Severe Transient Tests on Operating Steam Generators: Analysis of the Fluid-Structure Dynamic Thermal Interaction

F. Billon

Framatome, Division des Fabrications, B.P. No. 13, F-71380 Saint Marcel, France

J. David, H. Procaccia

Electricité de France, Direction des Etudes et Recherches, 25, allée Privée – Carrefour Pleyel, F-93206 Saint-Denis Cedex 1, France

Summary

The operating efficiency of steam generators (S.G.s) and their structural integrity depend on the design configurations of the feedwater spray within the S.G., and on the operating procedure.

To check the merit of some design modifications, and to verify the fluid-structure interaction with a view to preserve the S.G.s integrity during severe operating transients, a special instrumentation that admits the determination of the instantaneous thermal hydraulic characteristics of the flow in the secondary water and the corresponding metal temperature, in particular in the S.G. downcomer and near the S.G. tube sheet, has been installed by EDF on one steam generator of Tricastin unit 1 power plant.

In parallel, FRAMATOME has developped a computer code, TEMPTRON, that allows the calculation of the thermal loads and the consequent stresses in the most sollicited zones of the steam generator during transient operation of the plant.

This code divides the S.G. into three parts :

- the first concerns the S.G.s region above the downcomer, zone where the mixing between hot water and cold feedwater occurs,
- the second is the downcomer itself which is divided into n segments,
- the third concerns the tube sheet zone which is also divided into n segments.

The most severe transient test performed is the auxiliary cold feedwater injection into the steam generator during a hot standby of the plant : two levels of flow rate have been realised : 55 and 110 m^3/h of 42° C feedwater.

The tests have shown that if the cold feedwater injection occurs when the steam generator water level is below feedwater ring, the lowest fluid temperature reached at tube sheet inlet is about 230° C. The stress induced by those water temperature fluctuations are below the level for which fatigue cracking could be induced at stress concentration zones in the tube plate or the shell.

Following the tests and calculation results the operating procedure of the plant and the auxiliary feedwater regulation have been modified with a view to effecting the water injection only when the steam generator level is below the feedwater ring.

1. Introduction

A special instrumentation has been installed by Electricité de France (EDF) on series 51 and 68/19 steam generators (S.G.s) in order to verify, the thermal hydraulic characteristics of the secondary flow inside the S.G.s, in normal conditions of operations of the plants.

Steady and common transients tests have been performed already in two 900 MWe PWR EDF units, Bugey 4 and Tricastin 1. The next series of tests will be realized at Paluel 1, the first EDF 1300 MWe unit.

These tests have allowed for a better understanding of the operating behavior of S.G.s and for validation of 3D computer models of this behavior [1], [2], [3].

The tests were performed within the scope of a four party agreement (PWS 4-5) between the Commissariat à l'Energie Atomique, Electricté de France, Framatome and Westinghouse, and within a special agreement between EDF and Electric Power Research Institude (EPRI).

In order to determine the S.G. thermal hydraulics and more specifically the resulting stress field and the consequent load cycle fatigue index of critical regions, during severe plant incident transients, Framatome has developed a theoretical mathematic model allowing :

- the dynamic calculation of the secondary water mixing temperature at the top of the S.G., for different water level,
- the resulting instantaneous thermal exchange in the S.G. downcomer,
- and finally the calculation of the dynamic thermal loads applied to the S.G. tube sheet, thus allowing for the calculation of the structural integrity.

French Safety Authorities have asked EDF and Framatome to validate this theoretical model by on site tests at Tricastin unit 1, with using the S.G. special instrumentation existing on this unit : this validation concerns mainly the limit assumptions taken into account in the model, by introducing realistic fluid evolutions into the S.G.

This report describes the thermal hydraulic instrumentation used during the test, the tests conditions and realisation, the mathematical model, and the comparison between the test and the model results.

2. Steam generator instrumentation

The distribution of test points on the S.G. is shown on fig. 1. It includes :

. Two secondary water temperature and sampling probes, laid on the tube sheet, along a diameter perpendicular to the tube lane. These probes allow water sampling at eight points along this diameter, for chemical analysis purposes and the sampled water local temperature is measured by eight thermocouples housed in the sampling probes.

. Eight pseudo-Pitots allow measurement of the total and static pressure in the downcomer and the local fluid temperature over a circumference located 620 mm above the tube sheet.

These Pitots should allow determination, after calibration corrections, of the fluid velocity and, consequently, the recirculation rate, through comparison between the water flow rate across the downcomer and that of the feedwater measured through a calibrated device at steam generator inlet. The pseudo-Pitots are inserted in the downcomer through eight special tappings.

. Opposite the eight pseudo-Pitots, eight thermocouples, crimped in studs welded on the S.G. outer shell, allow measurement of the metal temperature at the same level of the fluid temperature measurement. The surface temperature of the heat insulation and ambient temperature are also measured : the heat transmission factors can thus be determined.

. Eight other "metal thermocouples" are fitted on the same generatrix lines, just under the cylindrical/truncated cone shell junction ; combined with the other metal temperatures, they allow an estimate of the flow direction in the downcomer.

. Finally, a tapping is made on the S.G. wide range collector level in order to measure the absolute steam pressure in the upper part of the unit.

Data from the normal operation instrumentation are recorded on the test computer : steam and feedwater flowrate, primary and secondary water temperature and pressure, in particular, are measured.

3. Tests conditions and realizations

The aim of the tests was to simulate a very severe cold shock on the S.G. tube sheet following a reactor scram. The test history is as follows :

- load decreasing from 100 % to 15 % at the rate of 5 % nominal power/minute, followed by 15 minutes of stabilisation,
- load decreasing from 15 % to 0 % to obtain hot shut down conditions with normal feedwater flowrate regulation,
- S.G. level decreasing, after feedwater regulation isolation, until the operation of cold auxiliary feedwater system with the maximum admissible water flowrate (108 m^3/h : 3 pumps operating),
- when the normal level is reached, the 3 auxiliary feedwater pumps are shut down, the level decreases, and new auxiliary feedwater is injected at the normal injection flowrate (54 m^3/h),
- load increasing.

4. The mathematical model

In this model the transients with secondary water circulation are described separately from the transients with cold water injection : a combination of these two cases is possible to simulate a realistic operation, such as a scram for instance.

4.1 Transients with auxiliary cold water injection

In this case the S.G. is divided into 3 main zones (see figure 2).

- in zone 1, where the water mixing occurs, the mixing temperature $\theta_1(t)$ is calculated as a fonction of the S.G. saturated secondary water temperature T_S, the S.G. shell temperature θ_M, and the injected cold water temperature θ_I, by numerical integration of the following system of differential equations :

$$\frac{d\theta_1}{dt} = X_I \cdot \theta_I + X_E \cdot T_S + X_M \cdot \theta_M - X_1 \cdot \theta_1 \quad (1)$$

$$\frac{d\theta_M}{dt} = (\theta_1 - \theta_M) \cdot Y_M \quad (2)$$

with (see figure 2)

$$Y_M = h_1 \cdot (\Omega_{M0} + p_M \cdot L) / (V_{M0} + S_M . L) \cdot Cp_M \quad (3)$$

$$X_I = Q_I \cdot CpI / (V_{f0} + S_f . L) \cdot Cp_f$$

$$X_E = h_1 \cdot (\Omega_{E0} + p_E \cdot L)/(V_{f0} + S_f \cdot L) \cdot Cp_f$$

$$X_M = h_1 \cdot (\Omega_{M0} + p_M \cdot L)/(V_{f0} + S_f \cdot L) \cdot Cp_f$$

$$X_1 = X_I + X_E + X_M \quad (7)$$

The variable L expresses the increasing, or the decreasing of the S.G. water level.

From the Explicit Euler algorithm, the time integration gives :

$$\theta_1(tn+1) = \theta_1(tn).[1 - X_1(tn).\Delta t] + [X_I(tn).\theta_I(tn) + X_E(tn).T_S(tn) + X_M(tn).\theta_M(tn)].\Delta t \quad (8)$$

$$\theta_M(tn) = \theta_M(tn-1) \cdot [1 - Y_M(tn-1) \cdot \Delta t] + \theta_1(tn-1) \cdot Y_M(tn-1).\Delta t \quad (9)$$

- in zone 2, the space-time fluid temperature $\theta_f(x,t)$ in the downcomer, is calculated as a function of the S.G. secondary water temperature T_S, the S.G. shell temperature T_M, by numerical integration of the system of differential equations :

$$\frac{\partial\theta_f}{\partial t} + U_f \cdot \frac{\partial\theta_f}{\partial t} = \tau_M \cdot T_M + \tau_E \cdot T_S - \tau_f \cdot \theta_f \quad (10)$$

$$\frac{dT_M}{dt} = \gamma \cdot (\theta_f - T_M) \quad (11)$$

with (see figure 2)

$$\gamma = h_2/k' . e_M \cdot Cp_M \qquad (k' = R_M/R_e) \quad (12)$$

$$\tau_M = k \cdot h_2/e_f \cdot Cp_f \qquad (k = R_f/R_i \simeq R_e/R_f) \quad (13)$$

$$\tau_E = H_2/k \cdot e_f \cdot Cp_f \quad (14)$$

$$\tau_f = \tau_M + \tau_E \quad (15)$$

U_f is the independent variable corresponding to the real mixing velocity, or the pseudo velocity in the downcomer (D.C.), or the cold front propagation velocity.

A certain number of assumptions can be considered for this variable, but taking into account the present state of our knowledge, this variable is considered as independent, and from the Implicit Euler algorithm the space-time integration gives :

$$\theta_f(t_{n+1},x_n) = A.\theta_f(t_n,x_n) + B.\theta_f(t_{n+1},x_{n-1}) + C.T_S(t_{n+1}) + D.T_M(t_n,x_n) \quad (16)$$

$$T_M(t_n,x_n) = E \cdot T_M(t_{n-1},x_n) + F \cdot \theta_f(t_n,x_n) \quad (17)$$

with

$$A = \left[1 + \Delta t \cdot \frac{U_f}{\Delta x} + \Delta t \cdot \tau_E + \frac{\Delta t \cdot \tau_M}{1+\gamma . \Delta t}\right]^{-1} \quad (18)$$

$$B = \frac{\Delta t}{\Delta x} \cdot U_f \cdot A \quad (19)$$

$$C = \Delta t \cdot \tau_E \cdot A \quad (20)$$

$$D = \frac{\Delta t \cdot \tau_M}{1+\gamma . \Delta t} \cdot A \quad (21)$$

$$E = [1 + \gamma \cdot \Delta t]^{-1} \quad (22)$$

$$F = \gamma \cdot \Delta t \cdot E \quad (23)$$

- in zone 3, above the tube sheet, we assume that a constant thickness of fluid flows along the tube sheet with a velocity decreasing towards the center of this tube sheet.

The fluid space-time temperature distribution $\theta_f(x,t)$ as a fonction of the primary fluid temperature T_p, is calculated by numerical integration of the differential equation :

$$\frac{\partial \theta_f}{\partial t} + U_{(x,t)} \cdot \frac{\partial \theta_f}{\partial t} = \xi \cdot (T_p - \theta_f) \quad (24)$$

with (see figure 2)

$$\xi = \frac{H_3 \cdot \chi \cdot \Omega_t + H'_3 \cdot (1 - \chi \cdot S_t)}{e' \cdot Cp_f \cdot (1 - \chi \cdot S_t)} \quad (25)$$

$$U_{(x,t)} = U_f(t) \cdot \frac{R_o - x}{R_o} \quad (26)$$

$U_f(t)$ is the downcomer fluid velocity, or pseudo velocity, and therefore the velocity of the fluid entering the tube sheet.

It is assumed that, the space velocity decreases linearly and becomes nil in the center of the tube sheet ($x = R_o$). From the Implicit Euler algorithm, the space time integration gives :

$$\theta_f(t_{n+1},x_n) = a.\theta_f(t_n,x_n) + b.\theta_f(t_{n+1},x_{n-1}) + c.T_p(t_{n+1}) \quad (27)$$

with :

$$a = \left[1 + \Delta t \cdot \left[\frac{U(t_{n+1}\, x_n)}{\Delta x} + \xi\right]\right]^{-1} \quad (28)$$

$$b = \frac{\Delta t}{\Delta x} \cdot U(t_{n+1},x_n) \cdot a \quad (29)$$

$$c = \xi \cdot \Delta t \cdot a \quad (30)$$

This model allows to analyse the particular case when the injected fluid is not heated in zone 1, and a free surface film flow is established on the S.G. shell ; the S.G. being partially or totally without secondary water.

4.2 Transients with secondary water recirculation

In this case we assume that the injected water is perfectly mixed with the recirculation water, and that the temperature and the velocity of the mixture in the downcomer, and on the tube sheet, are such that it is possible to neglect the heat transfer between the fluid and the shells.

The downcomer fluid temperature and the tube sheet fluid temperature are assumed to be the same as the mixture temperature θ_f, which is calculated as a function of the injected water temperature θ_I and the recirculation water temperature θ_R by the relation :

$$\theta_f = \frac{Cp_I \cdot \theta_I + (\tau_L - 1) \cdot Cp_R \cdot \theta_R}{Cp_I + (\tau_L - 1) \cdot Cp_R} \qquad (31)$$

where τ_L is the local recirculation ratio which is a fonction of the steam flow rate, or the S.G. thermal power ; the latter values are function of the time during a transient.

From the complete theoritical model a specific computer code, called TEMPTRON, has been developped.

5. Comparison of measurements with computations

For the comparison between measurements, described in paragraphe 3, and calculated temperature given by the model, we examine if the observed phenomena are well reproduced by the theoritical model.

Only some significant results are given here, concerning the fluid temperature at the bottom of the downcomer during the following tests :

- power decreasing from 100 % to 15 %, transient with recirculation,
- cold water (42° C) injection with a flow rate of 108 m^3/h (6 %).

The comparison between measured and calculated temperatures during the decrease in power is given in figure 38, where only the lower envelop curves of mesured cold leg and hot leg temperatures are compared with the calculated theoritical curve which was based on the local recirculation ratio τ_L.

The theoritical curve calculated from the average recirculation ratio τ_M is also given.

For the injection test, the comparison is more difficult because of the role of the important parameter U_f. Therefore, we have drawn 4 theoritical curves based on the following four assumptions :

- 1st assumption : $U_f = Q_I/\Omega_{DC}$ = 0,047 m/s constant during the time of injection.
- 2nd assumption : U_f = 10 times the precedent velocity = 0,47 m/s, constant during the time of injection.
- 3rd assumption : $U_f(t) = U_{f0} \cdot (1 - t/t_I)$ linearly decreasing velocity during the time of injection, with U_{f0} = 0,82 m/s and t_I = 720 s.

U_{f0} is estimated as the penetration velocity of cold fluid in a warm fluid i.e. as a function of $(\Delta\rho/\rho)$.

- 4th assumption : $U_f(t)=U_{f0}.(1-t/t'_I)$ linearly decreasing velocity with a shorter time that the time of injection t'_I = 500 s.

The corresponding four theoretical curves are given in figure 3A together with the lower envelopes of the curves mesured for the S.G. hot and cold legs.

6. Conclusions

The theoritical model gives a correct simulation of the observed temperature levels and their time variation.

These first results encourages us to continue the development and the refinement of the mathematical model, in parallel with an experimental program for on site measurements and mock-up tests, in order to obtain a better understanding of the main parameter governing the actual phenomena.

We note that these first results indicate that the assumptions used until now to calculate the thermally induced stresses were too pessimistic.

Therefore following these tests and calculations, the operating procedure of the plant, and the auxiliary feedwater regulation have been modified with a view to effecting the cold water injection only when the steam generator water level is below the feedwater ring ; this procedure serves to further reduce the thermally induces stresses.

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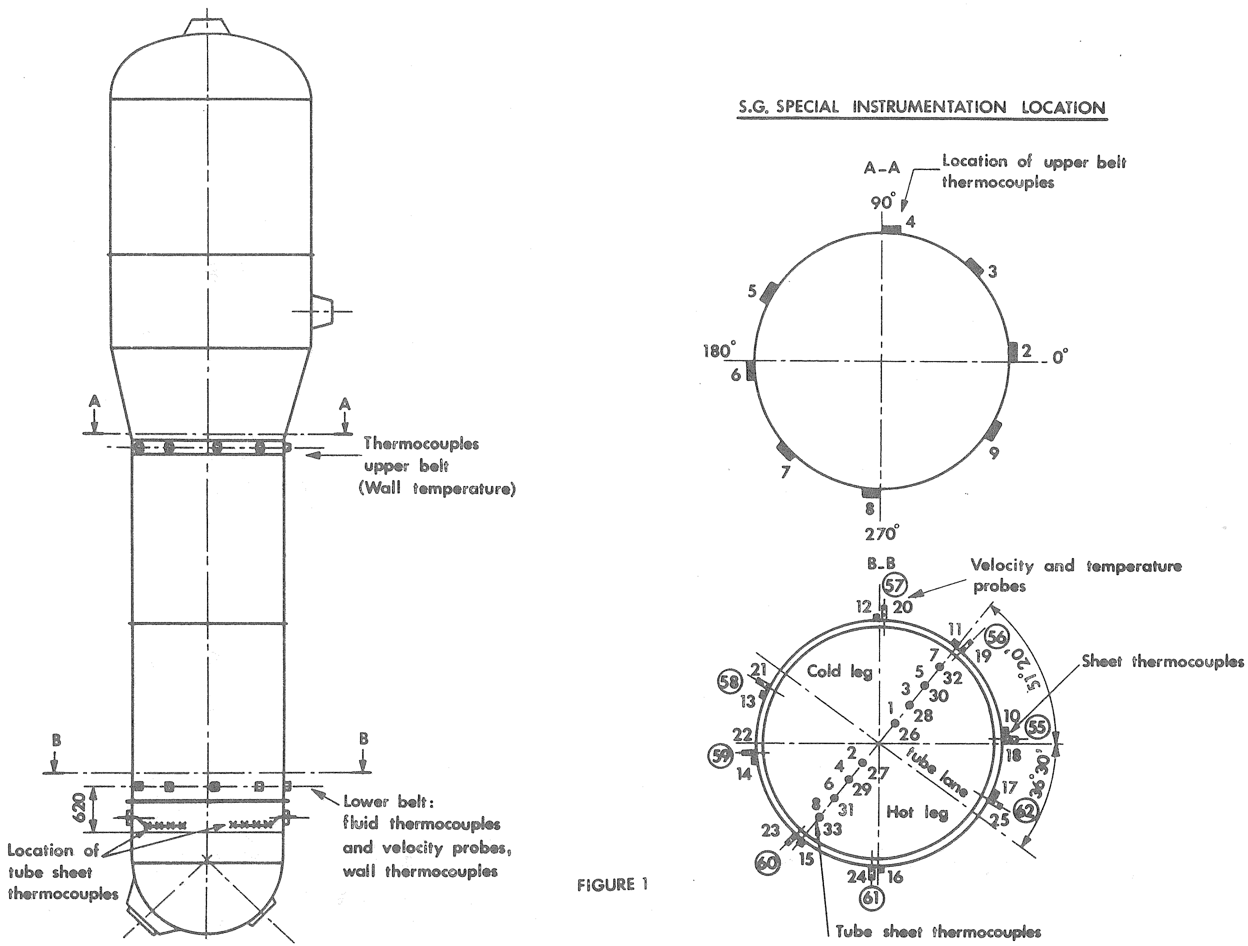
S.G. SPECIAL INSTRUMENTATION LOCATION
A–A
Location of upper belt thermocouples
90°
180°
0°
270°
2
3
4
5
6
7
8
9
A
B
Thermocouples upper belt (Wall temperature)
620
Lower belt: fluid thermocouples and velocity probes, wall thermocouples
Location of tube sheet thermocouples
B–B
Velocity and temperature probes
Sheet thermocouples
Tube sheet thermocouples
Cold leg
Hot leg
tube lane
51°20'
36°30'
55
56
57
58
59
60
61
62

FIGURE 1

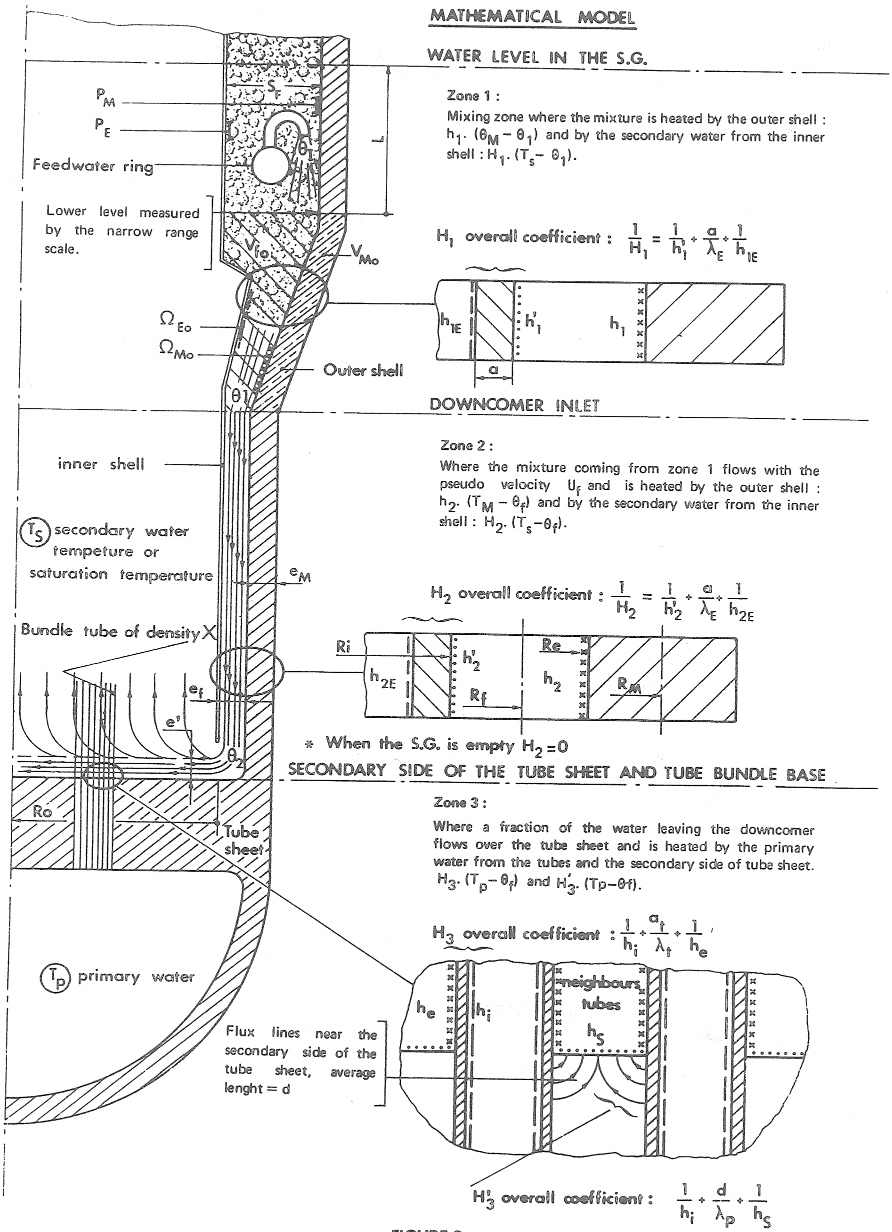
MATHEMATICAL MODEL
WATER LEVEL IN THE S.G.
Zone 1 :
Mixing zone where the mixture is heated by the outer shell : h1. (θM − θ1) and by the secondary water from the inner shell : H1. (Ts − θ1).
H1 overall coefficient : 1/H1 = 1/h'1 + a/λE + 1/h1E
h1E
h'1
h1
a
DOWNCOMER INLET
Zone 2 :
Where the mixture coming from zone 1 flows with the pseudo velocity Uf and is heated by the outer shell : h2. (TM − θf) and by the secondary water from the inner shell : H2. (Ts − θf).
H2 overall coefficient : 1/H2 = 1/h'2 + a/λE + 1/h2E
Ri
h2E
h'2
Rf
Re
h2
RM
* When the S.G. is empty H2 = 0
SECONDARY SIDE OF THE TUBE SHEET AND TUBE BUNDLE BASE
Zone 3 :
Where a fraction of the water leaving the downcomer flows over the tube sheet and is heated by the primary water from the tubes and the secondary side of tube sheet. H3. (Tp − θf) and H'3. (Tp − θf).
H3 overall coefficient : 1/hi + at/λt + 1/he
he
hi
neighbours tubes
hS
H'3 overall coefficient : 1/hi + d/λp + 1/hS
PM
PE
SF
L
Feedwater ring
Lower level measured by the narrow range scale.
Vfo
VMo
ΩEo
ΩMo
Outer shell
θ1
inner shell
Ts secondary water tempeture or saturation temperature
eM
Bundle tube of density X
ef
e'
θ2
Ro
Tube sheet
Tp primary water
Flux lines near the secondary side of the tube sheet, average lenght = d

FIGURE 2

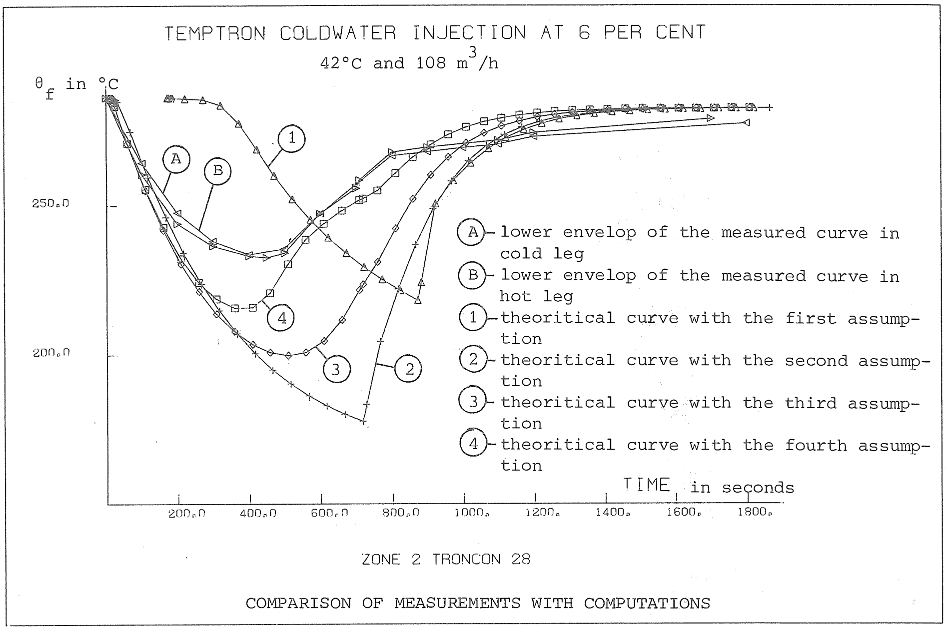

Fig. 3A : VARIATION OF THE WATER TEMPERATURE AT THE BOTTOM OF THE DOWNCOMER

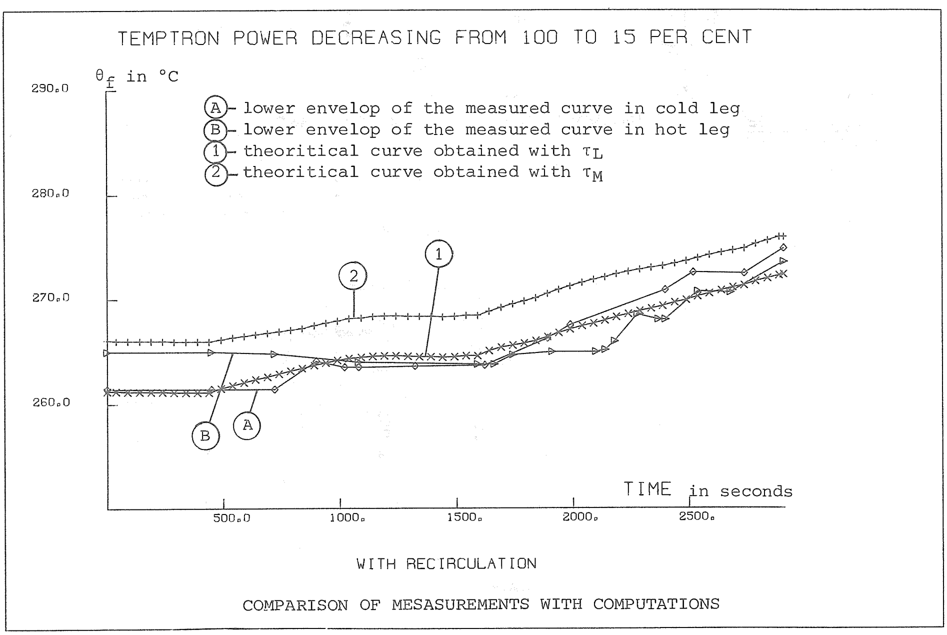

Fig. 3B : VARIATION OF THE WATER TEMPERATURE AT THE BOTTOM OF THE DOWNCOMER