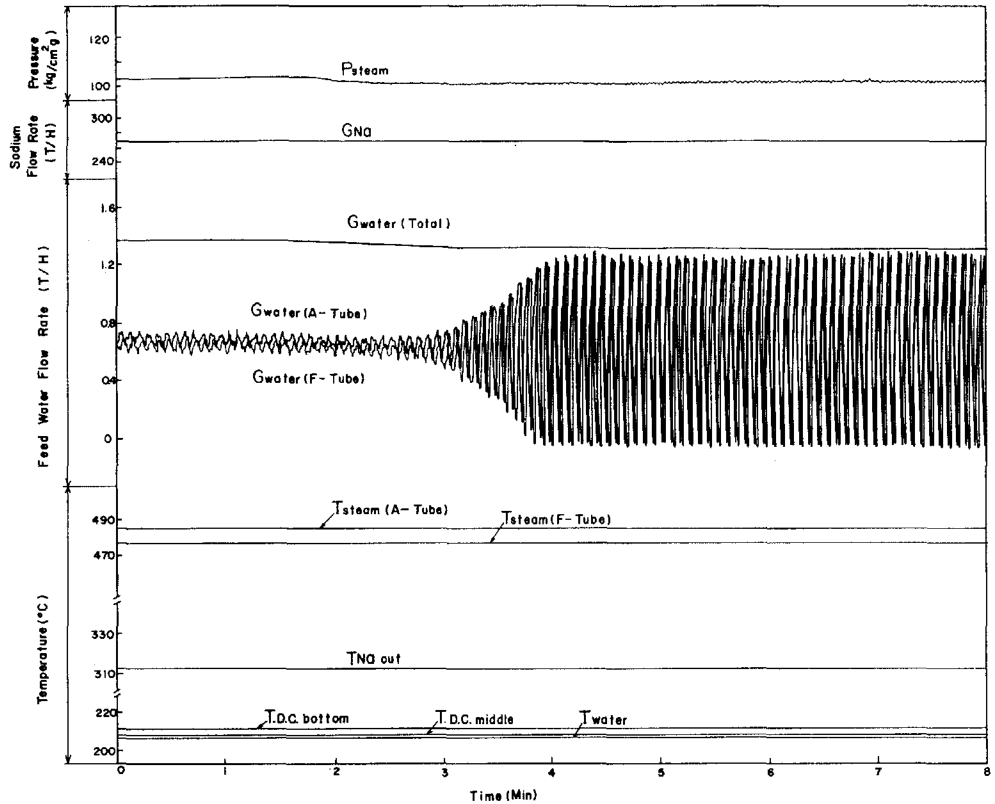

An Example of Flow Instability Test in Modified Steam Generator

Fig. 10.

CONCLUSION

The original and modified 1MW steam generator were operated successfully conducting various performance tests, and a great deal of useful thermo-hydraulic data were gained as expected at planning stage. Besides, dismantling of steam generator and material test were done after the operation of the original one, and small water leak was twice experienced during the operation of the modified one. All of them have been feeding back one after the other to 50 MW and MONJU steam generator.

1MW steam generator is scheduled to carry out flow instability tests in detail and sodium circulating operation through steam generator, and dismantling and material test will follow after these operation as well as the original one. In addition, another test model of flow instability is now planning to investigate moreover it's phenomenon.

H.3. Some results of the 50 MW Straight Tube Steam generator Test in the TNO 50 MW SCTF at Hengelo

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Abstract

A prototype 50 MW straight tube steamgenerator has been tested during more than 3000 hours under operating conditions. The steady state, transient and stability behaviour were tested. The most remarkable results of the experiments are given .

1. Introduction

In the period between april 1972 and june 1974 the straight tube steamgenerator was tested.
The tests were interrupted a number of times, due to a sodium fire, a leakage in the reheater, a supposed leakage in the evaporator and an initial test of a helical coiled evaporator.
A total of more than 3000 hours of operation under normal operating conditions was reached, at the end of june 1974. The evaporator is now in the workshop to be dismantled partially for inspection. With some modifications and additional instrumentation the evaporator will again be put into operation in the 50 MW circuit in the middle of 1975.
This paper will deal with two main aspects of the steamgenerator test: the constructional and operational aspects.
Chapter 3 will deal with the constructional aspects, such as thermal shields, expansion bellows, support grids and heat transfer surface.
Chapter 4 will deal with the thermal and hydraulic performance.
Chapter 5 will deal with the operational aspects like instability, control and dynamics.

A description of the steamgenerator and 50 MW SCTF will be given in chapter 2.

2. Description of the steamgenerator and the 50 MW SCTF

2.1. Description of the steamgenerator

Originally the steamgenerator consisted, like in the original SNR design, of an evaporator, a superheater and a reheater.

The initial tests were carried out with these three components. After the reheater leakage in september 1972 the test has been continued with an evaporator and a superheater only.
In order to avoid large movements of the boiling region the steam conditions at the outlet of the evaporator are controled. To realize this NERATOOM chose for a sort of recirculation concept. Therefore a water separator between the evaporator and the superheater is an integrated part of the steamgenerator. The water separated from the steam flows over a throttle valve to the low pressure side of the preheater.
The three steamgenerator components, the evaporator, superheater and reheater are of the same type (figure 1), characterized by:

- straight tubes;
- flat tube sheets;
- expansion bellows in the shell;
- a shroud around the bundle;
- support grids (no baffles);
- inlet of sodium in the bundle from the ringshaped sodium header over a perforated section of the shroud;
- outlet of sodium from the bundle again over a perforation;
- thermal shields, to protect the tube sheets;
- material 2¼ Cr 1 Mo stabilized ferritic steel.

The main dimensions are given in tabel 1.

	evaporator	superheater	reheater	dim.
tubes dimensions OD/ID	17.2/12.6	17.2/10.6	20.0/16.0	mm/mm
pitch	27.5	27.5	27.5	mm
effective tube length	18.64	13.88	8.33	m
total tube length	19.34	14.58	8.97	m
number of tubes	139	139	139	-
heat transfer surface	140.0	104.2	72.7	m^2

Tabel 1 dimensions of steamgenerator components

Critical points in the design are:

- the support grids;
- the expansion bellows;
- the radial temperature distribution;
- the thermal shields.

The design conditions of the 50 MW steamgenerator are given in table 2.

	evaporator	superheater	reheater	dim.
sodium side design pressure	12	12	12	bar
sodium side design temperature	505	540	540	°C
water side design pressure	180	180	44	bar
water side design temperature	505	540	540	°C
hours of operation	100.000	100.000	100.000	h
pressure due to Na-H_2O reaction	133	118	44	bar

Tabel 2 design conditions

The operational conditions of the 3 component steamgenerator are given in tabel 3.

	evaporator	superheater	reheater	dim.
sodium inlet temperature	441.7	529.7	529.7	°C
sodium outlet temp.	343.5	442.1	440.6	"
water/steam inlet temp.	288.8	353.9	325.0	"
water/steam outlet temp.	355.2	510.0	498.9	"
sodium mass flow	210.5	147.9	62.6	kg/sec.
water/steam mass flow	21.81	20.72	16.90	"
steam quality outlet	0.95	1	1	--
outlet steam pressure	176.3	166.8	41.5	bar
power	26.35	16.50	7.15	MW

Tabel 3 Full load operation conditions of the three component steamgenerator

A detailed description of the steamgenerating components is given in ref. 1.

After the reheater accident the full load operation conditions for the two remaining components had to be changed. These conditions are given in table 4.

	evaporator	superheater	dimensions
Sodium inlet temperature	454.6	527.7	^oC
Sodium outlet temp.	337.8	454.6	"
water/steam inlet temperature	284.7	454.1	"
water/steam outlet temperature	355.2	510.0	"
outlet steam pressure	176.3	166.8	bar
sodium mass flow	185.8	185.8	kg/sec.
water/steam mass flow	22.6	21.5	kg/sec.
steam quality outlet	0.95	1.0	--
power	27.84	17.25	MW

Tabel 4 Full load operation conditions of the two component steamgenerator

2.2. Description of the TNO sodium component Test Facility for testing of steamgenerator

A basic scheme of the testfacility is given in figure 2.
The main components are:

1. sodium system with
   - 3 sodium furnaces with a maximum capacity of 58 MW;
   - an 1800 m^3/hr sodium pump;
   - a 15 MW aircooler.
2. a water/steam system with
   - one electrical and one turbine feedwater pump in parallel; total capacity 33 kg/sec. at 245 bar;
   - a pre-heater to produce feedwater of max. 300^oC;
   - a steamgenerator; straight tube steamgenerator or helical coiled evaporator;
   - a turbine valve;
   - pressure reducing valves;
   - water injection coolers;
   - an aircooled condensor;
   - a deaerator

The circuit has by-passes to generate thermal shocks.

2.3. Instrumentation

The steamgenerator is extensively instrumentated with thermocouples to measure axial and radial temperatureprofiles, outlettemperatures of individual tubes, temperature between tubesheet and thermal shields and tubesheet temperatures.

Sodium and water/steam in- and outlettemperatures are measured threefold.
Water and steam flows are measured with orifices.
Sodium flows are measured with electromagnetic flowmeters.
Furtheron the steampressure and the water- and sodiumside pressure losses are measured.

The data collection is performed with a computer system. This system is able to collect the data from 512 measuring points with a frequency of 1 set per second.
Normally under steady state conditions only one set of values per minute is written on a magnetic tape. When a transient condition arises the system automatically starts with writing down the values with a frequency of one set per second.

3. Test results with regard to critical constructive details of the steamgenerator

3.1. Expansion bellows

The expansion bellows have to compensate the different thermal expansion between tubes and shell. Under steady state conditions the movements of the bellows are so small they could have been omitted.
Under transient conditions however the movements of the

bellows are large. These movements are caused by the big difference in the time constants of the tubes and the shell.
The time constant of the tube wall is in the order of 0.5 seconds, that of the shell in the order of minutes.
The latter large time constant is caused by the inner shroud and the stagnant sodium layer between inner shroud and shell. Shroud and shell have the task to protect the shell wall against corrosion/erosion by pinhole leaks.

A survey of the movements of the expansion bellows under transient conditions is given in table 5.

	bellows compression	start cm	end cm	min. cm	max. cm	ΔL_{max} cm
cold start simulation	evaporator superheater	-- 2.60	-- 2.72	-- 2.59	-- 2.93	-- 0.34
hot start simulation	evaporator superheater	2.50 2.64	2.08 2.76	2.08 2.59	2.50 3.07	0.42 0.48
normal plant stop simulation	evaporator superheater	1.89 2.56	2.34 2.51	1.83 2.30	2.34 2.58	0.51 0.28
reactor scram simulation	evaporator superheater	1.72 2.54	2.43 2.64	1.46 1.94	2.49 3.04	1.03 1.10

Table 5 Survey of expansion bellows movement under transient conditions

3.2. Tube support grids

The function of the tube support grids is the prevention of large vibrations and the prevention of buckling of relatively hot tubes.
There are no direct measurements of the functioning of the grids.
The major problem with tube support grids is the possibility of damage of the tubes due to vibration of the tubes in the grids.
In august 1973 a single tube was removed out of the evaporator; no fretting was observed after about 2000 hours of operation in sodium.
At present the evaporator is dismantled for inspection.
A first observation showed that no fretting of the tube surfaces after about 4000 hours of operation in sodium can be found.
We therefore expect that no steamgenerator damage, caused by vibration of the tubes, will occur in the straight tube SNR steamgenerator.

3.3. Thermal shields

There are two types of thermal shields in the steamgenerator components:

1. thermal shields to protect the tube sheet against thermal shocks;
2. thermal shields in the ring-shaped sodium headers to ascertain a smooth temperature gradient between the "cold" tube sheet and the "hot" shell of the header.

The thermal shields to protect the tube sheet are flat, perforated plates with a thickness of 100 mm. We found that under steady state and transient conditions about 90% of the temperature difference between sodium and water or steam is absorbed by the shield.

The second type of thermal shield is shown in figure 1.
In figure 3 the temperature gradient at full load over the conical part of the sodium header is given.
As can be seen a sufficient smooth gradient is present.

3.4. Tube sheets

The temperature of the tube sheets is defined by the water or steam temperature. As the thermal shields work very well, the influence of the sodium temperature on the tube sheet temperature will be negligible.
Large temperature gradients are observed in the upper tube-sheet of the evaporator due to different steam outlet temperatures of individual tubes. An explanation of the origin of these temperature differences will be given in paragraph 4.3.

4. Thermal and hydraulic performance

4.1 Measured and calculated power

The power that should have been transferred with the measured proces conditions has been calculated with our computer code STMGEM.

This code can do two things:

1. it calculates a required heat transfer surface if power, in- and outlet conditions are given;

2. it calculates power and outlet conditions if surface, flows and inlet conditions are given.

It is a normal procedure to apply an allowance on the calculated heat transfer surface. In the computer code this is done by dividing every calculated heat transfer coefficient by an allowance factor F_a ($F_a > 1$, in the design)
This procedure has the advantage of an immediate correct calculation of the pressure drop.

In the evaluation of the test results, by iteration, the allowance factor was defined that gives exactly the same power in the calculation as it was measured in the experiment. This value of F_a gives the average deviation of the measured heat transfer coefficients from the heat transfer coefficient calculated with the used heat transfer correlations.

The calculated values of F_a in the evaporator and superheater at full load are:

Evaporator :	power	24.94 MW
	F_a	1.20
Superheater :	power	17.22 MW
	F_a	0.93

This means that the evaporator behaves 20% worse and the superheater 7% better than assumed.
We shall see in the next paragraphs that the bad performance of the evaporator is caused by bypass flows around the tube bundle. These bypass-flows can be avoided by a simple change in the construction.

4.2. Axial temperature profile

The axial sodium temperature profiles are measured by 26 thermocouples located in the centre of the bundle, fixed on the tubesupportgrids.

The measured and calculated temperature profiles at full power are given in figures 4 and 5.

It attracts the attention that the measured sodium temperature profile in the centre of the bundle deviates from the calculated one. The temperature measured on the first support grid, situated in the middle of the inlet perforation is already 12K lower that the sodium inlet temperature.
The temperature measured on the last grid is 22K lower than the sodiumoutlettemperature.
The first mentioned temperaturedifference is caused by the heat transfer during the cross flow of the sodium in the direction of the bundel centre.
The latter temperaturedifference is caused by the large quantity of barely cooled sodium that leaks along the outside of the bundle (see also 4.3.).

4.3. Radial temperature profile

Radial temperatures are measured on the 7th and 21th tube support grid at about 25% and 75% of the evaporator length. Radial profiles at full power are given in figure 6.

As can be seen from the profile at grid 21 the assumed leakflow causes a temperature gradient of more than 30K at this grid. The leak flow is possible because the bundle with its triangled tube pattern is surrounded by a round shaped shroud (figure 7). In the large channels at the outer side of the tube bundle the sodium can flow down with velocities up to two times the velocity in the bundle, causing a leak flow of 20%.

In the steamgenerator for the SNR-300 the tube bundle is surrounded by a hexagonal shroud situated as close as possible to the tube bundle. In this design the calculated velocity in the boundary channels is lower than in the bundle.

4.4. Correction of the overall thermal performance with regard to the leakflow

In order to predict the thermal behaviour of a straight tube steamgenerator without leakflows we calculated the thermal performance in the centre of the bundle, leaving out of consideration the bundle zone influenced by the hot sodium by-pass around the bundle.
If we assume no mixing between the sodium around the bundle and the sodium in the bundle we find values of F_a of 0.66 for the evaporator and 0.82 for the superheater.
With the radial temperature profile of grid 21 a mixing rate can be calculated. Doing this we find values of F_a of 0.93 for the evaporator and 0.87 for the superheater.
Establishing this we conclude that the heat transfer surface of the SNR-steamgenerators calculated with the same correlations and the F_a value of 1.1 will be large enough to ascertain the transfer of its specified power within the specified conditions.

4.5. Pressure drop

4.5.1. Pressure drop on the sodium side

Measured and calculated pressure drop on the sodium side of the evaporator are given in figure 8. It can be seen that the measured pressure drop is lower than the pressure drop calculated with coefficients from ref. 2.

4.5.2. Pressure drop on the steam/water side

The water/steam side total pressure drops are given in table 6.

experiment	42MW	35MW	33MW	29MW	22MW	15MW	dim.
evaporator							
measured	1.95	1.83	1.71	1.65	1.55	1.52	bar
calculated	2.30	2.05	1.82	1.66	1.46	1.31	bar
superheater							
measured	3.53	2.77	2.22	1.83	1.17	0.76	bar
calculated	6.28	4.85	3.77	3.02	1.80	0.92	bar

Table 6 Steam/water side pressure drop.

It attracts the attention that at high power levels measured pressure drops are lower than the calculated ones.
The total pressure drop consists of three components: hydrostatic head, acceleration pressure drop and friction pressure drop.
The first two components can be calculated very accurately, and a difference between the measured and calculated pressure drop has to be found in the pressure drop due to friction.

Tabele 7 gives the calculated and "measured" pressure drop due to friction

experiment	42MW	37MW	33MW	29MW	22MW	15MW	dim.
evaporator							
measured	0.85	0.71	0.60	0.54	0.44	0.34	bar
calculated	1.20	0.93	0.71	0.55	0.31	0.13	bar
superheater							
measured	3.19	2.48	1.96	1.60	0.97	0.61	bar
calculated	5.94	4.56	3.51	2.79	1.60	0.77	bar

Tabel 7 calculated and "measured" pressure drop due to friction

The values of the measured pressure drop at low load are very inaccurate.

The given pressure drop data point to the existence of very smooth inner tube surface. Especially the superheater has a very small pressure drop.

The pressure drops are calculated with a surface roughness of 0.05 mm. The measured pressure drop in the superheater tends to an existent roughness of 0.005 mm.

5. Operating experience

5.1. Steamgenerator control

The load following control scheme is given in figure 9.
The feedwater control unit FC 321 is controled with the proportion adjusting unit by the sodium flow; the tap off flow controller gives a correction to the proportion control.
The level in the water/steam separator is held constant with the level controller LC 325.
The tap off flow from the separator is measured and gives via the flow controller FC 400 the above mentioned correction signal. The set point of the flow controller FC 400 is constant over the load range from 0-100%.
The steam flow is controled with FC 313 and the valve E 302.
The set point of FC 313 (the required steam quantity) is also setpoint of the sodium flow controller FC 110 with a correction by the steampressure controller PC 313.

The following remark has to be made:
the use of one setpoint for FC 313 and FC 110 is not correct.
The common setpoint has to take care of a fixed proportion between sodium flow and steam flow.
The range of the steam flow measurement is 100 t/h and the range of the sodium flow measurement is 250 kg/sec.
The proportion of these two ranges is not the desired proportion; therefore the pressure controller has to give a correction.

As a consequence, in large power variations, the deviation of the steam pressure from the setpoint value will be larger than would have been the case if the proportion between the two setpoints had been correct.

A large number of experiments, load steps and ramps, pressure setpoint steps etc. were carried out. In the next paragraph two examples will be given.

1. A power step of 5 MW at 40 MW power.
2. A power variation from 40 MW (95%) to 25 MW in 4 minutes.

5.2. Steamgenerator dynamics

The dynamic experiments can be divided into two main parts:

1. Uncontrolled behaviour of the steamgenerator.
2. The controlled behaviour of the steamgenerator.

5.2.1. Uncontrolled behaviour

In order to improve our knowledge about the dynamic characteristics of the steamgenerator we have carried out a number of experiments on the steamgenerator with only the level control of the separator in operation.
It showed that the steamgenerating process is a stable process; after a variation of a flow, an inlet temperature or a pressure, the steamgenerator reaches a new stable situation in a short time.
Figure 10 gives as example the response of the steamgenerator to a step of + 8.2% of the feedwater flow at a power of 35MW.

5.2.2. Controlled behaviour

As already mentioned a large number of experiments were carried out. These experiments showed that the steamgenerator responds quickly and in a stable way to disturbances.
Two examples will be given. The first example is a + 5 MW step in the required power at a nominal power level of 40 MW. The result is given in figure 11.

As can be seen there are large fluctuations in the tap off flow; on the other hand, due to an optimal adjustment of the control units, these fluctuations do not result in fluctuations in temperatures and feedwater flow.
The steam pressure fluctuates between + 4 bar and - 3 bar from the nominal pressure, caused partly by the process described at the end of paragraph 5.1.

The second example is a linear power variation from 40 MW to 25 MW in 4 minutes. The result is given in figure 12.

We see the same phenomenon as with the first example. The steam pressure now fluctuates between +4 bar and -4 bar from the nominal pressure.
It was demonstrated that the steamgenerator with a controlsystem as described in paragraph 5.1. can be submitted to the specified variations in the required steam production.

5.3. Dynamic instability

In order to define a domain within which the evaporator behaves in a stable way an extensive testprogram has been carried out.

The experiments are carried out under the following conditions:

steam-pressure	60-170 bar
sodium inlet temperature	370-450 °C
feedwater temperature	200-300 "
sodium flow	30-210 dm^3/sec.
proportion: sodium/feedwater massflow	8.7- 43

Under extreme conditions far remote from the SNR-300 operational conditions, instabilities were observed. The nature of these instabilities is stochastic or periodic.
The frequency of the periodic instability is between 0.125 and 0.25 H_z; the maximum observed amplitude was 90K at the outlet of a tube.

The experiments are carried out in the following way:

With fixed values for the sodium flow, the feedwater and sodium inlet temperature and the steam outlet pressure, the feedwater flow is reduced step by step until either an outlet temperature variation of one individual tube becomes more than 25K or an normal operational limit is reached.
Instabilities always were observed in the outer tube first.
With very high sodiumflow/feedwaterflow proportions the inner tubes can also become unstable.
The difference between the outer and inner tubes is a consequence of the bad radial flow distribution on the shell side of the evaporator (see 4.3.).

Typical examples of stochastic and periodic unstabilities are given in figure 13.
The test results were plotted in graphs with on the ordinate the value $(T_{Na,\ in} - T_{sat}) \times G_{Na}/G_{F.w}$ and $(T_{sat}-T_{F.w})$ on the abscis. These graphs show that the influence of the subcooling is relatively low.
It can be concluded from the graphs that $(T_{Na,in}- T_{sat}) \times G_{Na}/G_{F.w}$ has to be lower than 1300 K in order to prevent periodic instability.
This means that the stability of the SNR steamgenerator is guaranteed under the normal operation conditions including the start up conditions.

5.4. Decay heat removal

In the SNR-300 the decay heat of the reactor will be removed over the steamgenerator. In order to be able to have a hot start up the steamgenerator will operate during the first 24 hours after a reactor scram with a pressure of about 170 bar. In the meantime the power and the flows in the steamgenerator will be reduced to 2-3% of the maximum values.
It has been demonstrated by simulating experiments that the hydraulic stability on the sodium side and the dynamic stability on the steam/water side are guaranteed under these extreme conditions.

6. Conclusions

The experiments carried out with the prototype straight tube

steamgenerator until now, have shown that the SNR straight tube steamgenerator will be able to transfer its power within the specified operation conditions.
The effectiveness of thermal shields and bellows was demonstrated. Even the extreme bad radial flow and temperature distribution on the sodium side, leading to large differences in individual tube temperature did not cause any damage or buckling of the tubes.
The operating experience has shown that the choosen type of recirculation process guarantees a definitely stable steam-generating process.
The control system as it was described in 5.1. guarantees a fast and smooth adjustment to new operation conditions.
The dynamic stability over the total range of operation of the evaporator is assured.
The straight tube steamgenerator can operate under extreme low power conditions and will be able to remove the decay heat from the reactor on a high pressure level thus making possible a hot start up.

Our final conclusion is that the relatively simple and straight steamgenerator is excellently suitable to generate steam in Liquid Metal Fast Breeder Reactors.

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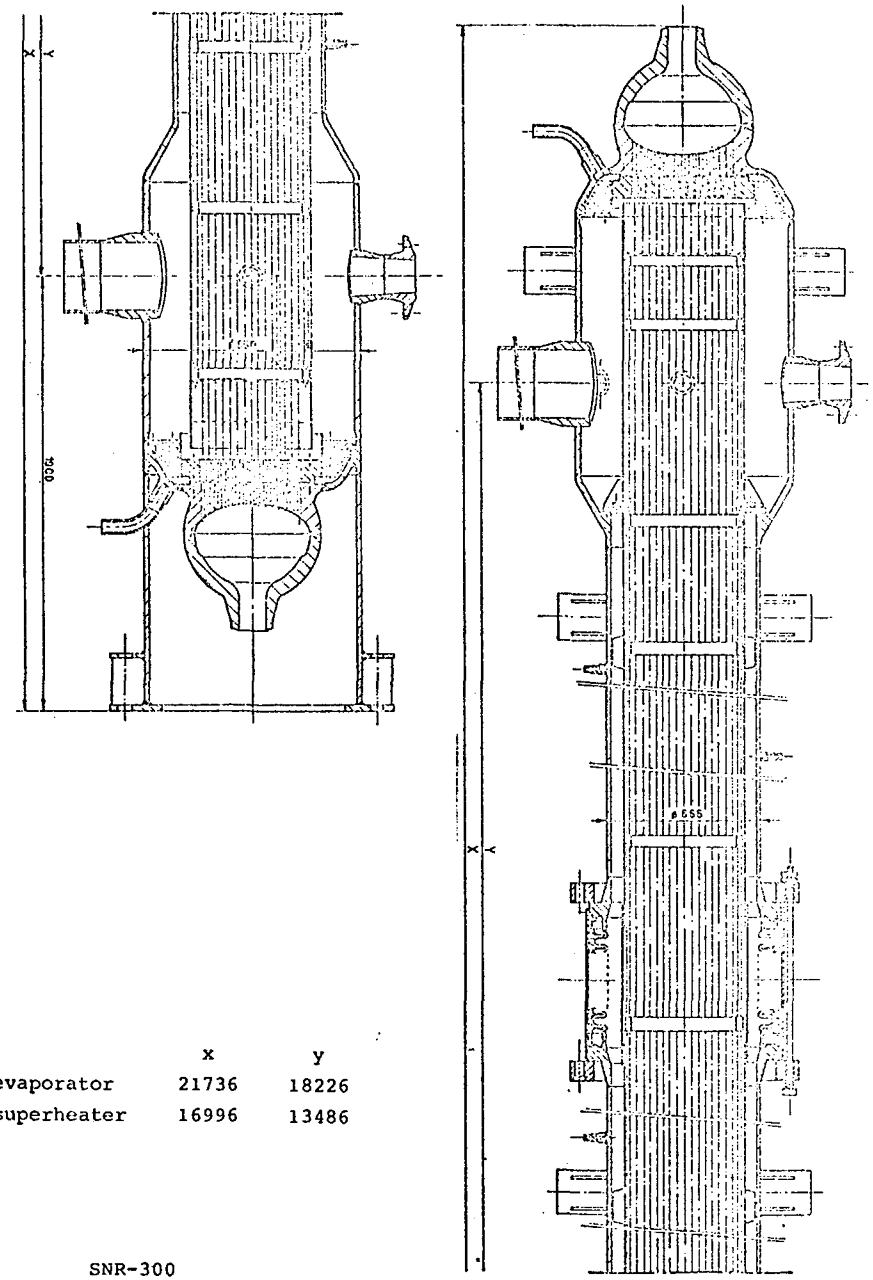


	x	y
evaporator	21736	18226
superheater	16996	13486

SNR-300
steamgenerator

FIG. 1.

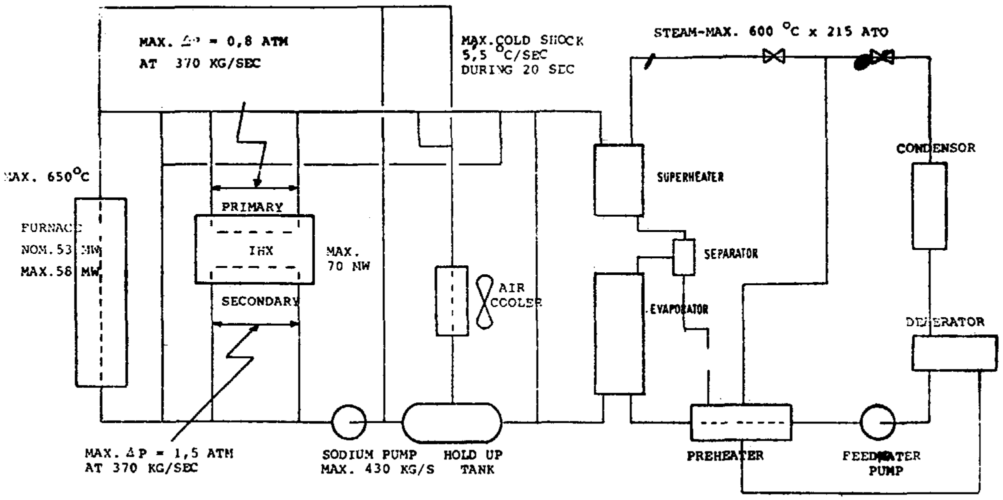
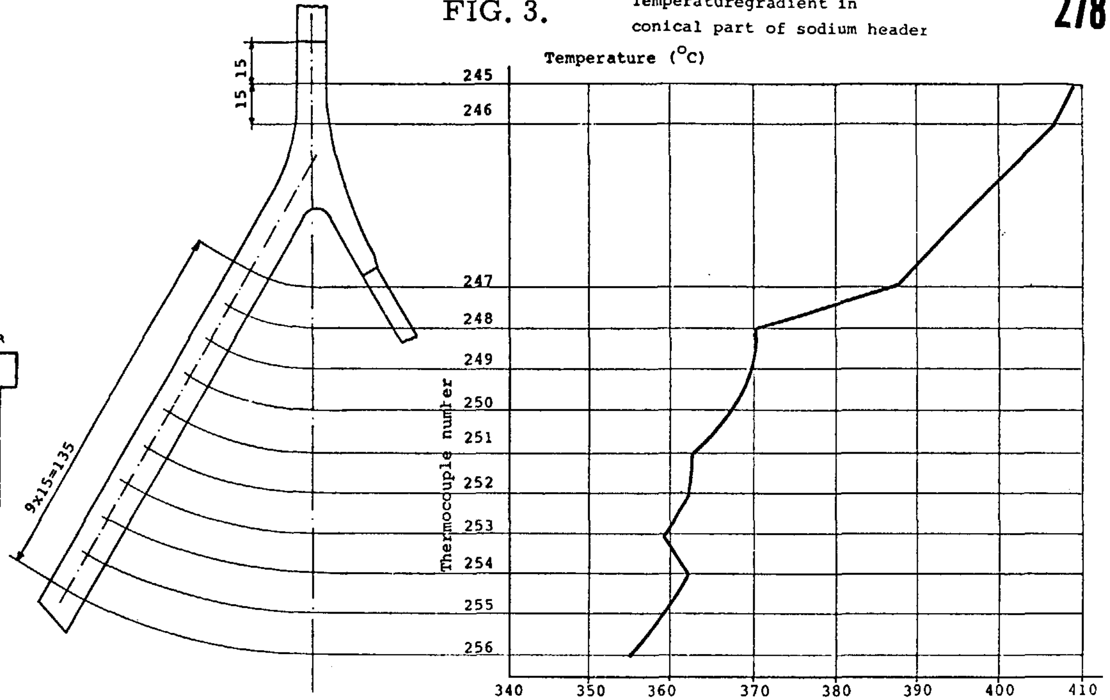


FIG. 2. BASIC SCHEME OF 50 MW SCTF

FIG. 3. Temperaturegradient in conical part of sodium header



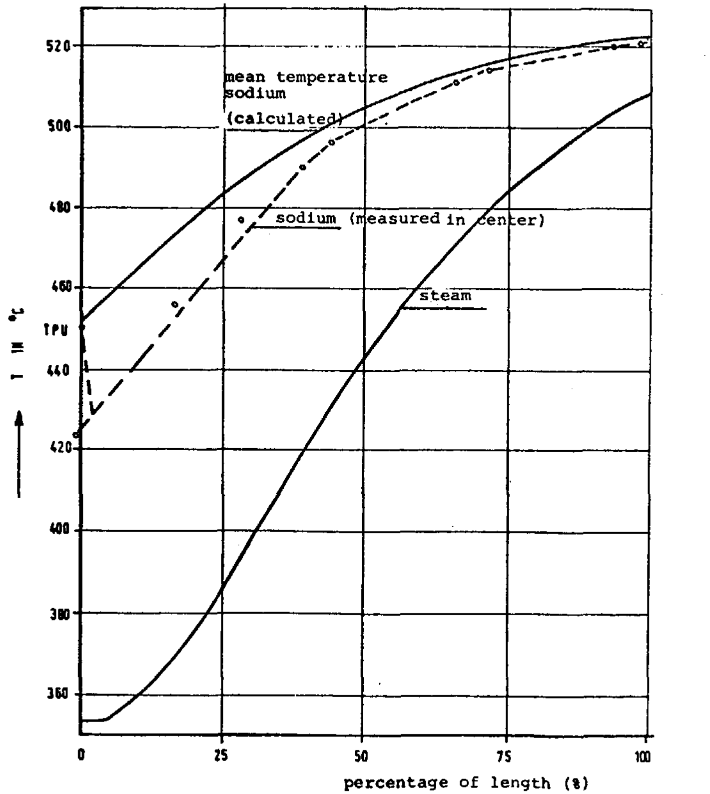


FIG. 5. Axial temperature profile superheater

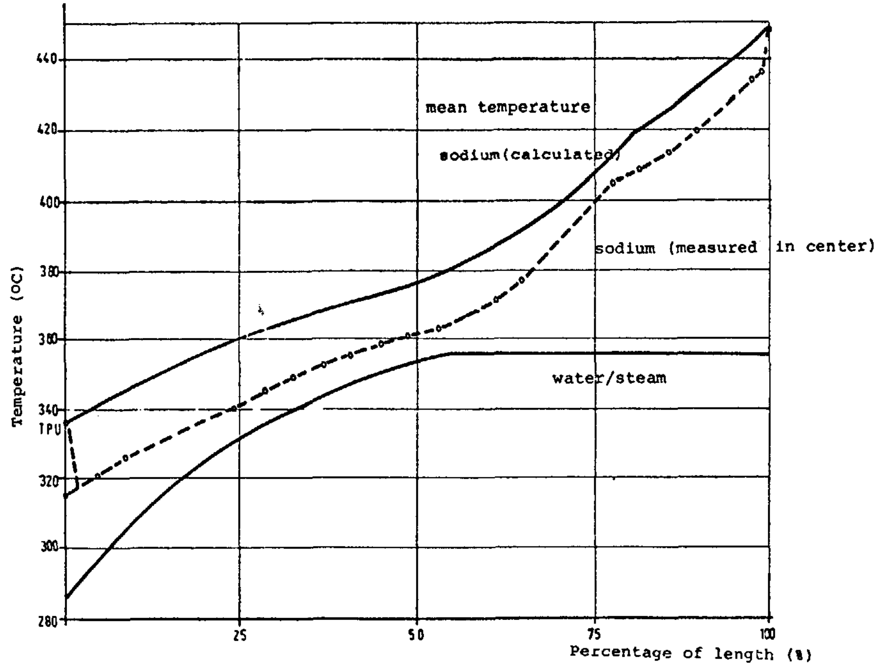
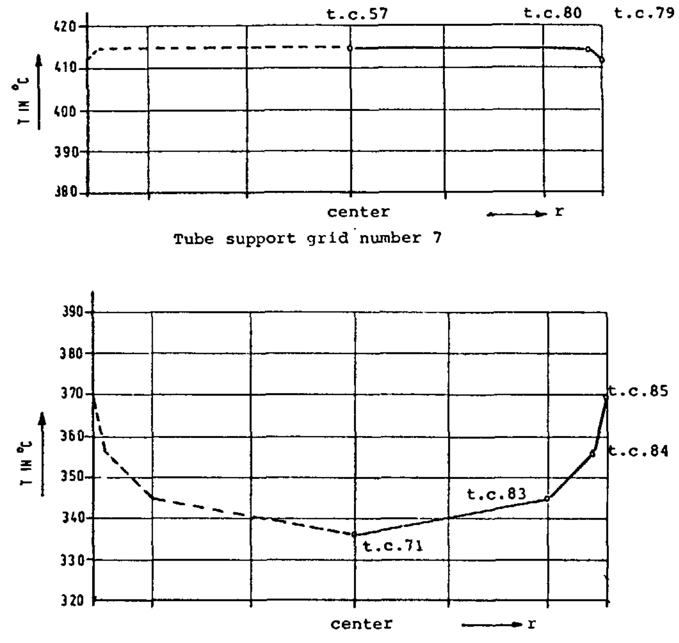


FIG. 4. Axial temperature profile evaporator



Tube support grid number 7

Tube support grid number 21

FIG. 6. Radical temperature distribution

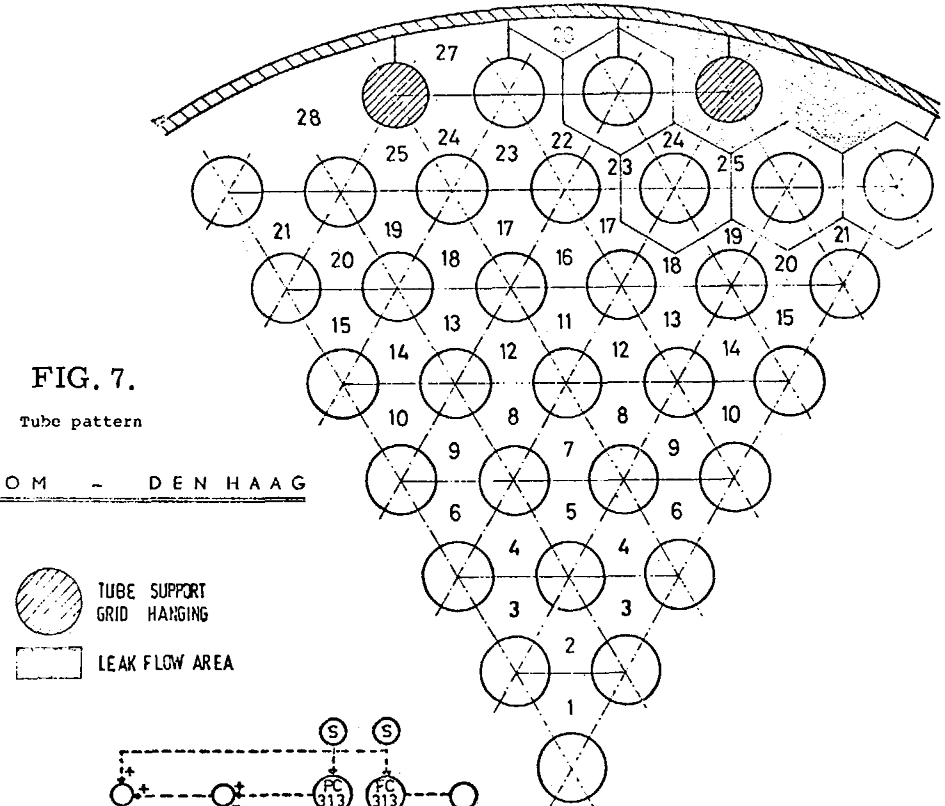


FIG. 7.

Tube pattern

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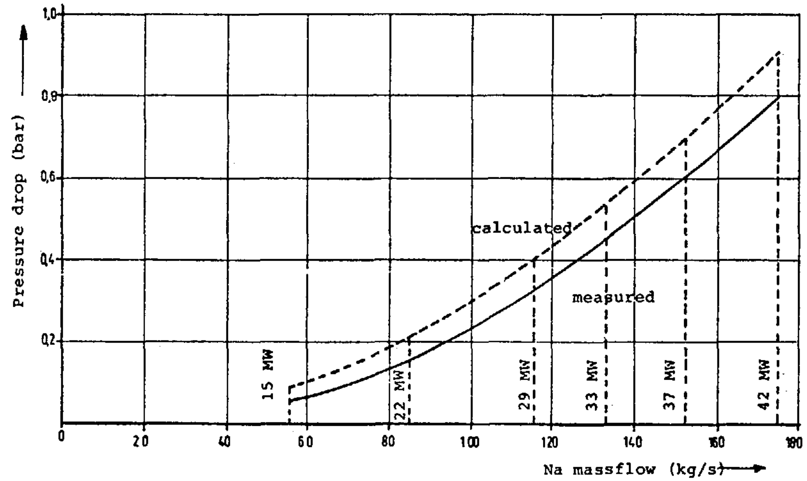


FIG. 8. Pressure drop in evaporator sodium side.

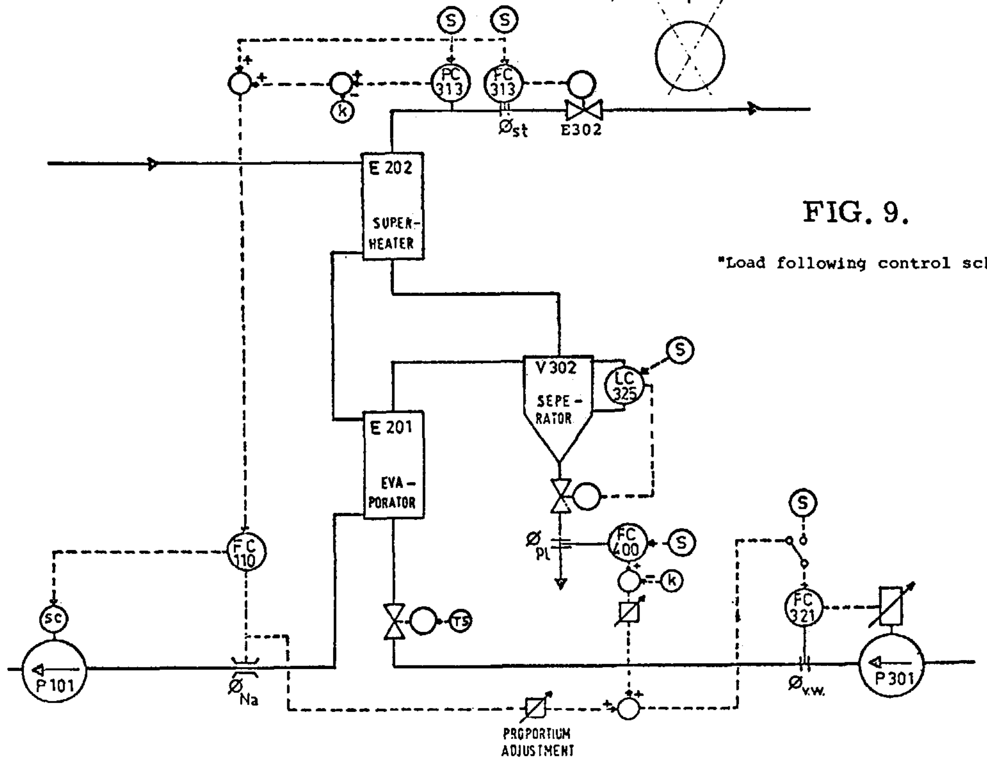
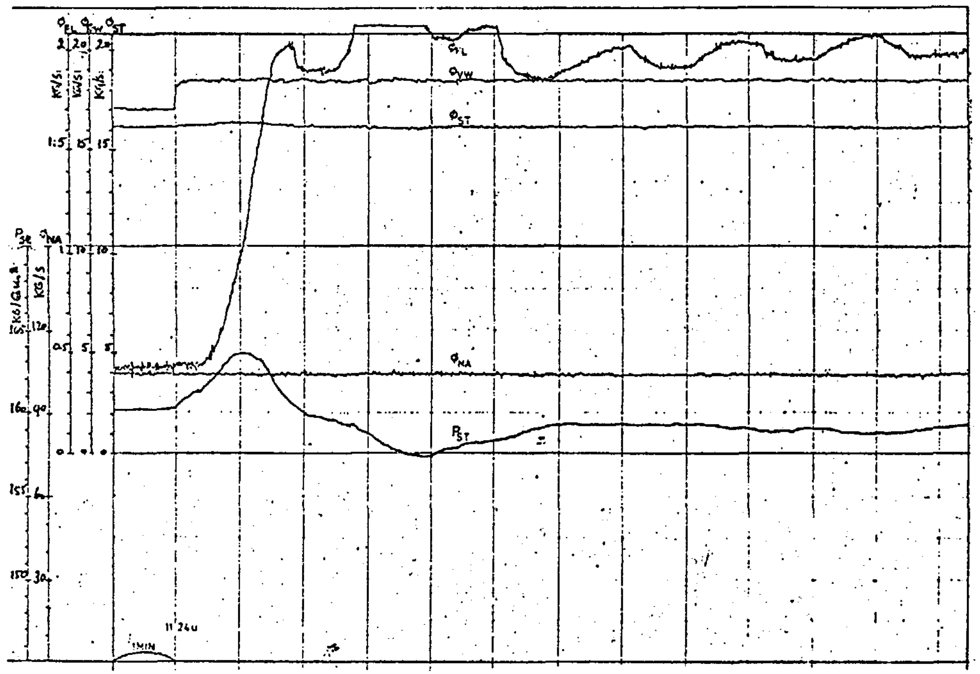


FIG. 9.

"Load following control scheme



Uncontrolled behaviour; Respons to step of +8.2% of the feed waterflow

FIG. 10.

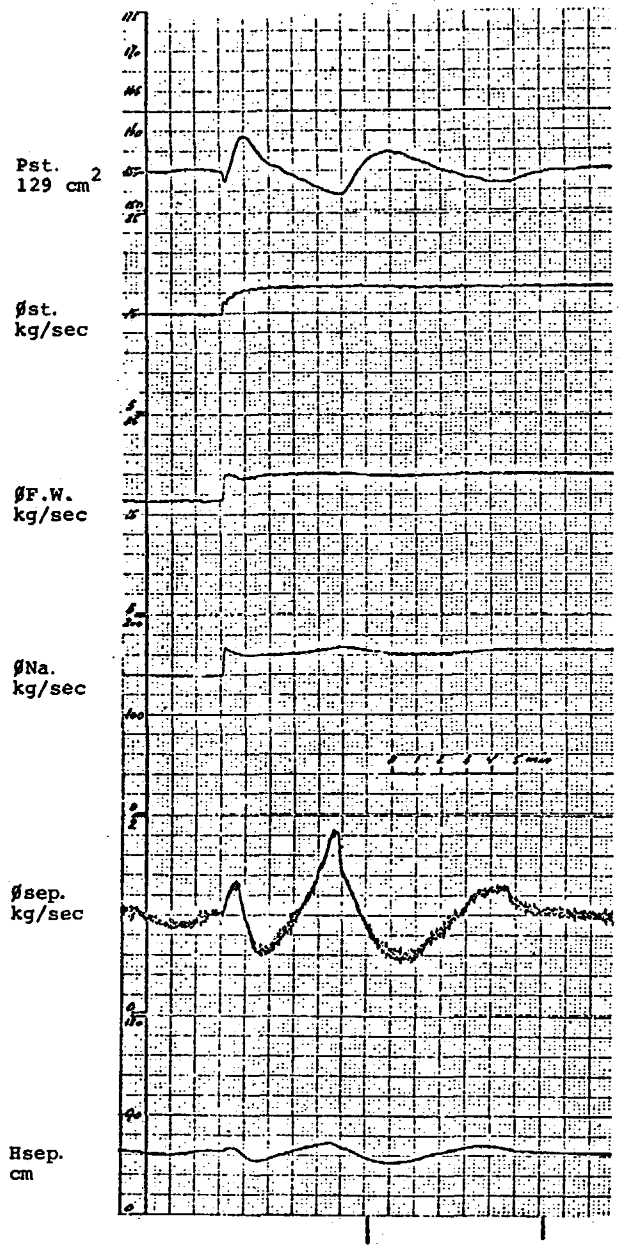
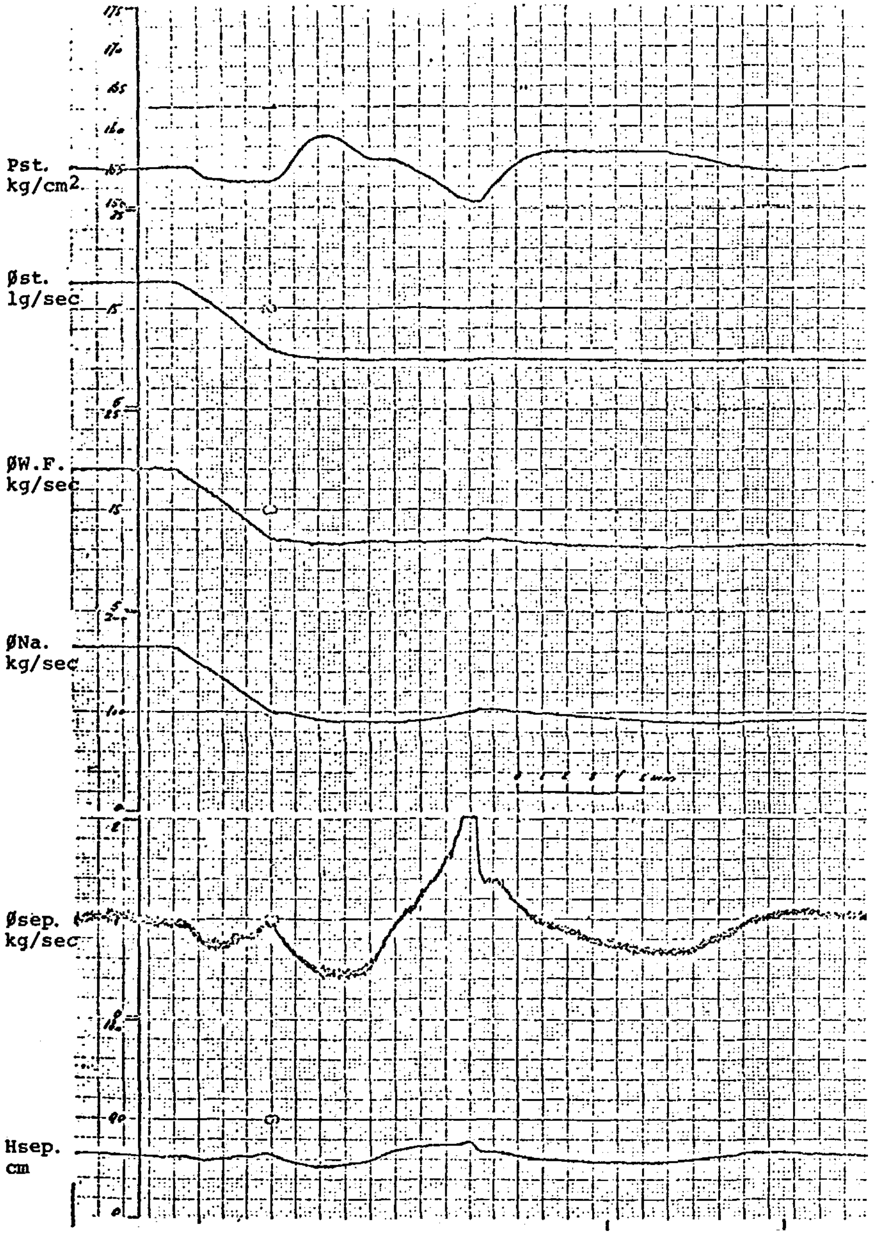


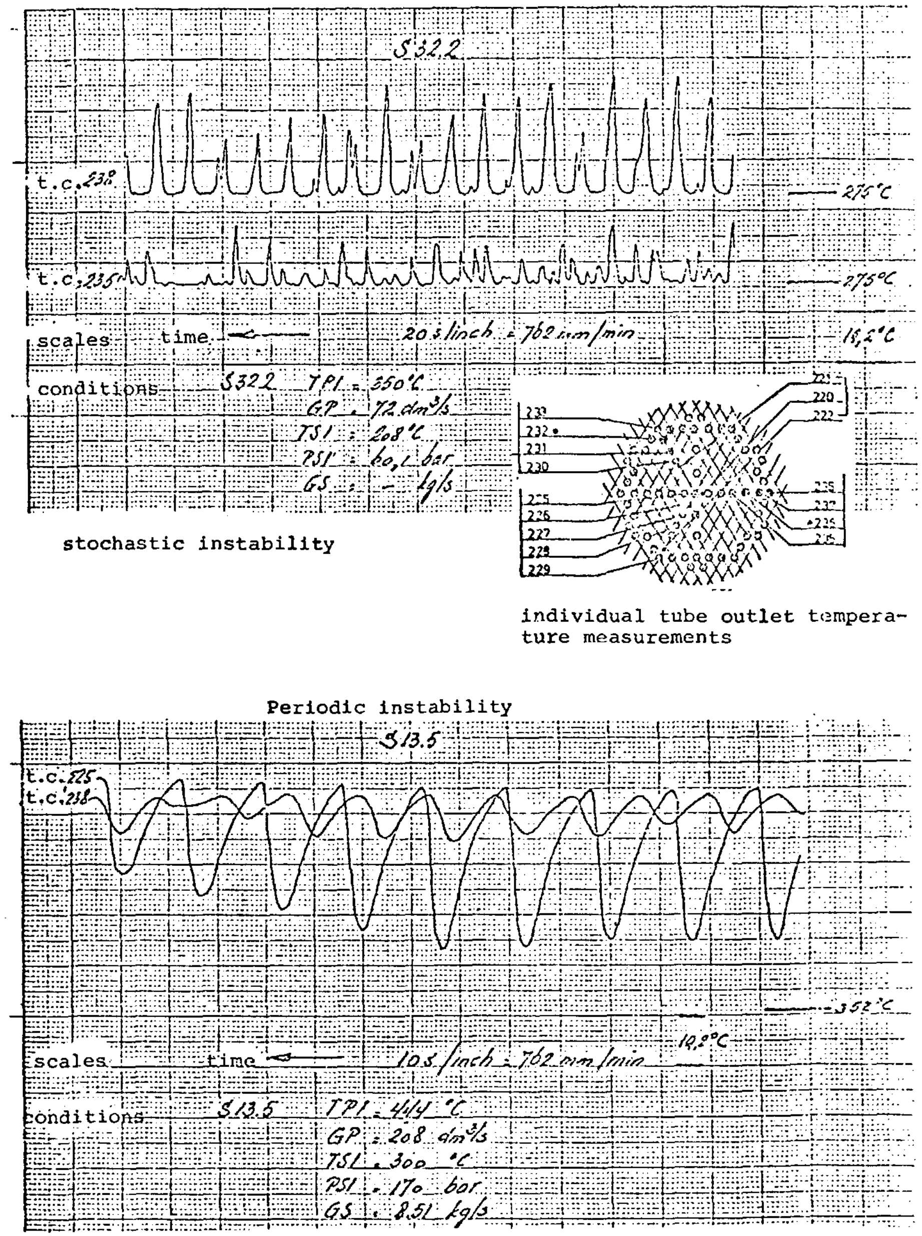
FIG. 11.

Response to a load step of + 5 MW at 40 MW power



Response to a load ramp from 40 MW to 25 MW

FIG. 12.



Typical measured instabilities

FIG. 13.