I.W.G.F.R. SPECIALISTS' MEETING ON FLOW-INDUCED VIBRATIONS

Paris , October 21-24 , 1986

ANALYSIS OF FLOW-INDUCED VIBRATIONS IN THE PEC DESIGN

L.Cornaggia (+) , A.Martelli (o) , M.Reale (+) , M. Zambelli (o)

(+) - ANSALDO S.p.A. , Genova , Italy
(o) - ENEA , Fast Reactor Dept., Bologna, Italy

ABSTRACT

This paper summarizes the studies performed for the Italian PEC fast reactor test facility with regard to flow - induced vibration problems. Reference is made to the reactor - block , the primary and secondary coolant loops and the emergency loops. Studies in progress and future developments foreseen are also mentioned.

This paper was written with the contributions of Messrs. A. Alemberti, R. Capello, M. Ciaravolo , A. Donati, P. Elia, G.P. Fazio and A.Perfumo of ANSALDO, M. Zola of ISMES, and P. Gori and D. Tirelli of ENEA, Fast Reactor Department.

1. REACTOR FEATURES

PEC (Prova Elementi di Combustibile, i.e. Fuel Assembly Test Facility) is an experimental semi-integrated loop-type fast reactor, whose construction is nearing completion at the Brasimone site, in the Appenines midway between Bologna and Florence. The main feature of this reactor, characterized by a power of about 120 MWth, is the in-pile study and development of fast reactor fuel.

To meet this requirement, a test loop has been provided at the centre of the core and the vessel. The test loop has its own cooling circuit and is hydraulically and thermally insulated from the driver core. It contains the test element section which is neutronically coupled to the driver zone.

The driver zone of the core consists of groups of seven elements, forced together at the contacting pads.

The main vessel also contains the neutronic and thermal shields which surround the core.

The two intermediate heat exchangers and the two circulation primary pumps are contained in a separate vessel (component vessel). The corresponding components of the test circuit are contained in an analogous vessel.

The reactor emergency circuit consists of a special loop, that exits from the main vessel, passes through an electromagnetic pump and a U- heat exchanger and returns to the vessel.

The secondary reactor loops are provided each with three sodium-air heat exchangers in parallel and a centrifugal pump, which is contained in an expansion vessel. The secondary test loop and the secondary emergency reactor circuits are both provided with a sodium-air heat exchanger and an electromagnetic pump.

2. CRITERIA AND METHODOLOGIES

In the PEC design no general criteria nor methodologies have been defined or applied for the analysis of flow-induced vibration phenomena, due to the fact that the reactor is characterized by rather stiff structures, low pressure levels and relatively reduced mass-flow rates. We note that no steam generators are present in the reactor: this excludes the flow- induced vibration problems which might arise in the presence of such components.

Thus, the flow-induced vibration problem has been considered, for the different components, basing on an "engineering judgment" approach. For those components which could be easily modelled due to their simple shape, the natural frequency values were computed and compared to the flow-induced vibration frequencies: in the case of differences larger than 20%, no further analysis was required; on the contrary, in the case of differences less than 20%, the maximum stress levels were computed in resonance conditions, and it was checked that the permissible limits were respected. In a few cases only, this has lead to the necessity of design modifications.

For complicated component shapes, the technical judgment was based on practice, experience on similar plants and data available in the literature. Furthermore, for the most relevant components, experimental tests and detailed numerical studies have been carried out.

3. STUDIES PERFORMED

The circuits considered up to now with regard to fluid-structure interaction have usually been the main circuits: -

- reactor-block
- primary and secondary reactor coolant loops
- primary and secondary reactor emergency loops
- primary and secondary test loop coolant circuits.

For these circuits the analysis referred to those plant conditions which general experience, and in particular that derived from Superphénix-1, have indicated as the most critical.

3.1 Reactor-block

The reactor-block components on which possible flow-induced vibration effects should be taken into account are: -

- vessel and core diagrid
- fuel assemblies and pins
- hold-down and shut-down systems
- sodium level transducers
- pipes of the purification, drainage and emergency systems
- test channel.

3.1.1 Vessel and core diagrid

The vessel and the core diagrid have not been considered as possible sources of significant fluid-structure interaction effects due to their high stiffness.

3.1.2 Fuel assemblies and pins

With regard to fuel assemblies, a series of experimental tests has been performed in water on the single assembly, a group of seven elements and a mock-up of the pin bundle. All tests were performed in full scale. The results indicated that the natural frequencies are never excited by the fluid.

3.1.3 Test channel

For the test channel an extensive experimental programme has been carried out by ISMES in pressurized water at 95 °C at the ENEA Centre of Casaccia, in the CV2 plant. The main purposes of the tests, relevant to flow-induced vibrations, were: -

- to evaluate flow-induced vibration intensity and identify the dynamic interaction phenomena between the coaxial walls of the channel ;
- to evaluate, at different flow rates, the possible excitation phenomena due to coolant flow, in the presence of sudden changes in flow direction, obstacles and cross-section changes;
- to characterize the channel from the dynamic point of view /1/.

Pressure,displacements and acceleration transducers were placed inside and outside the channel at several locations. A first series of tests was performed recording the pressure pulses inside the channel walls, while varying the flow rate. During these tests modifications of the hydraulic circuit were introduced to make it possible to identify the pulses originating inside and outside the channel, and to separate the flow-induced vibrations from the ones generated by other sources, such as rotating machinery, etc.

The second series of tests concerned the dynamic characterization of the channel. To this aim the channel was excited with a sinusoidal force applied at different points by means of an electrodynamic exciter. The explored frequency range was 10-500 Hz. Different force amplitudes and restraint conditions were examined. Preliminary tests were performed by means of a mechanical shaker to make it possible to dynamically characterize the channel support tower, thus obtaining the corresponding frequency response functions.

The test results showed that no dynamic excitation phenomena due to the coolant flow occur in the channel, and that the pressure pulse characteristic frequencies, originating inside the channel, do not interact with natural frequencies. However, the channel response appeared to be strongly non-linear.

3.1.4 Hold-down and shut-down systems

An extensive experimental study was also carried out, again by ISMES, on the hold-down and shut-down systems. This study is described in detail in a technical paper presented at this meeting /2/. Here we only mention that the tests were performed in water on full-scale mock-ups of the actual systems, including all hold-down system solutions, a shut-down system and a simulation of the upper part of the core elements.

Steady-state conditions with different flow rates up to the nominal one were analysed, as well as start-up and shut-down transients of different durations. Among other results, it was verified that flow-induced vibration levels remain below the specified limits, signals from the thermocouples located on the hold-down systems are not affected by the vibrations, and the hold-down systems remain correctly supported.

3.1.5 Sodium level transducers

The sodium level transducers are those components which were most sensitive to flow-induced vibrations. This was especially true for the cans,containing the transducer sensitive elements, which can be modelled as tubes closed at one end and welded to the vessel plug at the other end.

The computed natural frequencies of these components have been compared to the flow-induced vibration frequency values evaluated on the basis of flow-rate distribution measurements performed in water on a 1/4-scaled mock-up of the entire vessel.

Since the frequency difference was less than 20%, the transducer cans have also been restrained at the lower end, by means of "cups" fixed to the vessel inner wall (these cups hinder horizontal displacements, the vertical ones remaining free). One transducer, which is considerably longer than the others, was also fixed at an intermediate level, by means of a ring again welded to the vessel.

The adequacy of the new design solution was verified according to Ref. /3/: the flow-induced vibration frequencies correspond to 4.1 Hz, against transducer natural frequency values larger than 10 Hz.

3.1.6. Pipes of the purification, drainage and emergency systems

Such pipes are all contained inside the main vessel.The purification and the emergency suction pipes are welded to nozzles located on the vessel, while the drainage and the emergency delivery pipes are welded to nozzles located on the primary circuit pipes and enter the vessel inside these pipes.

The computed natural frequencies were compared to the flow-induced vibration values estimated according to Ref. /3/. The difference was large enough so as to exclude the necessity of further analysis.

3.2 Primary reactor coolant loop

The components of the primary reactor coolant loop of interest with regard to possible flow-induced vibration effects are: -

- suction and delivery pipes
- component vessel and its plug ,

as well as the following components, which are all contained in the above-mentioned vessel : -

- intermediate heat exchangers and their parts
- primary pumps and their parts
- sodium level and temperature transducers
- damping box attached to component vessel plug.

3.2.1 Pipes

The natural frequency values have been estimated on the basis of approximate evaluations. This resulted in a value of about 13 m/s for the sodium critical velocity. Since the actual fluid velocity is lower than 4 m/s, no further analysis was necessary.

The absence of negative effects of pump rotation frequency has also been demonstrated.

3.2.2 Component vessel

Since the component vessel walls are quite stiff, they have not been considered to be critical with regard to flow-induced vibrations. On the contrary, the natural frequency values have been computed for the intermediate baffle, which divides the vessel into two equal parts over a certain height (3.2 m out of the overall height of 5.3 m of the vessel).

It appeared that these frequencies could be excited by the fluid. Thus, the baffle was stiffened by attaching to it horizontal stiffening ribs on both faces (in order to preserve the symmetry).

With regard to the intermediate heat exchangers it is necessary to distinguish the tube bundle from its feeder. For the tube bundle the sodium critical velocity at the external tube ring was computed. The actual fluid velocities were calculated by CEA for all operating conditions of interest, by use of methodologies already applied to Phénix and Superphénix-1. These values were all rather lower than the critical velocity. Furthermore, in a similar way to Superphénix-1, experimental tests were performed on a mock-up reproducing a part of the tube bundle. These tests were carried out at CEA-DEMT in Saclay. They allowed the correct dynamic behaviour of the tube bundle to be confirmed.

A similar approach, taking advantage of both numerical and experimental analysis, was used for the intermediate heat exchanger feeders. In fact, this is quite a slender structure with a rather complicated shape: therefore, the adequacy of the theoretical methods needed to be confirmed by experimental results.

The above-mentioned numerical study, performed by NOVATOME, also gave information with regard to the feeders, by providing the pressure values inside these devices. Furthermore, a study was performed by ANSALDO with the ANSYS code modified by the "reduced Householder procedure", by modelling the feeder as an axisymmetric structure (the adequacy of the method was verified by studying the benchmark problem of Ref. /4/). This study enabled the natural frequency values to be computed.

The experimental tests were performed in water on a full-scale mock-up of the vessel and its internals, in order to investigate not only the dynamic behaviour of the feeder, but also that of the intermediate heat exchangers, the sodium level and temperature transducers, the damping box, the reinforced baffle and the primary pump "skirt" in the various operational conditions foreseen. The test results demonstrated that the natural frequency values are never excited by the fluid.

3.3 Reactor secondary coolant loop

The components of the reactor secondary coolant loop which could potentially be affected by flow-induced vibration problems are: -

- suction and delivery pipes
- sodium-air heat exchangers
- expansion vessel and centrifugal pump.

3.3.1 Pipes

No specific studies were carried out on the suction and delivery pipes of the secondary coolant loop, due to the positive results obtained for the primary coolant loop. Anyway, in the case of occurrance of flow-induced vibration phenomena during the non-nuclear tests, the pipe supports will be easily modified "in situ" (as done for FFTF). This is possible because these supports are located outsite the contaminated area.

3.3.2 Sodium-air heat exchangers

Each of these components consists of a C-shaped finned tube bundle, connected to two collectors. For them, air-structure interaction effects have been evaluated by use of analytical methods. The flow-induced vibration frequencies have been calculated for the various air mass flow-rates of interest according to Ref./5/, while the tube first natural frequency values have been determined according to Ref. /3/. The results showed that resonance phenomena could only occur in a particular operational situation , consisting in one exchanger out-of-work and the other two in natural circulation conditions.

In this case, in fact, the flow-induced vibration frequency was 11.5 Hz, against the first natural frequency value of 11.7 Hz. However, the corresponding stress value was less than 0.025 daN/ mm^2, thus negligible with respect to the permissible limits.

3.3.3 Expansion vessel and centrifugal pump

The centrifugal pump is located inside the expansion vessel,which is of spheroidal shape. Experimental tests have been carried out in water on the prototype of the vessel (including the pump) by the constructor (FIAT-TTG). All operational conditions of interest have been examined. Resonance phenomena due to flow-induced vibrations never occurred.

3.4 Reactor emergency coolant loops

Only the secondary coolant loop has been considered, due to the fact that the primary loop is rather stiff and of simple shape (only the pump will be tested).

Concerning the emergency secondary coolant loop, in a similar way to the reactor secondary coolant loop, the components of possible interest with respect to flow-induced vibration phenomena are: -

- suction and delivery pipes
- sodium-air heat exchangers
- electromagnetic pump.

3.4.1 Pipes

Concerning the pipes of the reactor emergency secondary coolant loop, the approach was that mentioned in Par. 3.3.1 for the reactor secondary loop.

3.4.2 Sodium-air heat exchanger

This component is similar to the reactor sodium-air heat exchangers. Thus, it was analysed by use of the same methodologies already mentioned in Par. 3.3.2. Significant resonance phenomena were excluded.

3.4.3 Electromagnetic pump

This component is still under construction. Experimental tests to analyse flow-induced vibration levels are foreseen.

3.5 Test loops

With regard to the primary test loop, along series of tests in sodium was performed in the CPC-1 plant of the ENEA Centre of Brasimone to analyse the loop general performance (pressure losses, thermal behaviour, etc.). During the very long test experience, flow-induced vibration phenomena have never been detected.

Concerning the secondary test loop, we note that this circuit is similar to the reactor emergency secondary coolant loop. Thus , the analysis approach was the same.

4. STUDIES IN PROGRESS

Further studies are in progress at ANSALDO, concerning both PEC and more general analyses of flow-induced vibration phenomena.

With regard to PEC, "in situ" fluid-dynamic tests are in progress on the sodium-air heat exchangers, which have already been mounted. They aim at better analysing air-structure interaction effects.

Furthermore, tests in sodium are in progress on the pumps of the reactor emergency primary coolant loop and will be soon initiated (as mentioned) on the pumps of the secondary test and emergency coolant loops. The latter tests aim at analysing flow-induced vibration effects on the pump stator.

Concerning the more general activities on flow-induced vibrations it is worth noting that ANSALDO is participating in the CLOTER European Project on flow-induced vibrations in steam generators. More precisely, ANSALDO is working on the assessment of a general methodology for the analysis of flow-induced vibrations in two - phase flow conditions. This methodology should allow a sufficiently detailed theoretical model to be formulated. This model will be implemented in a special purpose computer code, which should be available in 1987.

5. FUTURE DEVELOPMENTS

It is foreseen to rationalize the approach adopted for PEC, in order to define a general methodology for the study of flow-induced vibrations. The purpose is to utilize the component vessel mock-up mentioned in Par. 3.2.2 (which represents the actual vessel in full scale) and to develop pipe mock-ups containing hydraulic obstacles, vessel mock-ups containing shells, etc., so characterizing the possible vibration sources.

By investigating the component dynamic behaviour in the most diverse operational conditions it should be possible to estimate the characteristic Strouhal and Froude numbers.

These studies should be of interest in the framework of the R&D activities on structural integrity of fast reactors foreseen by the European Agreements on Fast Reactor Development.

REFERENCES

/1/ "Experimental Activities in the Nuclear Field of ISMES' Dynamic Tests Department", ISMES publication, Bergamo, Italy (1985).

/2/ M.Macarti, A.Castoldi, M.Zola and A.Antonucci, "Flow-Induced Vibration Experimental Analysis of the Hold-Down and Shut - Down Systems of the PEC Fast Reactor", I.W.G.F.R. Specialists' Meeting on Flow-Induced Vibrations, Paris, France (1986).

/3/ R.D.Blevins , "Flow-Induced Vibrations", Van Nostrand Reinhold Company (1976).

/4/ M.Dostal P.Descleves, F.Gantenbein, L.Lazzeri, "Benchmark Calculations on Fluid-Coupled Co-Axial Cylinders Typical to LMFBR Structures", Seventh Intl. SMiRT Conf., paper B8/6, Chicago , U.S.A. (1983).

/5/ Y.N. Chen, "Flow-Induced Vibration and Noise in Tube Bank Heat Exchangers due to Von Karman Streetes", ASME - Pressure Vessel and Piping Design, vol.II (1972).

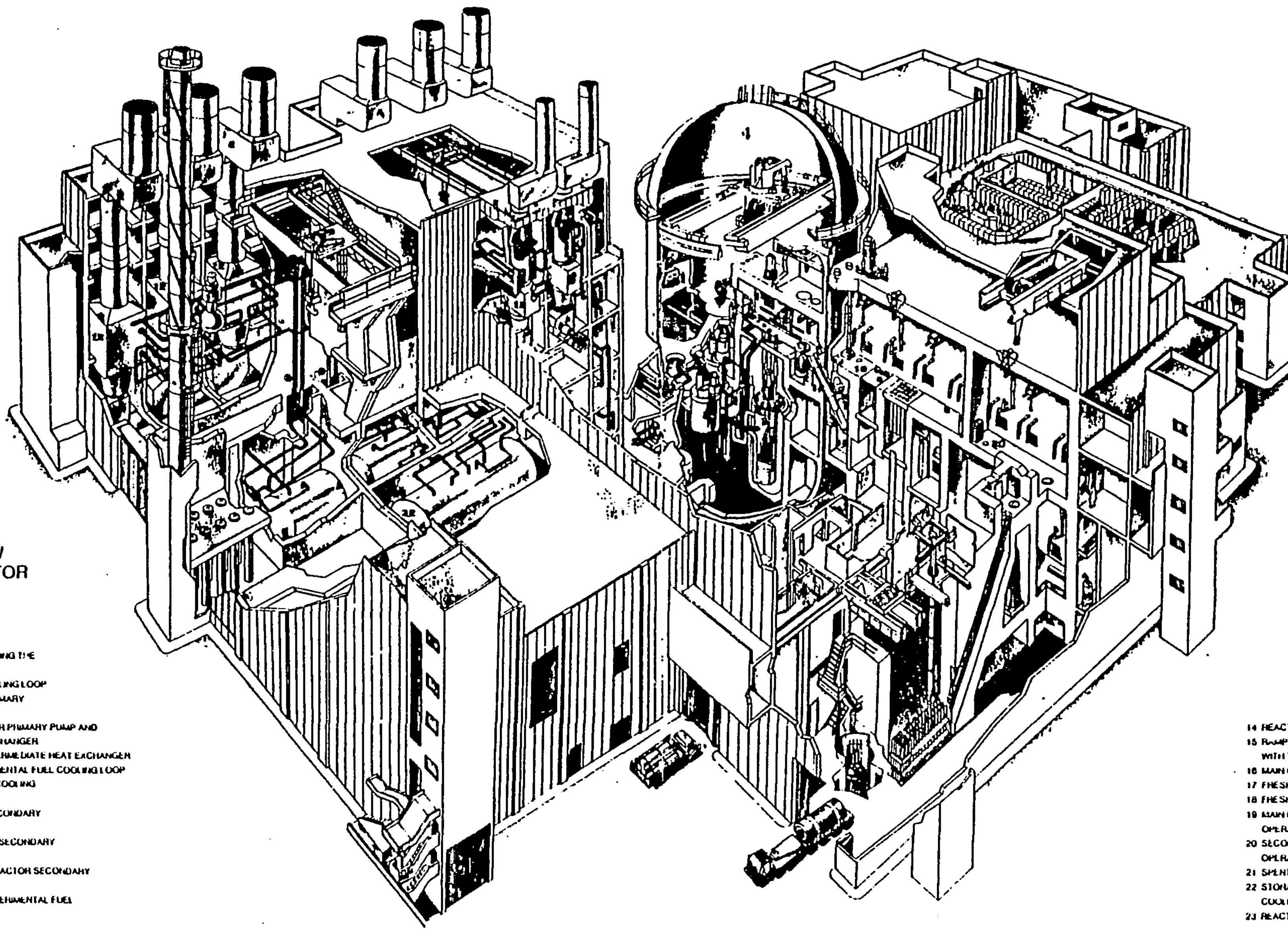


Fig. 1 :

GENERAL VIEW OF PEC REACTOR

1. STEEL CONTAINEMENT
2. REACTOR CORE
3. REACTOR VESSEL
4. TEST CHANNEL CONTAINING THE EXPERIMENTAL FUEL
5. REACTOR PRIMARY COOLING LOOP
6. EXPERIMENTAL FUEL PRIMARY COOLING LOOP
7. VESSEL OF THE REACTOR PRIMARY PUMP AND INTERMEDIATE HEAT EXCHANGER
8. PRIMARY PUMP AND INTERMEDIATE HEAT EXCHANGER VESSEL OF THE EXPERIMENTAL FUEL COOLING LOOP
9. REACTOR SECONDARY COOLING LOOP
10. EXPERIMENTAL FUEL SECONDARY COOLING LOOP
11. PUMP OF THE REACTOR SECONDARY COOLING LOOP
12. AIR COOLERS OF THE REACTOR SECONDARY COOLING LOOP
13. AIR COOLER OF THE EXPERIMENTAL FUEL COOLING LOOP
14. REACTOR FUEL TRASFER CELL
15. RAMP CONNECTING THE TRANSFER CELL WITH THE FUEL HANDLING BUILDING
16. MAIN CONTROL ROOM
17. FRESH FUEL CASK
18. FRESH FUEL TRANSIT CELL
19. MAIN CELL FOR SPENT FUEL OPERATIONS
20. SECONDARY CELL FOR SPENT FUEL OPERATIONS
21. SPENT FUEL TRANSPORT CASK
22. STORAGE TANK OF THE PRIMARY REACTOR COOLING LOOP
23. REACTOR EMERGENCY COOLING LOOP

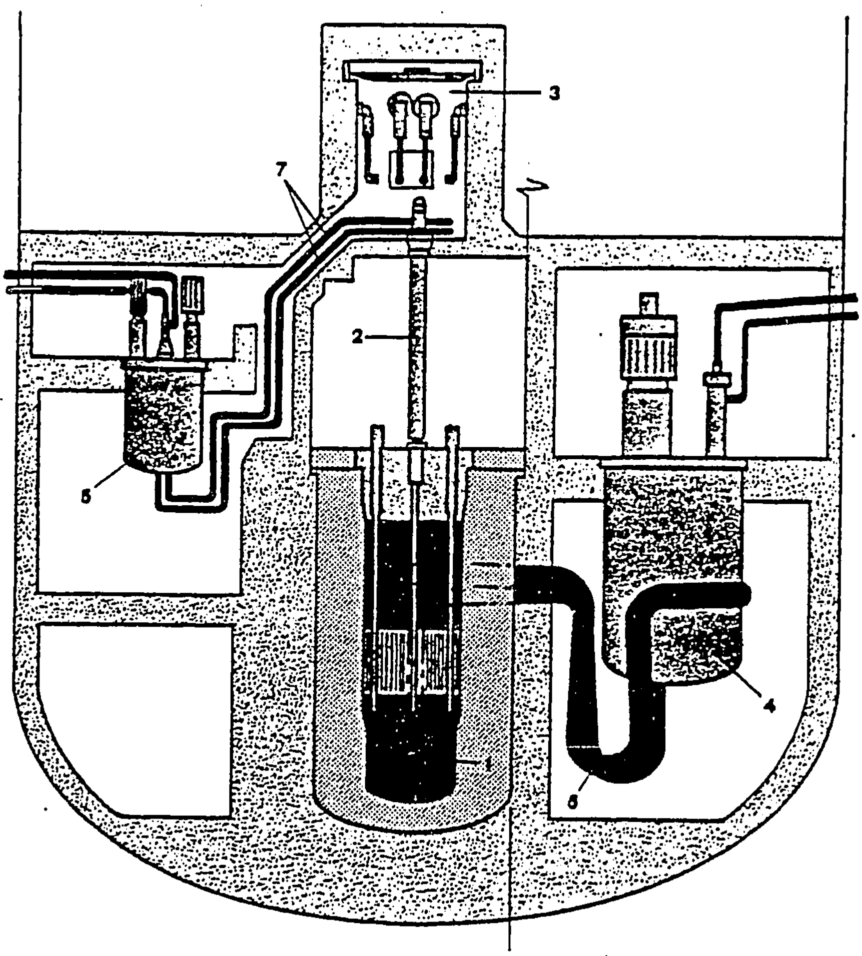


Fig. 2 : Reactor-block primary coolant loops and transfer cell

1 - MAIN TANK
2 - TEST CHANNEL
3 - TRANSFER CELL
4 - COMPONENTS TANK
5 - COMPONENTS TANK OF THE TEST CHANNEL COOLING LOOPS
6 - PRIMARY LOOP
7 - TEST CHANNEL PRIMARY LOOP

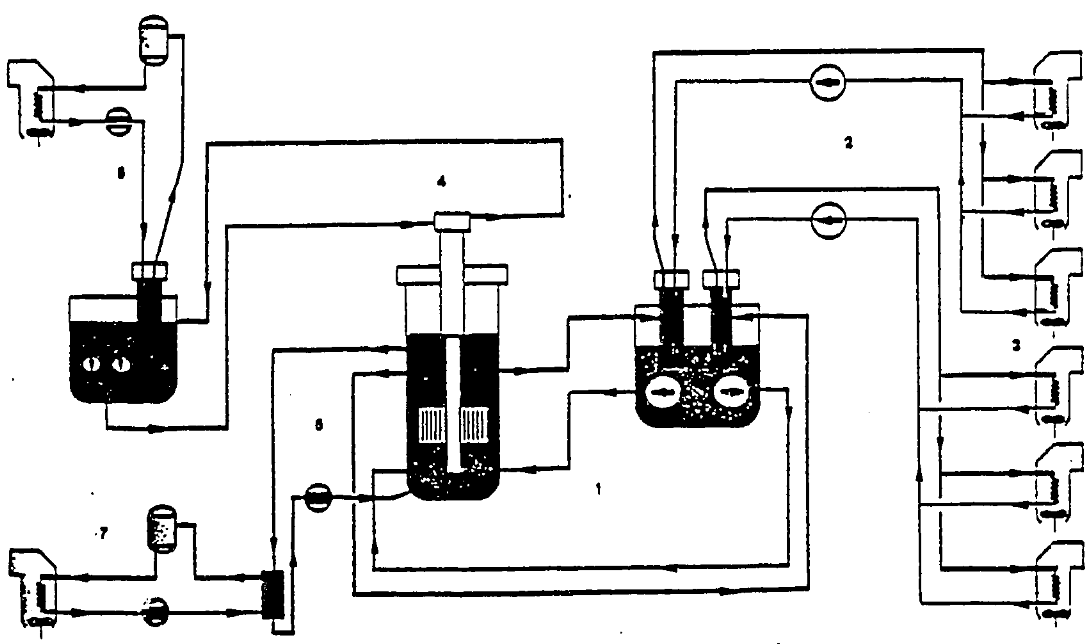
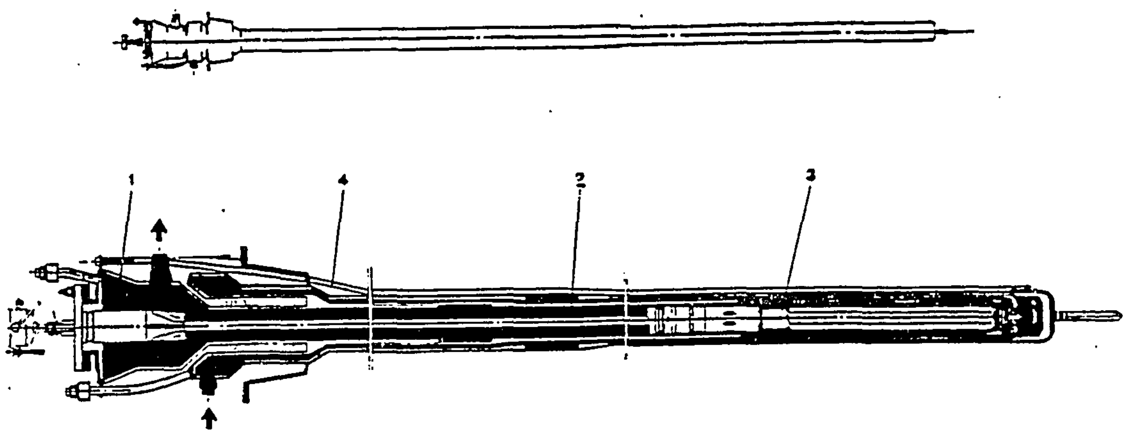


Fig.3 : Reactor cooling loops

1 - MAIN PRIMARY LOOP; 2 - MAIN SECONDARY LOOPS; 3 - MAIN AIRCOOLERS; 4 - TEST CHANNEL PRIMARY LOOP; 5 - TEST CHANNEL SECONDARY LOOP; 6 - EMERGENCY PRIMARY LOOP; 7 - EMERGENCY SECONDARY LOOP.



1 - TEST CHANNEL; 2 - HANDLING ARM; 3 - TEST SECTION; 4 - SPECIMENS CARRYING TUBES.

Fig. 4 : Sketch of the test channel of the PEC reactor

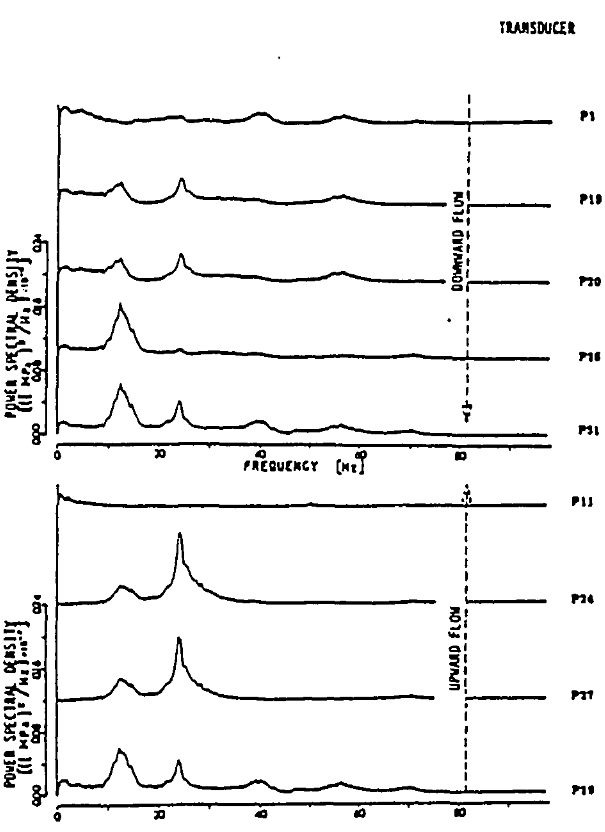


Fig. 5 : Characteristic frequencies of the pressure pulses inside the channel CV-2 due to the water flow

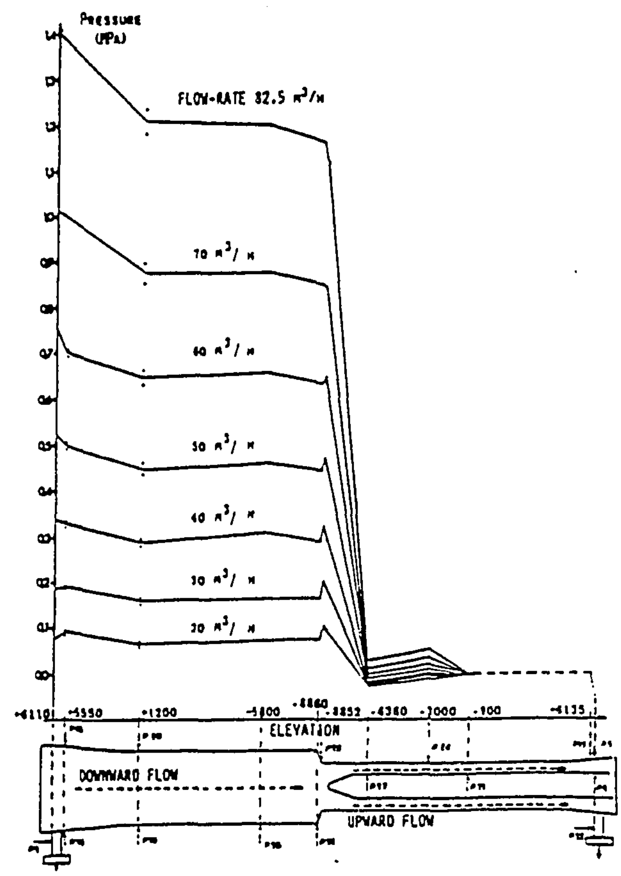


Fig. 6 : Pressure losses along the hydraulic circuit of CV-2 channel