# STARTING UP OF NEW STEAM GENERATOR OF N4 1450 MWE PLANTS

Bernard BUSSY*, Gilles DAGUE** & Georges SLAMA**

**ABSTRACT :**

The first N4 plant, CHOOZ B1, was commissioned in 1997. This plant of 1450 MWe capacity is equipped with four steam generators of a new design fitted with an axial economiser. The axial economiser principle essentially consists in directing all the feedwater to the cold leg of the tube bundle and about 90% of the recirculated water to the hot leg. A double wrapper along the downcomer allows cold water to enter tube bundle as in a boiler-type steam generator and prevents excessive vibration due to cross flow. The main result of this design is to enhance the heat exchange efficiency between the primary and the secondary sides and to increase the steam pressure as compared to a boiler steam generator having the same heat exchange area. As it is the common practice in France for the first plant unit of a new model, one of the four steam generators has been specifically instrumented in order to assess its actual operating characteristics and verify their consistency with the predicted values resulting from the design studies and from the qualification tests. The test programme and the dedicated instrumentation allowed measurement of essential S.G. thermal hydraulics parameters (saturation pressure, flow velocities, pressure drops, circulation ratios, temperature distribution,...) and assessment of vibratory behaviour of tube bundle. The results are in agreement with the tests carried out in the course of the steam generator development and qualification programme, notably a few years ago on the large 25 MWth MEGEVE test facility. They confirm adequacy of the axial economiser design.

The paper describes successively :

- the specificities of the new steam generator design,
- the instrumentation and the test programme,
- the main results obtained from the numerous tests performed during plant start-up.

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## 1. FUNCTIONAL PRINCIPLE AND MAIN ADVANTAGES

For EDF plants 1450MWe power (N4), FRAMATOME has designed and manufactured Steam Generators (SGs) more compact and efficient than previous boiler types by using a purely internal axial economiser.
The main benefit of the economiser is to provide a steam pressure increase at a low cost when compared with a boiler type SG of same heat exchange area.
In a standard boiler design, the feedwater entering the steam generator mixes with the recirculation water coming down from the separators and dryers located above the feedwater ring. Then the mixture flows down between the tube bundle wrapper and the pressure boundary to reach the tube sheet plate and enters hot and cold legs of the tube bundle simultaneously. The axial economiser design [Fig.1] works differently. All the feedwater is forcefully directed to the cold leg side of the tube bundle to obtain a preheating effect. This is achieved by partitioning axially the downcomer in two - one cold, one hot - by the use of a double wrapper and injecting the feedwater directly, and only, into the cold one, with longer J-tubes. The feedwater ring extends only over 180°. To maximise the economiser efficiency only about 10% of recirculated water mixes with the feedwater. The rest is directed to the hot leg. It is worth stressing that this device allows uniform hot temperature all around the pressure vessel and therefore prevents cold thermal shock in this area. Diagram [Fig. 2] gives a temperature profile on primary and secondary sides in the S.G. tube bundle.
To obtain a longitudinal flow along the tubes in both legs of the tube bundle and to prevent the feedwater to flow to the hot leg of the bundle a vertical plate separates the hot leg from the cold leg up to the sixth tube support plate. Apart from these points, the overall arrangement of the SG remains basically the same as for a standard boiler.
Because the feedwater entering the tube bundle cold leg is cooler than in a boiler, heat exchange efficiency between primary and secondary circuits is enhanced. A pressure boost of 3 bars is obtained [Fig.3] with economizer design for the same heat exchange area. To get the same pressure with boiler design supplementary 3400 $m^2$ of heat exchange area would be needed.

To ensure low carry-over and carry-under, high efficiency separator TI 14 with two vanes [Fig.4] has been qualified, 130 are fitted in the steam drum [Fig.5].

The dryers are arranged in 12 cells installed vertically at the top of the steam drum in a star pattern, 6 cells are at the periphery, the remaining 6 are radial [Fig.6]. This arrangement provides a flow area identical to the former two-stage arrangement. It is compact, easy to access and maintain.
Maintainability and inspectability have been paid great attention to. The design of the pressure boundary reduces the number of welds :
- Channel head nozzles are extruded,

- Coverhead and steam nozzle of the steam drum are made by hot spinning in one piece.

8 access holes are distributed around the secondary shell and the hydraulic and mechanical design of the lower internals has been optimised to facilitate lancing which has been actually performed conveniently in CHOOZ B1.

The other main characteristics of the N4 SG are :

| | | |
|---|---|---|
| - primary side : | flowrate | 23900 $m^2$ |
| | inlet temperature | 329°C |
| | outlet temperature | 292°C |
| | pressure | 155 bar |
| - secondary side : | feedwater temperature | 229,5°C |
| | steam flowrate | 600 kg/s |
| | saturation pressure | 73 bar |

- thermal power of 1065 MWth,
- total height of 21.94 m, steam drum diameter of 4.78 m,
- 5599 tubes (outer diameter 19.05 mm, thickness 1.09 mm) in alloy 690 thermally treated, arranged with a triangular pitch and corresponding to a heat transfer area of 7300 $m^2$.
- 9 broached Tube Support Plates and a flow distribution baffle made of 13% chromium steel. The broached holes allow flat land contacts with the tubes.

## 2. QUALIFICATION PROGRAMME

Qualification by tests of the axial economiser steam generator has been performed on large test facility "MEGEVE" at CEA CADARACHE.

The MEGEVE station (25 MWth) included :
- a primary side operating under N4 pressure and temperature conditions,
- the SG mock-up,
- a secondary circuit operating under N4 steam pressure with cooling towers as heat sink.

The mock-up of the SG was manufactured in FRAMATOME workshop in CHALON.
Its main features are:
- full scale in height from tube sheet to steam outlet,
- full scale U-tubes (length, diameter, thickness),
- 149 U tubes with same pitch as actual SGs,
- economiser features.

It was extensively instrumented with thermocouples, differential pressure measurements, flowrate and level measurements, strain gages and accelerometers.
The results of the experimental programme confirmed the predicted thermalhydraulical and mechanical behaviours of the economiser :

- steam pressure boost induced by the economiser (3 bars),

- very good stability during all transient tests (power steps, reactor trip and house load operation),
- separator/dryer high efficiency, no detectable carry-over or carry-under for loads between 50 % and 100 % of the power level,
- very low vibratory level of the tubes and comparable with the results for boilers.

The large database generated by these tests allowed also validating and adjusting correlations introduced in FRAMATOME thermalhydraulical codes.

## 3. CHOOZ B1 FULL SCALE SG TEST

As for the first plant of each new model in France, a SG of CHOOZ B1 unit has been fitted with special instrumentation in order to assess its actual operating characteristics and verify the good agreement with the predicted values resulting from the design studies and the qualification tests. The test programme was performed in partnership between EDF, CEA and FRAMATOME.

### Main objectives

The main objectives of the test programme are :

- to obtain measured values assessing the actual operating characteristics of the N4 steam generators,

- to verify that these values are in good agreement with the values predicted by the codes.

Two domains of interest are more specifically addressed :

- the parameters governing the behaviour and the performances of the axial economiser (saturation pressure in the tube bundle, circulation ratio in cold side and hot side, absence of carry-under in the downcomer, pressure drop and pressure drop coefficients in the recirculation loops, ...)

- the vibratory behaviour of the upper part of the tube bundle (vibration level induced by the turbulence, margins against fluidelastic instability).

### Description of the instrumentation

In addition to the standard instrumentation used during the industrial operation of the plant (cold leg and hot leg pressure and temperature on primary side; water level in the steam generators; feedwater flowrate, pressure and temperature; steam pressure and flowrate in main steam lines), the steam generator dedicated to the test programme is fitted with a temporary mounted specific instrumentation.

This instrumentation has been defined taking into account the feedback of experience coming from the test programmes performed in similar conditions on the first plants of the 900 MWe (BUGEY 4, TRICASTIN 1) and 1300 MWe (PALUEL 1) series. The different items of this instrumentation are:

- secondary flow velocity measurements in the lower part of the downcomers;
- downcomer temperatures at different elevations (measured by internal thermocouples and surface resistance temperature detectors);
- tube sheet temperature and pressure, measured by means of sampling probes inserted in the steam generator through inspection holes;
- absolute and differential pressure at different steam generator elevations, to determine the pressure drops in the whole recirculation loop;
- vibrations, measured by biaxial accelerometers, and stress, measured by strain gauges welded in the U-bend secondary side of the tube bundle. 10 large radius U-bends were instrumented.

All the temporary specific test instrumentation has been installed in factory and on site and its functional testing and calibration took place during the CHOOZ B1 hot tests.

**Results**

Results were obtained during unit hot functional tests and normal operation for transients and 100% power level.
Following table gives pressure measurements in tube bundle and at NSSS supply boundary as well as pressure drop between NSSS supply boundaries of feedwater and steam lines.

| | Expected minimum values from MEGEVE | Measured values at CHOOZ B1 |
|---|---|---|
| Steam pressure* at NSSS supply boundary (bar) | 71.4 | 72.1 |
| Saturation pressure* in tube bundle (bar) | 73.0 | 73.7 |
| Pressure drop between NSSS supply boundaries of feedwater and steam lines (bar) | <4.2 | 2.9 |

* Pressure measurements are made at various locations : tube bundle, steam drum, S.G. outlet, supply boundary.

Temperature, flowrates and circulation ratios* (1.3 for cold leg and 2.0 for hot leg), are in agreement with expected values from MEGEVE tests and thermohydraulical codes calculations.
Main feedwater and steam flowrates steps, positive and negative, were performed at different power levels. Good efficiency of water level regulation and good stability of SG were observed. An example of this behaviour is given [Fig.7].

Good vibratory behaviour of upper part of the tube bundle was obtained with very low tube displacement (<5 µm) and acceleration during various power levels conditions [Fig.8]. Vibratory level is in all conditions very far from instability.
More testing results or interpretation of numerous records performed over one year are yet to be obtained.

## 4. CONCLUSION

Although all the results programmed are not yet available, the large amount of data already obtained on the behaviour of N4 SGs, in agreement with expectations from MEGEVE tests, are very satisfactory.
These data encompass pressure delivered, thermalhydraulical stability and water level regulation, circulation ratios and vibratory behaviour.

All the objectives given for designing this N4 SG, also selected as basis for European Pressurised water Reactor (EPR) project, have been reached.

* Note : circulation ratio is defined as the ratio of the mass flowrate in the cold (resp.hot) leg to the total mass steam flowrate.

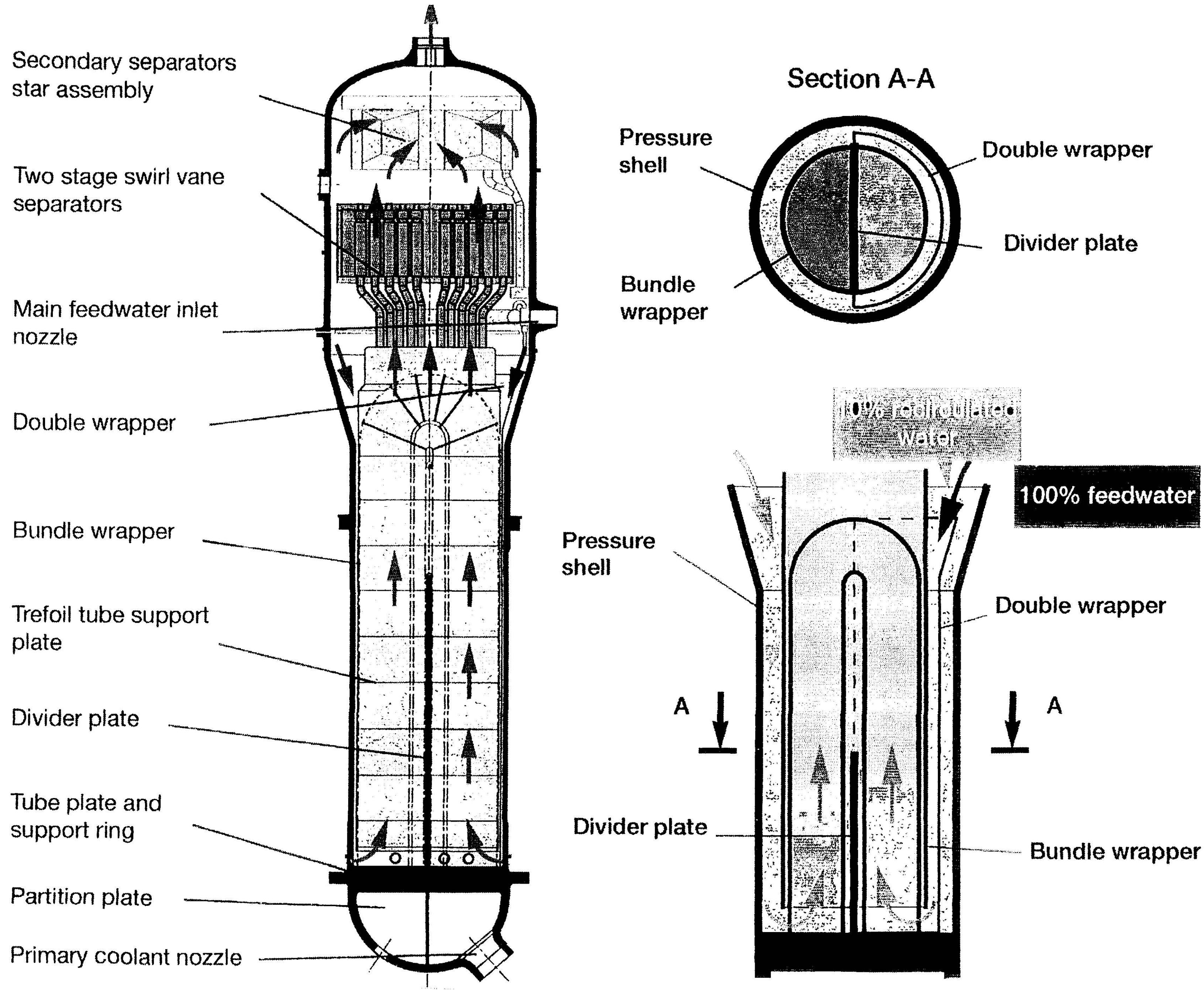



FIGURE 1 : ECONOMISER STEAM GENERATOR PRINCIPLE

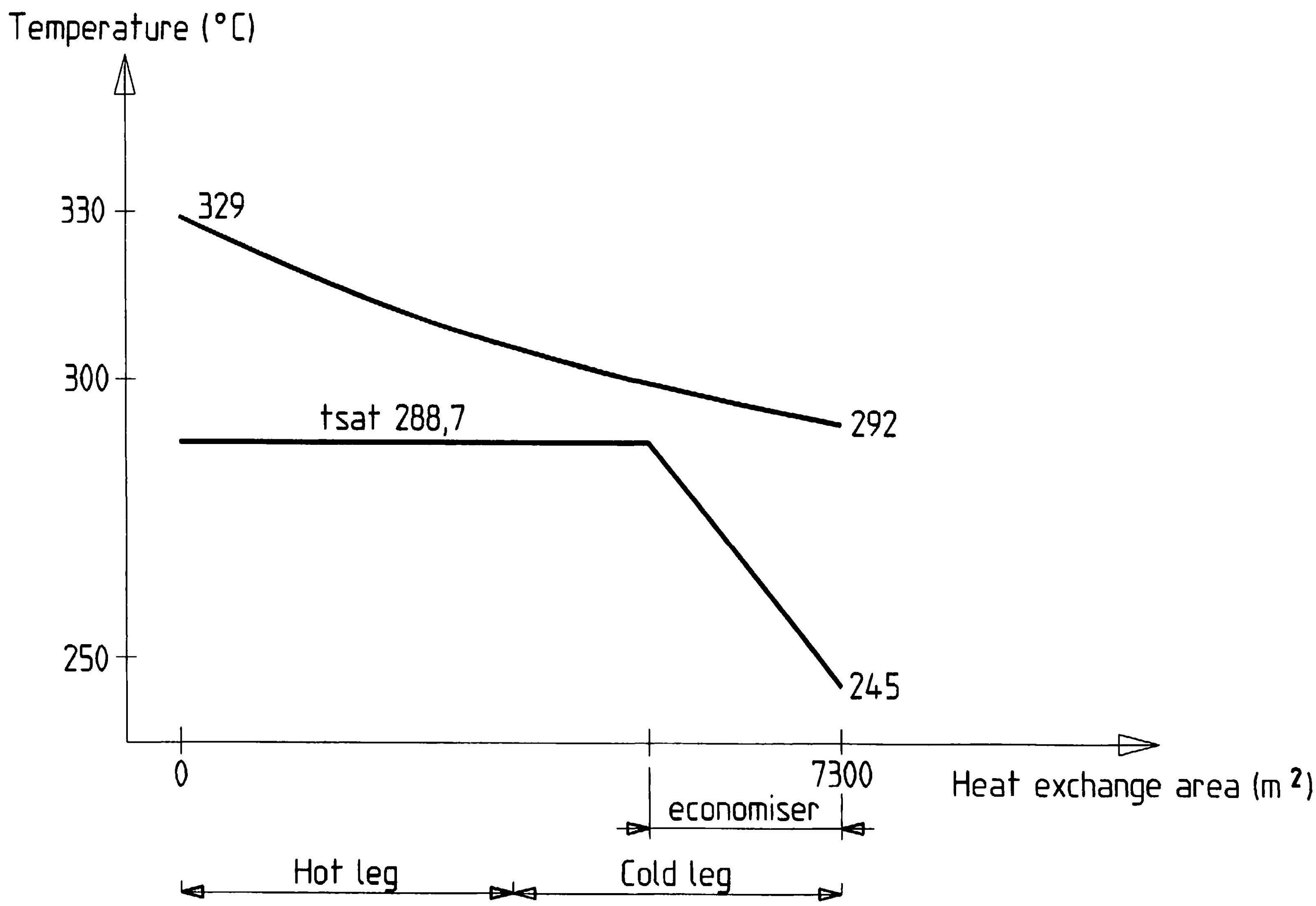



FIGURE 2 : TEMPERATURE DIAGRAM

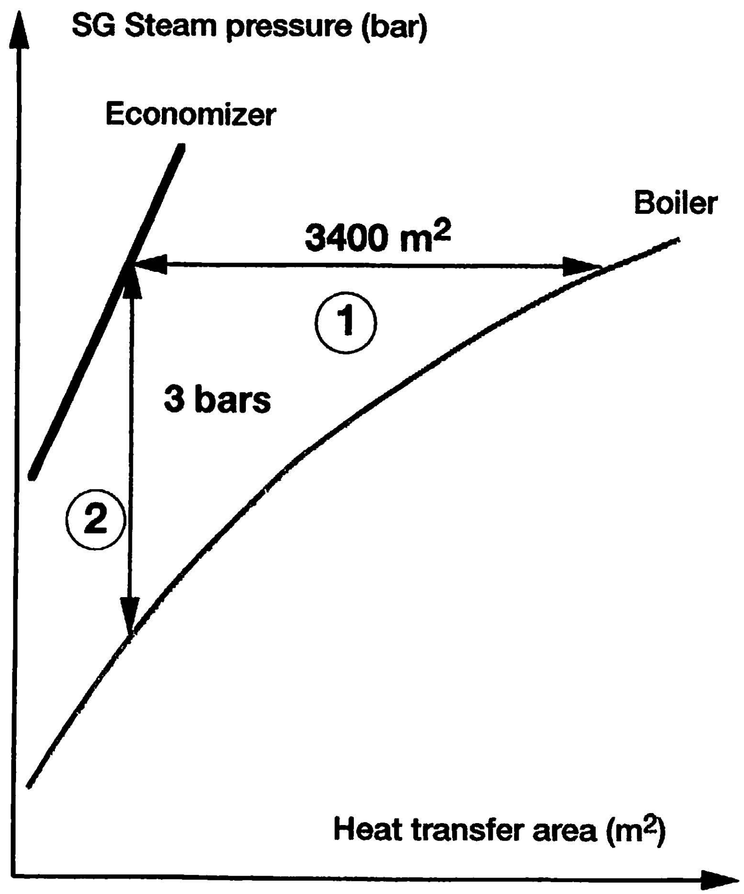



FIGURE 3 : COMPARISON OF PRESSURES GIVEN BY BOILER AND ECONOMISER DESIGNS

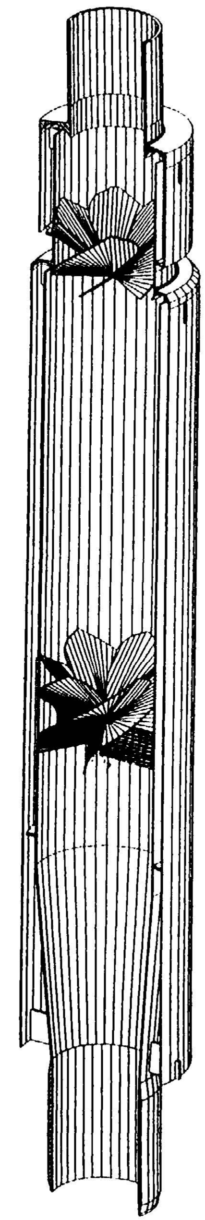


FIGURE 4 : TWO VANE - SEPARATOR TI 14

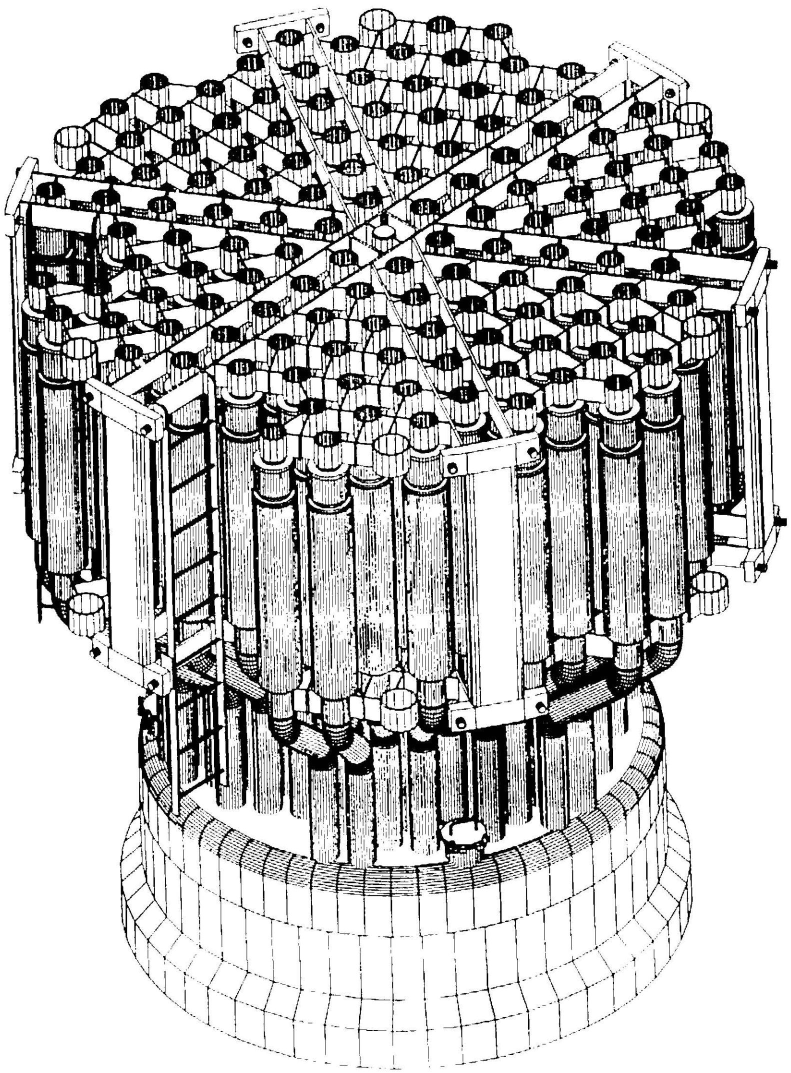


FIGURE 5 : SEPARATORS ARRANGEMENT IN STEAM DRUM

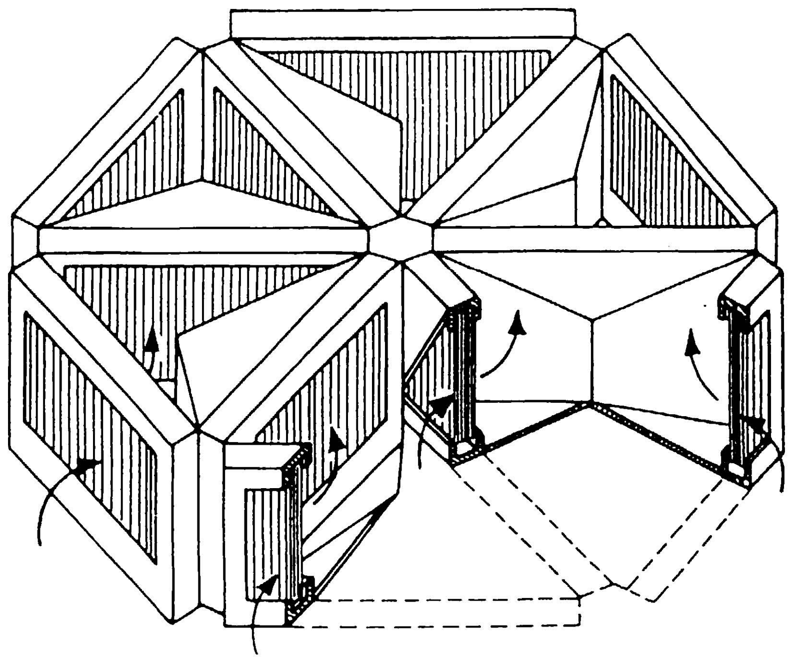
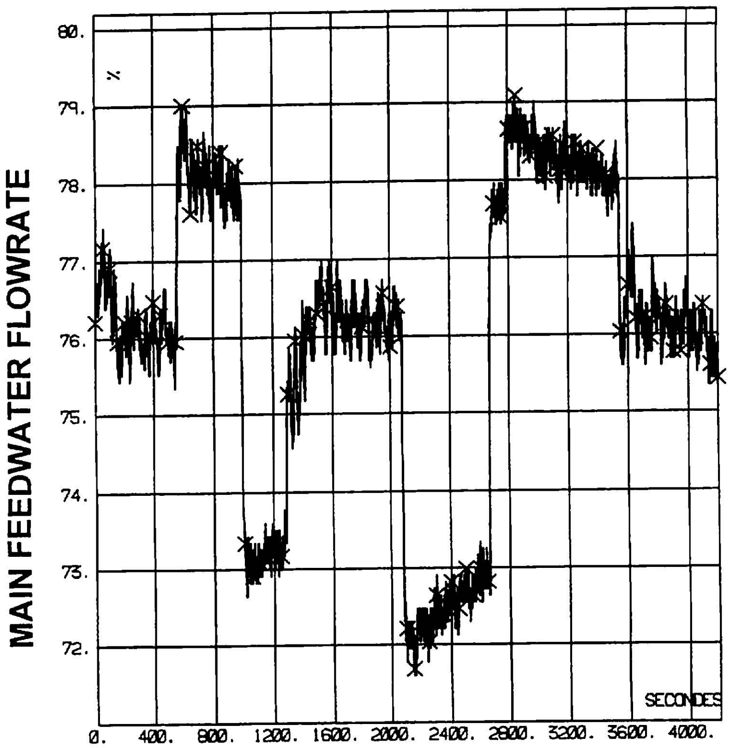


FIGURE 6 : DRYER ARRANGEMENT (STAR PATTERN)



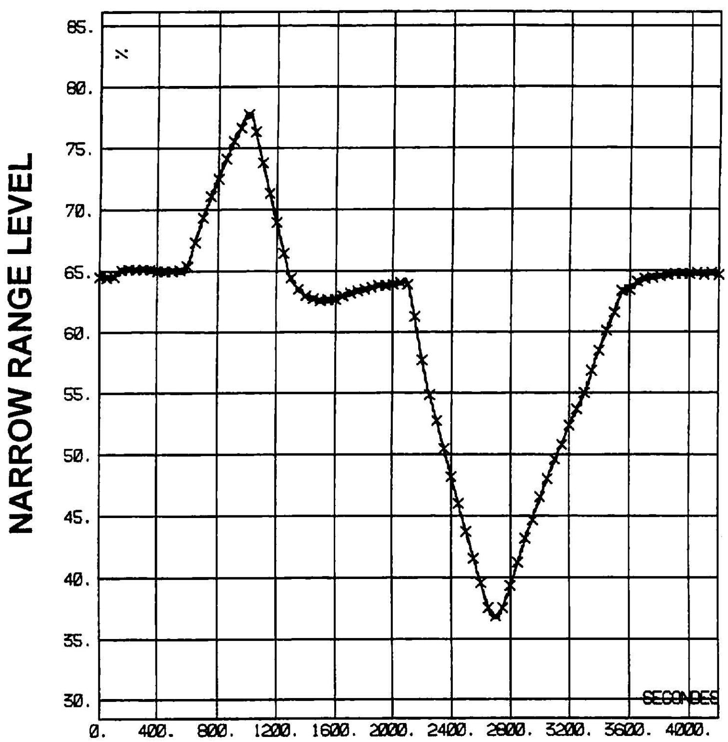




**FIGURE 7 : POSITIVE AND NEGATIVE STEPS OF MAIN FEEDWATER FLOWRATE AT 80 % FULL LOAD**

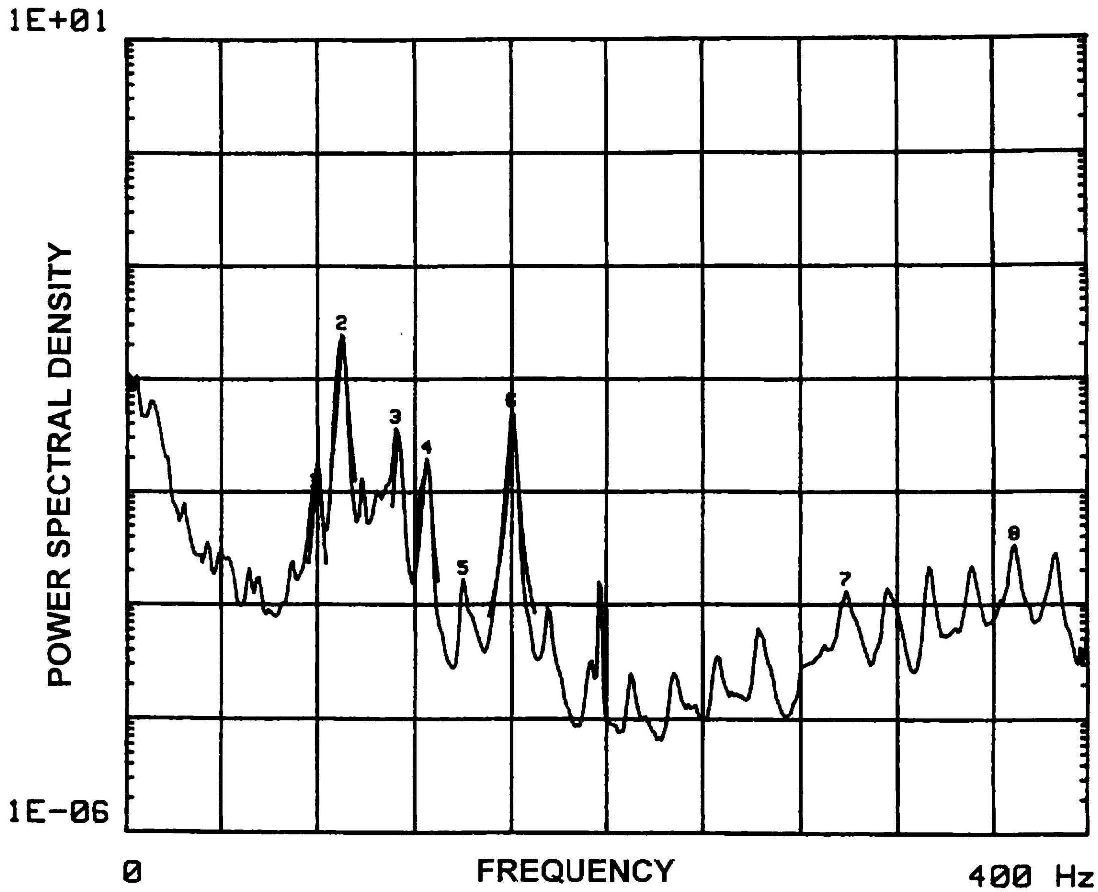



FIGURE 8 : POWER SPECTRAL DENSITY ( 100 % full load)

## DISCUSSION

**Authors:** B. Bussy, G. Dague, G. Slama, EDF and Framatome

**Paper:** Starting up of New Steam Generator of N4 1450 MWe Plants

**Questioner:** J. Nickerson, AECL

**Question/Comment:**

Was there a concern for thermal stresses in the region of the tubesheet due to cold feedwater and if so, were any special measures taken to ensure these are not detrimental?

**Response:**

One of the advantages of our economizer design is that, by partitioning the cold leg downcomer, all the pressure shell and the periphery of the tubesheet are at the same temperature during normal operation. No thermal stresses are induced. For transients, the situation is not significantly different from a boiler and we have verified by calculation that stresses generated are acceptable in all conditions. Direct measurements of temperatures on the tubesheet during service have confirmed all our input data.

**Questioner:** P.J. Prabhu

**Question/Comment:**

You mentioned sludge lancing. What provisions are included for access to the economizer for sludge lancing and other services?

**Response:**

Numerous ports are provided which allow sludge lancing in the cold leg and hot leg to be performed. They allow also use of multidirectional lancing as this SG has a triangular pitch. There is no significant difference with a standard boiler from this point of view (except that there is separated cold and hog leg). Lancing performed at the end of hot functional tests of the plant has demonstrated that very good cleaning of the tubesheet can be achieved without any problem.

**Questioner:** J. Gorman, DEI

**Question/Comment:**

(a) How much thermal margin has been included in the design (area margin)?

(b) How long before chemical cleaning is like to be required?

**Response:**

(a) Margin depends on your definition. With conventional definition our margin is about 10%.

(b) Need for chemical cleaning is very plant specific, some may never need it. It can depend on the policy of lancing, for instance and on the provisions taken on secondary chemistry, but the SG design is compatible with chemical cleaning.

**Questioner:** R. Schalleu, Arizona Public Service co.

**Question/Comment:**

The Palo Verde System 80 SG is of an economizer design with a hot side circulation ratio of 1.74 and we have experienced heavy tube deposits. Is this a concern in the N4 SG which has a circulation ratio of 1.3?

**Response:**

The circulation ratio of 1.3 is for cold leg only. For hot leg, this ratio is 2.0. We have carefully evaluated sludge deposition area in our SG and found that, thanks to the provisions taken on design of the lower part, a very limited number of tubes will be in this area. Furthermore, the deposition area is mainly located in a central zone where there are no tubes. At the last conference in 1994, the deposition area was shown in my paper.

**Questioner:** K. Bagli, OH/SESD

**Question/Comment:**

Can you briefly describe the following during your testing program (CHOOZE B1):

(a) Blowdown rate?
(b) Chemistry control regime?

**Response:**

(a) Blowdown rate in French plans is usually around 1%.
(b) Chemistry is morpholine conditioning, but ammonia conditioning would be also acceptable.