FRENCH STEAM GENERATOR DESIGN DEVELOPMENTS

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Abstract :

From the outset of the French nuclear power program, a significant R & D effort has been invested in improvement of the design and operation of Pressurized Water Reactors including a special committment to improving steam generators.

The steam generator enhancement program has spawned a wide variety of specific R & D ressources, e.g., low temperature hydraulic models for investigation of areas with single-phase flow, and freon-filled models for simulation of areas of steam generators experiencing two-phase flow (tube bundles and moisture separators).

For the moisture separators, a large scale research program using freon-filled models and highly sophisticated instrumentation was used.

Tests at reactor sites during startup of both 900 MWe and 1300 MWe have been used to validate the assumptions made on the basis of loop tests. These tests also demonstrated the validity of using freon to simulate two-phase flow conditions.

The wealth of knowledge accumulated by the steam generator R & D program has been used to develop a new design of steam generators for the N4 plants.

The current R & D effort is aimed at qualifying the N4 steam generator model and developing more comprehensive models. One prong of the R & D effort is the Megeve program. Megeve is a 25 MW steam generator which simulates operating conditions of the N4 model. The other prong is Clotaire, a freon-filled steam generator model which will be used to qualify thermal/hydraulic design codes used for multidimensional calculations for design of tube bundles.

1. INTRODUCTION

With the advent of an ambitious French nuclear program and the boom that resulted from the early seventies onwards, FRAMATOME had initiated an important research and development program in view of increasing the performance of its nuclear power stations and justify design and performance criteria as well plant reliability to the French Nuclear Authority.

In order to elucidate certain problems that might arise and to increase the performance of nuclear components, FRAMATOME has led an active coorperation in the research field with the French Atomic Commission (CEA) and the French Utility (EDF). Also a technology transfer agreement was signed by the French parties and Westinghouse whereby the latter communicated a certain technical know-how.

A particular effort was made in the understanding of problems (such as corrosion, excessive vibration, wear, excess humidity), that might arise in steam generators ; the satisfactory performance of steam generators is crucial to the reliability of nuclear power stations.

In what follows we describe the research program undertaken and still undergoing in order to ameliorate steam generator performance.

2. OVERVIEW OF THE EXPERIMENTAL PROGRAM

Figure 1 representing a steam generator, shows the main experimental programs devoted to study different phenomena (thermohydraulical, chemical, mechanical...) or to improve the design of some components such as the swirl vane separators or the steam dryer equipment.

Specific facilities were built for those different problems and most of them are located in the CEA Center of CADARACHE (south of France). Vibrational aspects are treated in the CEA center of SACLAY and some EDF laboratories.

When it is necessary to use water and steam in actual temperature and pressure conditions small size facilities were built in which analytical tests are possible.

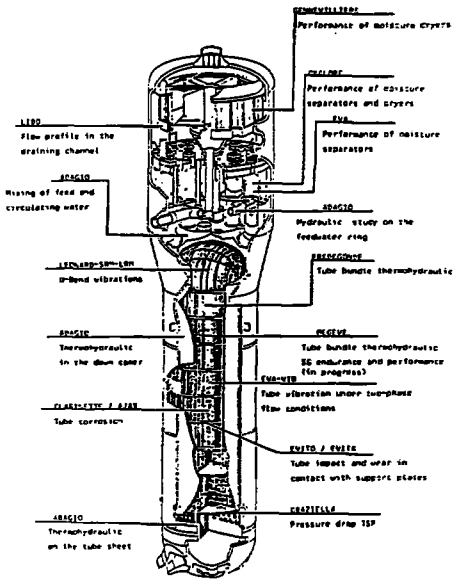

FIGURE 1 : MAIN EXPERIMENTAL PROGRAMS

They are mainly the case of corrosion tests and thermal shock tests.

In some cases a large scale is necessary and the use of freon simulation is very helpful to save energy. This technique has been largely used in our program.

Finally some phenomena can be reproduced in cold conditions using water or air or both.

But a test able to analyse the technological aspects needs a large steam and water facility. The choice of the scale results in compromises between the size and the phenomena that must necessarily be generated.

3. IMPROVEMENT OF SWIRL-VANE MOISTURE SEPARATORS

Steam generators of Pressurized Water Reactors (PWRs) deliver a steam-water mixture at the tube bundle outlet having a steam content of 20 to 50 % at full load. As the steam turbine requires better than 99 % steam quality in order to operate properly, moisture separators and dryers are installed at the top of the steam generator (SG). The steam drum is capable of eliminating virtually all water from the steam.

The first generation of steam generators built in France (model 51) experienced some moisture problems. As early as 1976, a large-scale development program was undertaken, to enhance design of SG separation equipment. The goal of this program was to enhance equipment operating efficiency by improving our understanding of separation phenomena.

3.1. 56" separator

Model 51 SGs used on French 900 MWe reactors are equipped with 56" swirl-vane separators. A number of functional anomalies were encountered on SGs of this type installed on the first units in the French 900 Mwe reactor program (Bugey nuclear power station). A series of performance tests were launched to remedy these anomalies. They were conducted on the EVA test facility, a steam-water loop operating at 30 bar. These tests identified a number of desirable separator design changes, which were subsequently implemented in the field.

Three changes turned out to be particularly effective :

No. 1) Addition of a hydraulic skirt around the main deck, and additional drains and vents,

No. 2) Provision of a liquid film skimmer at the separator stack outlet on the main deck,

No. 3) Transformation of manways through the deckplate into steam relief chimneys.

Subsequent field measurements revealed that these add-on components added considerably to SG efficiency. Fig. 2 plots carryover (moisture content at SG outlet, just upstream of the flow limiter) as a function of the ratio Q_g^2 to ρ_g, where Q_g is mass steam flow and ρ_g is steam specific mass. As can be seen from the graph, carryover was reduced by a factor of six.

3.2. 500 mm separator

500 mm swirl-vane separators (model DO) were installed on a number of US steam generators. Carryover on these SGs exceeded or barely met contractual requirements.

In order to use this model on French 1300 MWe model 68/19 SGs, an effort was undertaken, starting in 1977, to enhance model DO separator performance.

A battery of tests were run on several water/air, water/steam and freon test loops. The test program is summarized below.

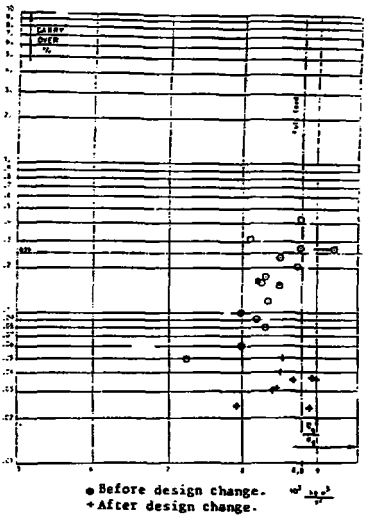

FIGURE 2 : MODEL 51 SG
Carry over values

TEST	TEST LOOP	TEST FLUID	PRESSURE (BAR)	SCALE
Visualize flow distribution	RAMSES	WATER — AIR	1,00	0,4
Select optimum model	EVA	WATER — STEAM	20 - 35	0,4
Study effect of fluid var.	CYCLOPE	Freon R114	4,2	0,4
Study effect of press.var.	CYCLOPE	Freon R114	9,4	0,4
Study effect of scale var.	CYCLOPE	Freon R114	9,4	1,00

Several new swirl-vane separator designs were evaluated on the EVA test loop to determine the optimum design. The reengineered separator (model D2.1) exhibited the following new features (see figs. 3 and 4) :

- blade leading edge redesigned to decrease pressure drop
- increase in separator outlet stack diameter and length
- skimmer added to stack orifice
- increased height between vane and upper rim of the riser.

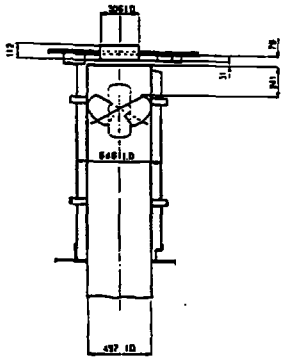

FIGURE 3 : MODEL DD
Moisture separator

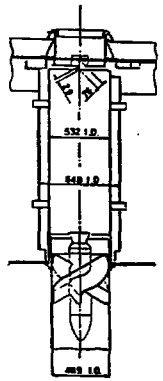

FIGURE 4 : MODEL D2.1
Moisture separator

Subsequent breakdown of test results made possible to establish rules of similitude between different pressures, types of fluid and scales, enabling model D2.1 separator performance under actual SG operating conditions to be predicted.

This prediction justified selection of the type D2.1 separator for use on the model 68/19 SG. Subsequently, it was also decided to install this separator on the model 55/19 SG utilized on M310 900 MWe reactors (the plant model used in French export contracts).

Measurements taken in early 1985 at Paluel nuclear power station, which is equipped with model 68/19 SGs, indicate that the enhanced separator design has considerably improved SG performance. Carryover at full power does not exceed 0.03 %

3.3. 200 mm separator

The 200 mm swirl-vane separator was specially developed for the FRAMATOME economizer SG (model 73/19E) designed to equip the new French 1450 MWe reactor (N4).

The objectives of the development program were three-fold :

- halve pressure loss across swirl-vane separators with respect to that in the model 68/19 SG,
- reduce moisture content at the dryer inlet to less than 5 %,
- generate low carryunder.

The latter requirement is particularly important in model 73/19 SG design. High carryunder presents the disadvantage of lowering recirculation rates and diminishing heat transfer within the economizer section.

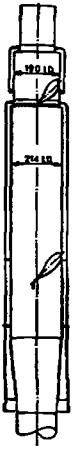

FIGURE 5 : TI 14 Moisture separator

To meet these goals, a new model moisture separator was developed. This model differs from the model D2.1 separator in the following respects (see fig. 5) :
- reduced separator diameter
- two-stage separation
- no tangential nozzles
- enhanced vane design.

These design changes were selected after thorough testing, at the ARGUS, EVA and FREDEGONDE test facilities. The test program is summarized on the following page.

The testing procedure employed for the new model swirl-vane separator, known as TI 14 was similar to that utilized for the model D2.1 separator. Tests enabled rules of similitude derived from 20" swirl-vane separator testing to be adapted to tests on the new model, and performance under SG operating conditions to be predicted with appreciable accuracy.

Predicted performance showed that design goals were virtually attained :

- discontinuity-related pressure drop of 99 mbar at (compared to 253 mbar on model 68/19 SG),
- moisture content at nominal water level of approximately 7 % upstream of dryers, irrespective of separator position above tube bundle,
- carryunder less than 1 %.

TEST	TEST LOOP	TEST FLUID	PRESSURE (bar)	SCALE
Visualize flow distribution Classify model by efficiency	ARCOS	WATER – FORANE VAPOR	3,2	0,7
Select optimum model		WATER – STEAM	30,00	1,00
Study effect of fluid and scale variations	TRIDECONIC	From 8 to	4,2	0,42
Study of pressure variation			9,4	

Next year, tests will be carried out on 3 full-scale model TI 14 separators at the MEGEVE test facility (steam-water system, 74 bar) to verify performance under actual steam generator operating conditions.

4. FULL-SCALE TESTS : SITE INSTRUMENTATION

Full-scale tests on real steam generators are carried out in parallel with experimentation on smaller mock-ups. Contrary to the mock-up tests which permit the study of one particular component or the elucidation of a typical phenomenon requiring parametrical studies, full scale tests provide on-site feedback informations at least in the first year of operation.

The full-scale tests are however much more expensive in terms of instrumentation and plant availability.

On-site research and development programs are done under a common agreement uniting FRAMATOME, CEA and EDF.

The instrumented steam-generators are generally prototypes, thus the actual steam-generators are that were instrumented.

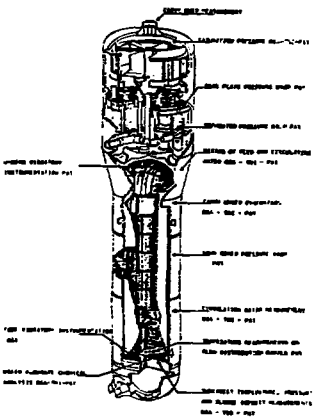

FIGURE 6 : PLANT INSTRUMENTATION

. BUGEY of 51A type
. TRICASTIN of 51m type (contract CPY)
. PALUEL 1 of 68/19 type (contract P4).

The new steam-generator which will equip the 1450 MW nuclear power stations (under N4 contract) will no doubt be likewise instrumented. This model is different from the others in the sense that it contains an economizer with an axial preheater (see § 5). The instrumentation of this steam-generator will be carried out during the 1985-1990 period ; the CHOOZ unit is supposed to become operational at the end of that period.

An example of plant instrumentation : Paluel 1

Thermohydraulic and vibratory instrumentation was installed in one of Paluel 1 steam generators ; it permits the determination of essential parameters such as circulation ratio, saturation pressure, recirculating flow configuration. Hence we can not only verify the correct operation of the steam-generator integrated in its real environment but also refine our predictive tools from experimental knowledge. As examples, we give in figure 7 and figure 8 calculated circulation ratios and saturation pressures for various power levels, together with values obtained from the instrumented steam-generator.

The main results are summarized as follows:

1. A better efficiency of the Paluel steam-generator is obtained due to uneven flow distribution ; in fact the hot-leg flow rate is 80 % of the total flow rate in the tubesheet region, and is obtained by a conveniently perforated flow distribution baffle

2. A mapping of the saturation zones on the tubesheet was carried out in view of showing their influence on sludge deposition

3. The instrumentation showed no heavy thermal transients obnoxious to welded zones

4 The carryunder was very low.

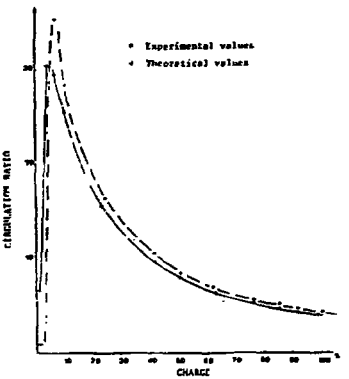

FIGURE 7

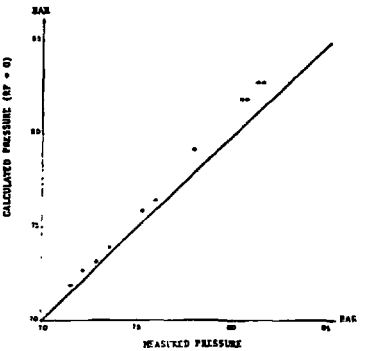

FIGURE 8

COMPARISON OF CALCULATED VALUES OF CIRCULATION RATIO AND SATURATION PRESSURE WITH FIELD DATA OF PALUEL

5. MEGEVE : FULL-SCALE STEAM GENERATOR SIMULATION

The MEGEVE mock-up is a N4 type steam generator designed for 25 MW power corresponding to 1/43 of the actual SG (see fig. 9). It posseses an axial preheater, and is provided with flow-rate distribution monitoring facilities. The aim of the MEGEVE program is to :

1) Study the thermohydraulic stability of the SG as well the effect of strong transients on water level, circulation, ratio, temperature...

2) Validate the global conception and working of N4 steam generators in steady and transient regimes

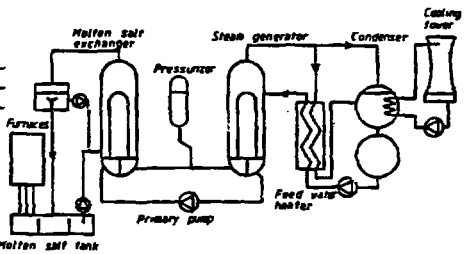

FIGURE 9 : MEGEVE EXPERIMENTAL LOOP

3) Study the preheater efficiency in function of the feedwater distribution and diverse constraints imposed by general operating conditions of the power station

4) Study the vibratory behaviour of the tube bundle

The MEGEVE program will thus provide useful informations for our future N4 steam-generators.

6. CLOTAIRE : FREON MOCK-UP FOR STEAM-GENERATOR SIMULATION

The CLOTAIRE mock-up is a freon-114 steam-generator, representing only half of the real steam-generator tube bundle (see fig. 10). The FREON operating conditions (∿ 80°C and ∿ 9 bars) permit relatively easy installation of thermalhydraulic and mechanical probes.

We expect a wealth of data from the CLOTAIRE program : local values of temperature, pressure, void fraction. Two-phase velocity field and tube vibration levels will be determined experimentally thus providing a unique chance for qualification of advanced 3D thermohydraulic codes as well as a greater knowledge of tube vibration levels.

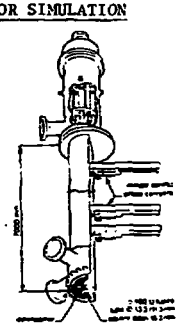

FIGURE 10 : CLOTAIRE MOCK-UP

7. CONCLUSION

FRAMATOME in collaboration with the CEA and EDF has launched an extensive R and D program in view of ameliorating steam generator performance and reliability . For example as early as 1976, a program was undertaken to improve our understanding of moisture separation ; the result is a very low humidity vapour output from actual 68/19 steam-generators. Other programs such as MEGEVE and CLOTAIRE were initiated in order to improve still further our knowledge. MEGEVE simulates the operating conditions of N4 steam-generators whereas CLOTAIRE will be used to qualify design codes for calculating multidimensional flow in tube bundles.
Also, reactor field instrumentation is an essential data source permitting feed-back information for code qualification.

We expect from the experimental program a better knowledg of the complex phenomena existing in the steam generators, and hence obtain a greater reliability and performance in our steam-generator.