9 - 2.35
4.1	3.02 - 3.06	2.68 - 3.15
5.1	5.04	4.16 - 4.43
6.1	6.78 - 6.85	5.87 - 6.25
Pumps crossings modes:		
Tangential	4.44 - 4.81	3.9 - 4.4
Radial	6.01 - 6.92	6.92 - 7.5

2 - Toroïdal redan vessels

n	Calculation	Tests
6.1	4.05 - 4.07	4.83 - 5.14
5.1	4.36	4.64 - 5.14
7.1	4.43	5.83 - ...
8.1	5.13 - 5.27	6.10 - ...
4.1	5.13 - 5.93	4.83
Pumps crossings modes:		
1st	5.13 - 5.93	4.55 - 5.5
2nd	7.59 - ...	7.6 - ...

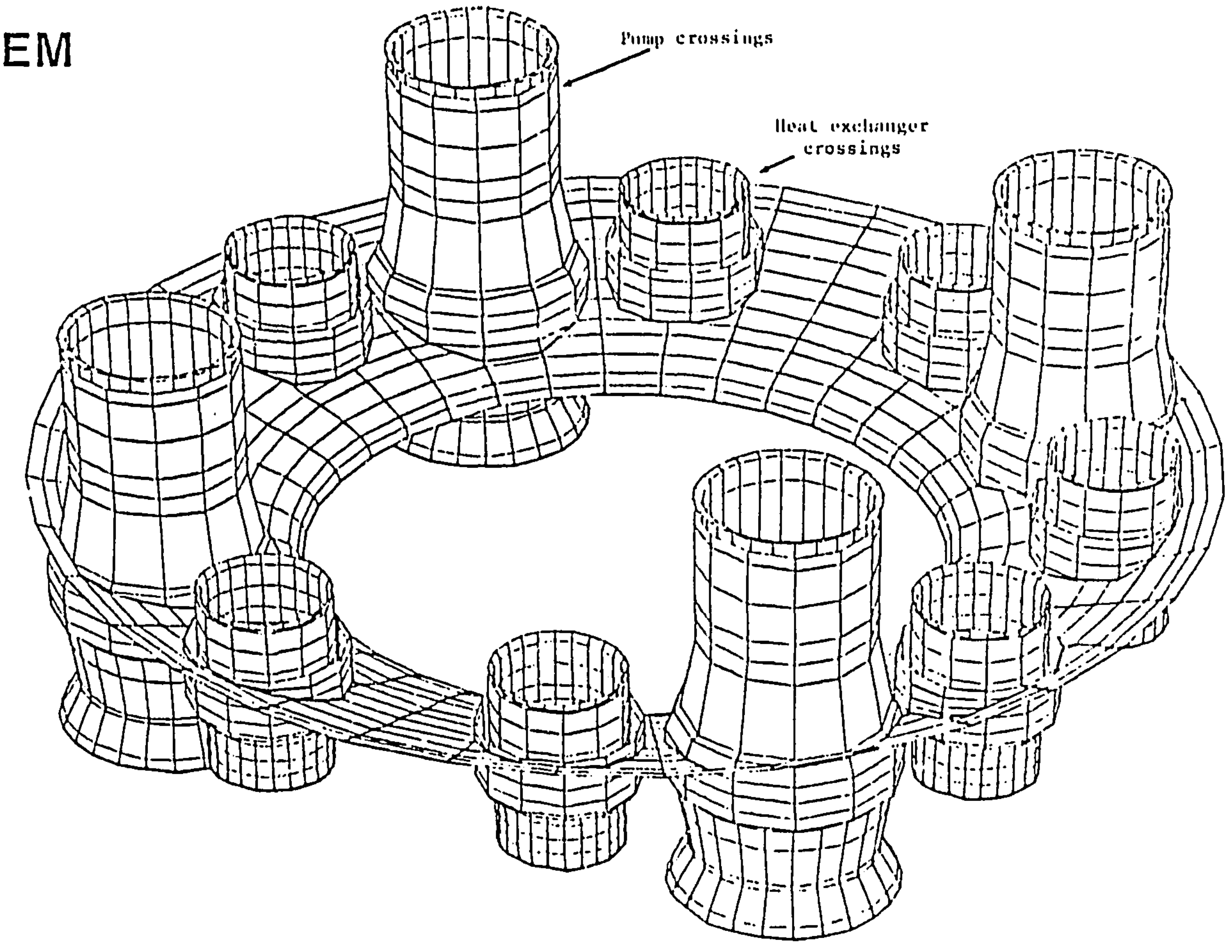
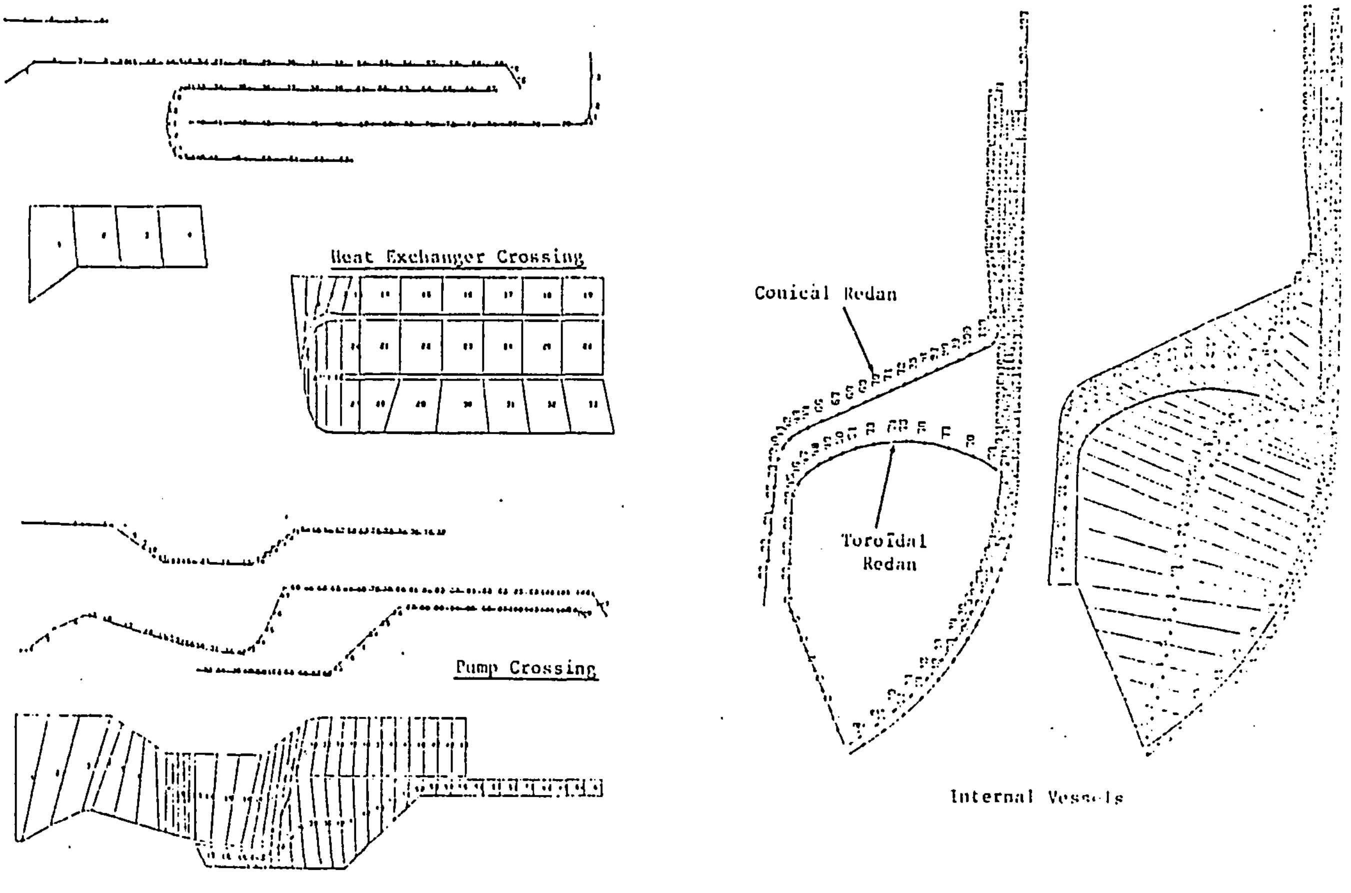
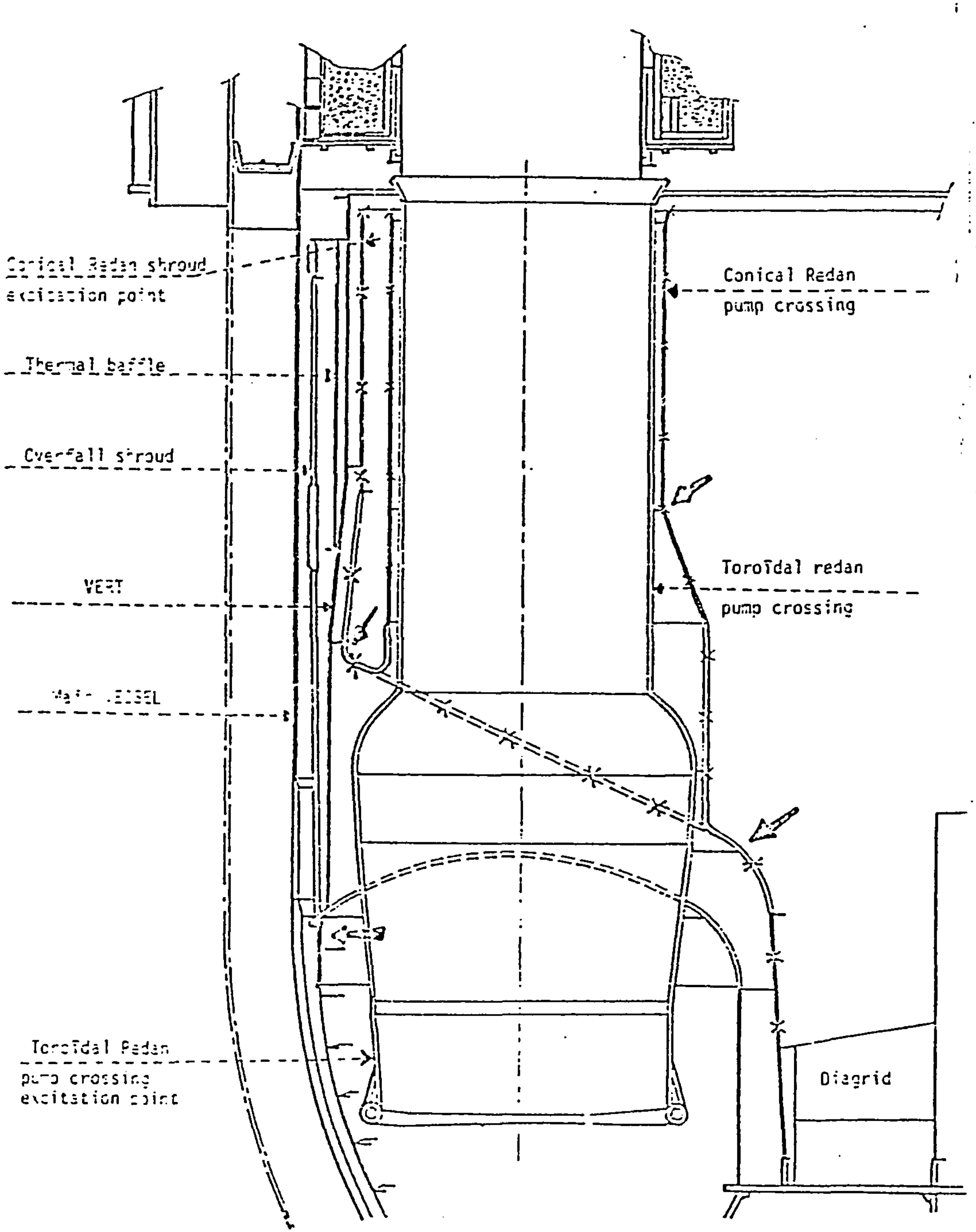


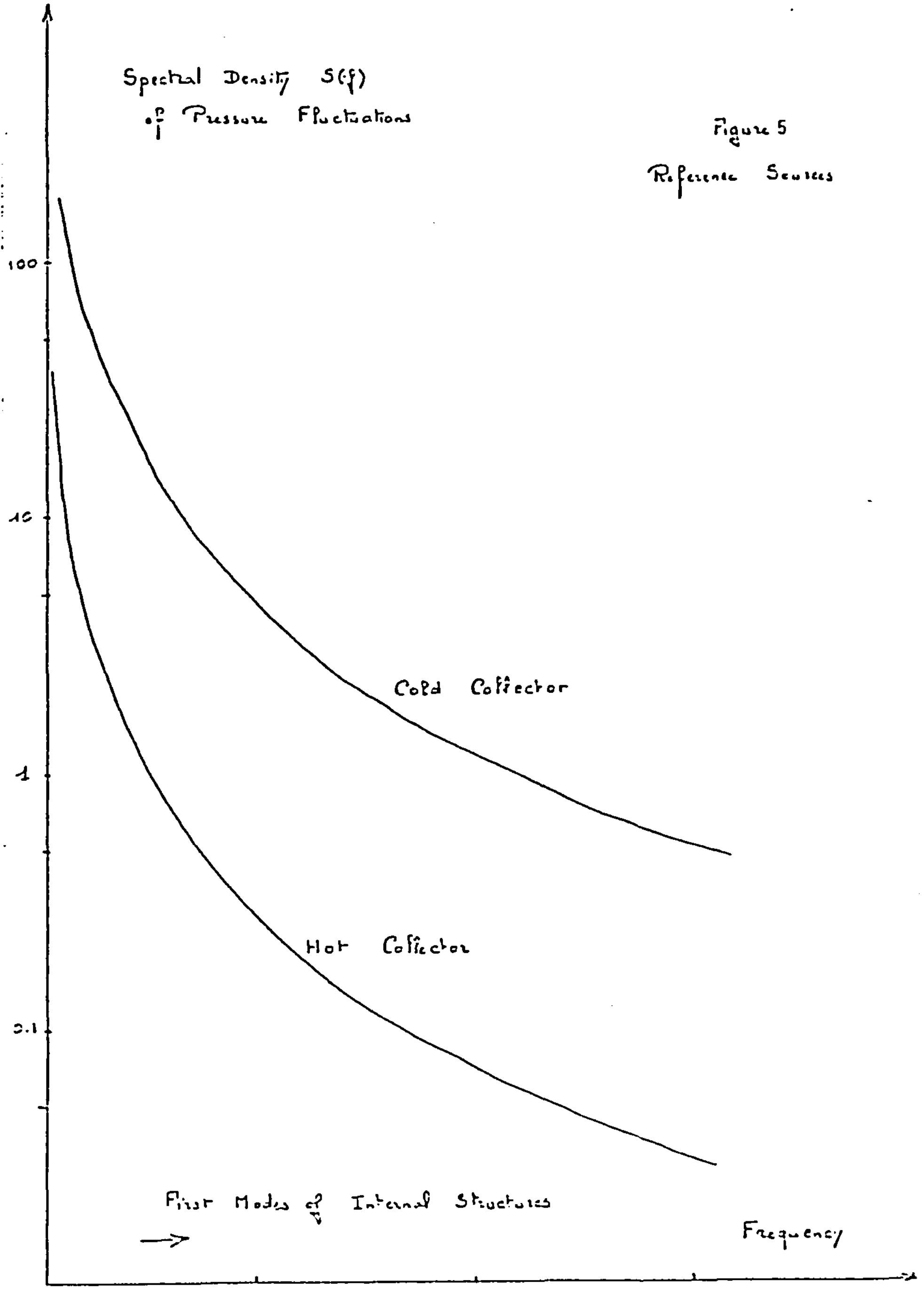
Figure 2 - General View of Disposition of Conical Redan and Crossings Disposition.

Figure 3 - Finite Element Model of Substructures




Conical Redan shroud
excitation point
Thermal baffle
Overfall shroud
VERT
Main VESSEL
Toroidal Redan
pump crossing
excitation point
Conical Redan
pump crossing
Toroidal redan
pump crossing
Diagrid

[illegible]


Spectral Density S(f)
of Pressure Fluctuations
Figure 5
Reference Sources
100
10
1
0.1
Cold Collector
Hot Collector
First Modes of Internal Structures
→
Frequency