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ABSTRACT

During the years 1966, 1967 and 1968 different studies were undertaken, in the frame of the ORGEL project, in order to investigate and to analyse the stability and the dynamic behaviour of an ORGEL type reactor coupled to a 250 MWeg power plant.

In the first part of the studies the heat exchanger attached to the reactor is a drum boiler. The model of simulating the power plant is explained.

The studies have been taken up again at the request of the industrial group participating in the "ORGEL Prototype Contest". According to their choice the heat exchanger investigated is of the Benson type.

KEYWORDS

CONTENTS

ORGEL DYNAMICS*)

I. INTRODUCTION

During the years 1966, 1967 and 1968, different studies were undertaken, in the frame of the ORGEL project, in order to investigate and to analyze the stability and the dynamic behavior of an ORGEL-250 MWe power plant. This report presents the sum of the effected work.

1. First part of the studies

The different prototypes ORGEL studied till now were characterized by a weak intrinsic stability; either they were slightly instable, or little stable. The following situations might occur:

- The stable reactor with its initial core becomes instable when its core is reaching the equili - brium, the fuel temperature coefficient being always negative and the coolant temperature coefficient always positive.

- The reactor is stable even at the equilibrium, but the coolant temperature coefficient is always positive.

- The reactor is still more stable, the two temperature coefficients being negative.

This situation led to search what might be the influence of the stability of the control-system design, and whether there was a clear advantage to choose a stable prototype, this by reducing the moderation ratio, which involves a loss of fuel burn-up and some technological difficulties in order to reduce the lattice pitch.

In this first part, then, the reactor stability aspect has been emphasized. After having designed a control system for the instable core, it has been searched which simplifications might be brought to this system when this core becomes stable. An analytic study has enlarged some results obtained during the analogue computation; it is reported in the Appendix of this report.

The power plant attached to the reactor has been defined from hypothesis chosen for the sake of simplicity but assuring a satisfactory run of the power plant from technological and economical points of view:

- The complex and expensive solutions (by-pass on exchangers and pumps, variable speed pumps, control valves) have been rejected; the loop is a constant primary flow loop, without by-pass and pump speed control.

- The heat exchanger is a natural circulation drum boiler.

- The control program must ensure the most stable variations:

  • in the primary, the smallest possible temperature variations in the channel to limit stresses in the cladding and in the channel; these problems have formed the subject of distinct studies because they concern local variables;

  • in the secondary, the smallest variations of steam conditions: the steam temperature variations limit the change of speed of the turbine charge, the maximum admissible temperature variation at the turbine is in the range of 3°C/min., pressure variations may not be superior to maximum pressure ratios of classical pumps (ratios about 1,4).

This first part presents the model of simulation of the power plant, i.e. reactor, loop and drum boiler, including the regulating system for the instable core; this regulating system will be justified when the analogue computation results will be reported. This model has completely been retaken in a digital code described in the Appendix, where all the numerical values used can be found.

2. Second part of the studies

The studies have been taken up again at the request of the industrial group participating to the "ORGEL prototype contest"; they enter in the frame of a preliminary design.

The power plant hypothesis have been deeply modified by the choice done by the industrial group of Benson-type heat exchangers equipped with primary by-passes; this has justified new studies and another design of the control system. Indeed, the transient behavior of the Benson heat exchangers is very different from the drum boiler and does not allow to extend the conclusions from one case to another. Its fast responses, because of weaker fluid quantities, and its variable behavior according to the power level (in contrast with the drum boiler, which presents a true internal stabilization because of its recirculation), are so that its dynamical behavior involves that of the whole plant.

The aspect of the plant seen from the reactor is rejected to the background; this is also due to the fact that the studies of the first part showed that the ORGEL reactor stability had not a determinant influence on the regulating system; however, as the stable reactors presented a behavior clearly more favorable in case of control loss, it had been chosen for the prototype a weak moderation ratio.

As in the first part, the power plant is foreseen for running as basic plant, and contains four identical loops. The group has decided on the following operating conditions:

Reactor side

The coolant flow is constant; the output temperature is held to its set Value.

Heat exchanger side

The steam temperature and the steam pressure are held to their set value.

This second part will not present the test results of the regulating design defined by the industrial group. It will mainly share in the original developments from EURATOM, which have been necessary for the representation of the Benson heat exchanger, and set off the conditions which have to be respected if one will design an efficient control and regulating system.

II. FIRST PART

1. The mathematic model

1.1. Introduction

This paragraph resumes the mathematic model for the simulation of the dynamic behaviour of the power plant. This model was originally derived to simulate the system on an Analogue Computer, but, as presented here, is quite general and has been utilized for numerical computation as well (see Appendix).

The validity is limited to the study of power excursions ranging from 25% to 100% of full nominal power, and of disturbances which do not change the neutron flux shape or the temperature distribution shape in the reactor, since a point-model is used for all equations related to the reactor. In the heat exchanger, a finite-difference approximation of the original equations is necessary, due to the important masses and transit time involved.

The validity of these assumptions have been verified by computation.

Section 1.2. will discuss briefly the formulation of the reactor kinetics and the thermal equation in a reactor channel.

Section 1.3. gives the derivation of the equation related to the heat exchanger, which is of the natural circulation type.

Section 1.4. gives the equations and a discussion on the regulator mechanism.

The turbine is not simulated, assuming that its time constants do not influence the dynamical behavior of the power station.

1.2. The reactor simulation

1.2.1. Symbols for the reactor equations

C_i	= delayed neutron precursor concentration (of species i)
$2H$	= reactor length
h	= reactor power density
K_{eff}	= effective reproduction constant
l	= neutron lifetime
n	= neutron thermal flux
p	= effective periphery for heat transfer
R	= reactor radius
r	= radial distance of a channel from core center
S	= effective cross-sectional area
T	= mean temperature
T_o	= coolant temperature outlet
T_i	= coolant temperature inlet
t_c	= local temperature of coolant
t_u	= local temperature of fuel
t	= time
U	= coolant velocity
V	= core volume
W	= channel power
z	= distance along channel measured from center
α	= heat transfer coefficient can to coolant
α_c	= temperature coefficient of coolant
α_u	= temperature coefficient of fuel
β_i	= delayed neutron fraction of species i
λ_i	= decay constant for latent nuclei of species i
μ	= heat capacity of unit reactor volume

Subscripts

c	indicates quantities applying to coolant
g	indicates quantities applying to can
o	indicates initial conditions
s	indicates value at the surface
u	indicates quantities applying to fuel

Δ is used for the difference between the actual value of a variable and its steady-state value (denoted by the subscript o) or between two steady-state values of the variable.

The reactor simulation involves two parts:

- the reactor neutron kinetics;
- the heat transmission in the reactor.

1.2.2. The reactor neutron kinetics

The kinetics equations are given for a one-point model and thus are spatially independent.

In this study, the effects of moderator temperature and Xenon poisoning are neglected because of their long time constants (about ter minutes for the moderator temperature, some hours for tre Xenon poisoning) in comparison with the other effects to occur. A constant coolant flow is considered.

The neutron flux and the power distribution in the reactor satisfy the diffusion equation for one diffusion group and six groups of delayed neutrons.

(1.1) $$\frac{dn(t)}{dt} = \frac{K_{eff}(t)\,(1-\beta)-1}{\ell}\,n(t) + \sum_{i=1}^{6} \lambda_i c_i(t)$$

where $\beta = \sum_{i=1}^{6} \beta_i$

$n(t) = \frac{W(t)}{K}$: K constant < 1 takes into account that all the fission power is not removed by the coolant.

$$(1.2.) \quad \frac{dC_i(t)}{dt} = \frac{K_{eff}(t)\, \beta_i}{\ell}\, n(t) - \lambda_i\, C_i(t)$$

The steady-state values of $K_{eff}(t)$ and $C_i(t)$ are:

$$K^o_{eff} = 1 \text{ by definition}$$

$$C^o_i = \frac{\beta_i n^o}{\lambda_i 1} \text{ from Eq. (2.2.)}$$

Assuming that the temperature coefficients are independent of the temperatures and of position in the reactor [1]

$$(1.3.) \quad K_{eff}(t) = K^o_{eff} + \alpha_u \frac{\int^V (t_u - t^o_u) n^2\, dv}{\int^V n^2\, dv} + \alpha_c \frac{\int^V (t_c - t^o_c) n^2\, dv}{\int^V n^2\, dv}$$

dv   element of volume varying in fuel and coolant temperature by amounts $\Delta t_u = (t_u - t^o_u)$ and $\Delta t_c = (t_c - t^o_c)$.

n   being the thermal neutron flux at the point dv and we assume that the temperature deviations do not modify the nuclear characteristics.

If, in a certain range, we assume that the relative distribution of temperature in the reactor remains approximately constant, the temperature at a given point maintains a fixed ratio to the value at any other point; Eq. (1.3.) may be written:

$$(1.4.) \quad K_{eff}(t) = K^o_{eff} + \alpha_u\, \Delta T^*_u(t) \left[\int^V \frac{\Delta t_u}{\Delta T^*_u} n^2 dv \Big/ \int^V n^2\, dv \right]$$

$$+ \alpha_c\, \Delta T^*_c(t) \left[\int^V \frac{\Delta t_c}{\Delta T^*_c} n^2 dv \Big/ \int^V n^2\, dv \right]$$

[1] α_u and α_c can be interpreted as averaged over the reactor so that a light modification of nuclear characteristics by temperature can be taken into account.

where $\Delta T_u^*(t)$ and $\Delta T_c^*(t)$ are the temperature changes at any chosen point or the mean values of given temperatures which will be defined later, evaluating for the reactor the bracketed expressions which are constants independent of the temperature changes.

1.2.3. The heat transmission in the reactor

Since a one-point model is used for the kinetic equations, it is unnecessary to establish a spatio - temporal thermodynamic model dividing the reactor into axial and radial zones and that is furthermore supported by the fact that the transit time delay of the coolant through the core is very short, about half a second.

Considering the heat balance for each of the elements of the cell shown in Fig. 1.1., the equations determining the fuel cladding and coolant temperatures may be written as:

$$(1.5.) \qquad \mu_u \; \frac{\partial T_u}{\partial t} = W - A(T_u - T_g)$$

$$(1.6.) \qquad \mu_g \; \frac{\partial T_g}{\partial t} = A \; (T_u - T_g) - B(T_g - T_c)$$

$$\mu_c \; \frac{\partial T_c}{\partial t} = B \; (T_g - T_c) - \mu_c \; U \; \frac{\partial T_c}{\partial z}$$

with μ_u, μ_g, μ_c heat capacities per unit volume of fuel, cladding and coolant in the channel, and where A and B are heat transfer coefficients and the coolant flows with the velocity U in the positive z direction.

A and B are obtained from the steady - state. Eqs. (1.5.) and (1.6.) give:

$$0 = W^o - A(T_u^o - T_g^o)$$
$$0 = A(T_u^o - T_g^o) - B(T_g^o - T_c^o)$$

then:

$$A = \frac{W^o}{T_u^o - T_g^o} \quad , \quad B = \frac{W^o}{T_g^o - T_c^o}$$

The term $\partial T_c / \partial z$ creates some difficulty, but, assuming that the time constant of the coolant perturbation is much longer than the transit time[1] of the coolant, we may write it as:

$$\frac{T_o - T_i}{2H} \quad \text{or}$$

$$\frac{T_c - T_i}{H} \quad \text{where } T_c = \frac{T_i + T_o}{2} \text{ , to obtain:}$$

(1.7.)
$$\mu_c \frac{\partial T_c}{\partial t} = B(T_g - T_c) - C(T_c - T_i)$$

$$\text{where } C = \frac{\mu_c U}{H} = \frac{W^o}{T_c^o - T_i}$$

We must then rewrite the previous system of equations in terms of differences between the actual and steady-state values:

(1.8.)
$$\mu_u \frac{d \, \Delta T_u}{dt} = \Delta W - A(\Delta T_u - \Delta T_g)$$

(1.9.)
$$\mu_g \frac{d \, \Delta T_g}{dt} = A(\Delta T_u - \Delta T_g) - B(\Delta T_g - \Delta T_c)$$

(1.10.)
$$\mu_c \frac{d \, \Delta T_c}{dt} = B(\Delta T_g - \Delta T_c) - C(\Delta T_c - \Delta T_i)$$

In order to obtain the real reactivity in steady-state conditions, we must evaluate the two following quantities of Eq. (1.4.):

---

(1)   It is the same argument which allows to consider a single average uranium temperature and ignore the variations through the fuel element.

(1.11.)
$$\int^V \Delta t_c \, n^2 dv \Big/ \int^V n^2 dv \quad \text{noted} \quad \Delta T_c^*$$

(1.12.)
$$\int^V \Delta t_u \, n^2 dv \Big/ \int^V n^2 dv \quad \text{noted} \quad \Delta T_u^*$$

First, we must establish the equations giving the steady-state local temperatures of coolant and fuel.

To investigate the process of heat exchange between the fuel rods and the coolant, a dz length of one channel is considered. Writing the heat balance for each of the elements of the cell shown in Fig. 1.1. gives:

a) $h(r,z)S_u \, dz = \mathcal{A}_c \, U(r)dt_c(r,z)$

       $h(r,z)$ is proportional to $n(r) \, n(z)$

       $U(r)$ is proportional to $n(r)$

then $dt_c = a \, n(z) \, dz$ (1.13.)

where a is a constant for a specified power level. Integrating the two parts of Eq. (1.13.) gives:

$$t_c(z) - T_i = a \, N(z)$$

where $N(z) = \int_{-H}^{z} n(z) \, dz$

and writing in differences between two steady-state values, we get:

(1.14.) $\Delta t_c(z) - \Delta T_i = \Delta a \, N(z)$

b) $\mathcal{A}_c \, U(r)dt_c(z) = \alpha(r)p_g \, dz \left[t_g(r,z) - t_c(z) \right]$

$t_g(r,z)$ is rather independent of r, as it was verified for ORGEL reactors when the flows in the channels are regulated to obtain the same temperature span; thus we must assume

that $\alpha(r)$ is proportional to the velocity and write with (1.13.):

$$t_g(z) - t_c(z) = bn(z) \qquad (1.15.)$$

where b is a constant for a specified power level

c)
$$t_u^s(r,z) - t_g(z) = \rho_c \frac{h(r,z)S_u}{P_u} \qquad (1.16.)$$

d)
$$t_u(r,z) - t_u^s(r,z) = \frac{h(r,z)S_u}{8\pi \lambda_u} \qquad (1.17.)$$

Combining Eq. (1.16.) and (1.17.) gives:

$$t_u(r,z) - t_g(z) = cn(r) \, n(z) \qquad (1.18.)$$

where c is a constant for a specified power level.

Combining Eqs. (1.15.) and (1.18.) gives:

$$(1.19.) \qquad \Delta t_u(r,z) - \Delta t_c(z) = \Delta b \, n(z) + \Delta c \, n(r) \, n(z)$$

Let us also calculate the averaged temperatures of coolant and fuel over the channel. By definition, the averaged temperature of coolant in any channel is:

$$\Delta T_c = \frac{1}{2H} \int_{-H}^{H} \Delta t_c(z) dz$$

Substituting Eq. (1.14.), we get:

$$(1.20.) \qquad \Delta T_c = \Delta T_i + \frac{\Delta a}{2H} \int_{-H}^{H} N(z) dz$$

By definition, the averaged temperature of fuel in the channel of radius r_o is:

$$\Delta T_u(r_o) = \frac{1}{2H} \int_{-H}^{H} \Delta t_u(r_o,z) dz$$

Substituting Eq. (1.19) gives:

$$(1.21) \qquad \Delta T_u(r_o) = \Delta T_c + \frac{\Delta b}{2H} \int_{-H}^{H} n(z) dz + \frac{\Delta c}{2H} n(r_o) \int_{-H}^{H} n(z) dz$$

Let us now develop ΔT^*_c and ΔT^*_u:

$$\Delta T^*_c = \int^V \Delta t_c \, n^2 dv \bigg/ \int^V n^2 dv$$

$$\Delta T^*_u = \int^V \Delta t_u \, n^2 dv \bigg/ \int^V n^2 dv$$

Eqs. (1.11.) and 1.14.) give:

$$\Delta T^*_c = \int_0^R \int_{-H}^H n^2(r)n^2(z) \left[\Delta T_i + \Delta N(z)\right] \cdot rdrdz \bigg/ \int_0^R \int_{-H}^H n^2(r)n^2(z)rdrdz$$

Separating the two space variables and substituting Eq. (1.18.) using the notation:

(1.22.) $\qquad \gamma_c = 2H \int_{-H}^H n^2(z)N(z)dz \bigg/ \int_{-H}^H n^2(z)dz \int_{-H}^H N(z)dz$

gives:

(1.23.) $\qquad \Delta T^*_c = \Delta T_i + \gamma_c \left(\Delta T_c - \Delta T_j\right)$

Eqs. (1.12.) and (1.19.) give:

$$\Delta T^*_u = \frac{\int_0^R \int_{-H}^H n^2(r)n^2(z)\left[\Delta t_c(z) + \Delta bn(z) + \Delta c(n)(r)n(z)\right]rdrdz}{\int_0^R \int_{-H}^H n^2(r)n^2(z)rdrdz}$$

$$\Delta T^*_u = \Delta t_c + \Delta b \frac{\int_{-H}^H n^3(z)dz}{\int_{-H}^H n^2(z)dz} + \Delta c \cdot \frac{\int_0^R n^3(r)rdr}{\int_0^R n^2(r)rdr} \int_{-H}^H n^3(z)dz \bigg/ \int_{-H}^H n^2(z)dz$$

From Eqs. (1.21. and 1.23.) and using the notation

(1.24.) $\qquad n(r_o) = \int_0^R n^3(r)rdr \bigg/ \int_0^R n^2(r)rdr$

(1.25.) $\qquad \gamma_u = 2H \int_{-H}^H n^3(z)dz \bigg/ \frac{\int_{-H}^H n^2(z)dz}{\int_{-H}^H n(z)dz}$

we obtain:

(1.26.) $\quad \Delta T_u^* = \Delta T_i + \gamma_c (\Delta T_c - \Delta T_i) + \gamma_u \left[\Delta T_u(r_o) - \Delta T_c \right]$

ΔT_c^* and ΔT_u^* are two temperatures linked linearly to the averaged temperatures of coolant and fuel of the channel of radius r_o defined by Eq. (1.24.) and called the representative channel.

Taking back Eq. (1.4.), we must write in dynamic conditions:

(1.27.) $\quad K_{eff}(t) = K_{eff}^o + \alpha_u \Delta T_u^*(t) + \alpha_c \Delta T_c^*(t)$

where ΔT_u^* and ΔT_c^* are expressed by Eqs. (1.26.) and (1.23.) and the variations in the time of ΔT_u and ΔT_c given by the system (1.8., 1.9., 1.10.), the steady-state values corresponding to the so-called representative channel.

The complete set of thermal equations is thus constituted by Eqs. (1.27., 1.26., 1.23., 1.8., 1.9., 1.10.).

For a cosine axial neutron flux, we have $n(z) = \cos \frac{\pi}{2H} z$ and from Eqs. (1.25.) and (1.22.), we must calculate:

$$\begin{cases} \gamma_u = 4/3 \\ \\ \gamma_c = 1 \end{cases}$$

The representative channel is obtained from the radial neutron flux distribution calculating the ratio of Eq. (1.24.). It is included between the central channel and the channel of medium power. We must then write Eq. (1.27), assuming the coolant temperature inlet to be constant:

(1.28.) $\quad K_{eff}(t) = K_{eff}^o + \alpha'_v \Delta T_v + \alpha'_c \Delta T_c$

where: $\quad \begin{array}{l} \alpha'_v = \frac{4}{3} \alpha_v \\ \\ \alpha'_c = \alpha_c - \frac{1}{3} \alpha_v \end{array}$

1.3. The drum boiler simulation

The heat exchanger is a drum boiler with natural circulation. The main circuit of the power station consists of two loops.

1.3.1. Organic side

As well known, the equations describing the thermal behavior of two fluids which exchange heat through a wall constitute a partial derivative system which states that, for every elementary volume of both fluids, the mass, momentum, energy are conserved, i.e., for the mass: the net difference between the masses which go in and out from the elementary volume equates the variation in time of the mass being in the volume (fixed walls are assumed); the energy and momentum conservation laws can be expressed in an analogue way.

As a partial derivative system cannot be handled by a traditional analogue computer, such a system has been reduced to the "finite differences" in space, that is, the heat exchanger has been divided in a number or zones or "cells" of finite volume for each of which the conservation equations has been written in global form; the equations obtained are thus in terms of "mean variables".

Fig. 12 gives a scheme of the cells in which the heat exchanger has been divided, the number of cells being limited by the amount of analogue elements required.

It must be remembered that a lumped parameter model of this kind described very well the behavior of the physical system at low frequency but finds its limit at high frequency where it behaves as a low band filter, that is, the high frequency transients of the physical system will appear smoothed when studied with a finite difference model as this.

In the primary, the specific heat of the organic liquid and its density can be considered as remaining constant.

The **heat transfer** coefficient different values have been assumed from zone to zone (superheater, boiler, economizer), but the same value, <u>constant in time</u>, has been taken for the cells in the same zone as there the velocities and the heat exchanging surfaces are the same.

The behavior of the primary is described by the energy balance equations:

$$(1.29.) \quad VO_i \; C \; \rho \; \frac{d \; TOL_i}{dt} = WOL \; C(TOL_i - TOL_{i-1}) - HLOS \; S_i(TOL_i - TPA_i)$$

where:

i	is the index related to the zone, (increasing in the direction of the organic flow)
VO_i	is the zone volume
ρ	is the density
TOL_i	is the average organic temperature in cell i
WOL	is the organic mass flow
C	is the organic specific heat
HLOS	is the heat transfer coefficient
S_i	is the wetted surface in the cell i

For the first zone, the variable TOL_{i-1} has to be replaced by the delayed outlet temperature of the reactor.

The approximation can be improved assuming C and ρ as constant in time but varying along the heat exchanger and taking for each cell the value corresponding to its steady-state temperature. In any case, a comparison of the steady-state temperatures computed with this model, with the steady-state temperature at the same powers computed with a digital code which takes account of the dependence of the organic liquid physical properties on the temperature, has shown that the error done in this way is reasonably low (see next section).

1.3.2. Wall equations

The wall is considered only as a thermal capacity in which a certain amount of heat can be stored and represents a time constant between the primary and the secondary side.

For each cell, the mean temperature of the mass of steel which is interested in the heat transfer is computed by writing energy conservation balance between the stored heat and the difference between the heat transferred from the primary and the heat transferred to the secondary.

No heat transmission between adjacent cells along the wall has been considered. This can be justified considering the big difference between the heat fluxes along and across the pipe walls.

The heat balance equations for the wall is:

$$
(1.30.) \qquad AP_i * ROP_i * CP \; \frac{d \; TPA_i}{dt} = HLOS * S_i (TOL_i - TPA_i) -
$$

$$
- HLV_i * SV_i \; (TPA_i - TSEC_i)
$$

AP   is the wall cross-section

ROP   is the density of the wall

CP   is the specific heat of the wall in cell i

HLV   is the heat transmission coefficient between wall and secondary

SV_i is the wetted perimeter at the secondary

$TSEC_i$ is the average temperature at the secondary in cell i

All other symbols are as defined for Eq. (1.29.).

To obtain a system of equations suitable for computation, equations (1.29.) and (1.30.) have to be developed,

giving to the indices values related to the physical dimensions of the heat exchanger. How this can be done is illustrated in figures 1.3., 1.4. and 1.5.

1.3.3. Secondary side

a) Economizer

What has been said for the primary side still holds true for the secondary side in the economizer, where we have one liquid phase; the only difference is that the secondary fluid mass flow rate is no more constant but varies following the power delivered to the turbine.

Note that, if the boiler free level is to be kept constant, as we assume, during transients the mass flow in the economizer will differ from the steam flow to the turbine. In our model, while the boiler free level is supposed to be constant, the difference between the mass flow in the economizer and in the superheater has been assumed to be negligible.

The mass flow rate, which is supposed to be the same in the economizer's cells, is computed as follows:

$$\text{WREQ} = \frac{\text{POWER}}{\Delta H} ,$$

where POWER is the power delivered to the turbine in Kcal/sec and ΔH the difference between the feedwater and steam enthalpy in Kcal/kg.

The cell's temperature is deduced from the energy conservation law. These are written for each cell in Fig. 1.8., where the usual schematic drawings, the list of symbols and the values of the constant coefficients are also represented.

To simulate the effect on the primary side
of an eventual boiling in the economizer, a circuit has been
added to prevent that the temperature of the last cell in the
economizer become greater than TSAT(p), the saturation temperature
at the secondary pressure.

b) Natural circulation boiler

Fig. 1.9. gives a schematic drawing of the
paths of the primary and secondary fluid in the boiler.

To have a detailed description of the
behavior of the boiler, this should be divided into cells, and
for each the conservation laws should be written (for mass, energy
and momentum).

Even if the slip ratio in the riser is dis -
regarded, and the water-steam mixture is considered as homogenous,
the equations will be highly non linear and present many
computational difficulties, in particular for the analogue
computer.

But, for the simulation of a power station,
the local behaviour of the variables in the riser is not
essential, since the interest lies in a realistic estimation of
the recirculation ratio WR (i.e. the ratio between the mass flow
rate in the boiler and in the economizer) during the overall
transients.

This ratio, which is of no importance for
steady-state calculations (as the heat-transfer coefficients in
the boiling region do not vary significantly with the speed of
fluids), becomes significant for transients as the amount of
steam generated can be different from the feedwater mass flow.

Rigorously, the recirculation ratio can be
defined only for steady states, as during transients the mass
flow is not constant, but determined by the local density variation:

$$\frac{\partial \, WR}{\partial X} = - \, AR \, \frac{\partial \rho}{\partial t}$$

where AR is the riser cross-section. Nevertheless, provided there are no local instability phenomena, as the hydraulic time constants are much shorter than the thermal ones, it is reasonable to disregard the local variations of WR along the riser and to consider the recirculation flow as being in every moment at the steady-state value corresponding to the driving force in that moment.

As, at steady-state, the sum of the friction head losses along all the boiler must equate the difference of weight of the liquids in the downcomer and in the riser, we can write:

$$WR \simeq K.(RO_{downcomer} - RO_{riser})^{\propto} \qquad (1.31.)$$

where K is an unknown coefficient depending on the geometry of the system (dimensions and head losses), and $\propto$, which has been taken equal to 0.5, is an exponent which takes account of the dependence of the head losses on the flow rate.

After a few manipulations from (1.31.), we get:

$$WR = K \, . \, \sqrt{\frac{X.VS(P)}{[VL + X.VS(P)] \, VL}}$$

where X is the mean quality in the boiler $\left(\frac{mass \, of \, steam}{total \, mass}\right)$, VL the liquid specific volume and VS the steam specific volume which depends on the secondary pressure P.

The steam water mixture which fills the riser has been considered a homogeneous fluid whose temperature is always equal to the saturation temperature corresponding to the system pressure P; the riser itself has been considered as a whole (one cell) and an average quality over it has been calculated by writing the energy and mass conservation laws as shown in fig. 1.10.

In fig. 1.10., the energy conservation laws have been written in terms of mean enthalpy and mean density; we rewrite them here to show how they can be manipulated to get a form suitable to the analogue machine:

MASS) $\qquad$ AR.LR $\dfrac{d\rho}{dt}$ = WR+WREQ-WOUT $\qquad$ (1.32.)

ENERGY) AR.LR . $\dfrac{d(\rho.IM)}{dt}$ = WR.ILIQ+WREQ.CLVE.TLVEC(OT)-WOUT IM + Q

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (1.33.)

where:

AR	= riser cross-section (m2)
LR	= riser length (m)
ρ	= riser mean density (kg/m3)
IM	= riser mean enthalpy (Kcal/kg)
ILIQ	= saturated water enthalpy (Kcal/kg)
CLVE	= water specific heat (Kcal/kg°C)
TLVEC(OT)	= water temperature at the outlet of the economizer (°C)
Q	= heat transferred from the wall (Kcal/sec)
WR	= downcomer mass flow rate (kg/sec)
WREQ	= economizer mass flow rate (kg/sec)
WR+WREQ	= mass flow rate into the riser (kg/sec)
WOUT	= mass flow rate from the riser (kg/sec)

Multiplying Eq. (1.32.) by IM and substituting it from Eq. (1.33.), we get:

AR.LR.ρ . $\dfrac{dIM}{dt}$ = WR.ILIQ+WREQ.CLVE.TLVEC(OT)-(WR+WREQ).IM+Q

and introducing the following relations:

$\qquad$ ρ = 1/VSPEC(P,X) $\simeq$ 1/ $\left[(1-X)VL+X.VS(P)\right]$ $\quad$ where X << 1

$\qquad$ IM = ILIQ(P)+CLAT(P).X

where:

VSPEC(P,X)   is the specific volume of the mixture (m3/kg)

VL   is the specific volume of the saturated water (m3/kg)

VS(P)   is the specific volume of the saturated steam at
              pressure P

P   is the pressure of the system (kg/cm2)

ILIQ(P)   is the enthalpy of the saturated liquid at pressure
              P (Kcal/kg)

CLAT(P)   is the latent heat at pressure P (Kcal/kg)

we have:

$$\frac{AR.LR}{VL+X.VS} \cdot \frac{d\ ILIQ}{dt} + \frac{AR\ .\ LR}{VL+X.VS} \cdot \frac{d(CLAT.X)}{dt} =$$

$$Q + WR.ILIQ + WREQ.CLVE.TLVEC(OT) - (WR+WREQ).(ILIQ + CLAT.X) \quad (1.34.)$$

The quantities VS, CLAT and ILIQ which appear
in Eq. (1.34.) are functions of P only and can be approximated
with the following expressions[1]:

$$VS \quad = AVS \ + BVS.P$$
$$CLAT \quad = ALAT \ + BLAT.P$$
$$ILIQ \quad = AIL \ + BIL.P$$

where AVS, BVS, ALAT, BLAT, AIL, BIL are constant coefficients
which have been computed imponing that Eq. (1.35.) fit at the
best the values of VS, CLAT and ILIQ obtained from the steam
tables, for P varying from 50 to 100 kg/cm2 (which is the
pressure range of interest).

Figs. 1.11., 1.12., 1.13., the real values
of these functions, are compared with the values given by Eq.
(1.35.) [2]. As can be seen by the maximum value of the errors

---

(1)   For numerical computation, these could be obtained by tabulation
       of the steam tables or by higher order polynomials.

(2)   These plots have been obtained directly by the CALCOMP plotter,
       using a program which computes the polynomial of order up to
       20, which fits at the best a given set of points.

this fitting is quite satisfactory. By substituting the expressions (1.35.) into Eq. (1.34.), we finally have the wanted equation:

$$\frac{AR.LR}{VL+X.VS} \cdot (BIL+BLAT.X) \frac{dP}{dt} + \frac{AR.LR}{VL+X.VS} \cdot CLAT \cdot \frac{dX}{dt} =$$

$$= Q+WR \ (AIL+BIL.P) + WREQ.CLVE.TLVEC(OT) -$$

$$(WR+WREQ).(AIL+BIL.P+X.(ALAT+BLAT.P)) \qquad (1.36.)$$

Note that, with respect to Eq. (1.36.), the term $\frac{dP}{dt}$ is a known quantity, its value being determined else - where (see c)).

The term $\frac{AR.LR}{VL+X.VS} \cdot (BIL+BLAT.X) \cdot \frac{dP}{dt}$ in Eq. (1.36.), which is null in steady state, is very important during transients, as it represents the heat which must be given to (or taken off from) the mixture in the boiler to maintain it at the saturation condition when the pressure changes (this because the amount of water involved, in this type of boilers, is very large)[1].

c) Upper Dome

Since we assume to have a perfect regulation of the free level in the boiler upper dome, the volume of the upper dome is to be considered constant in time. How large this volume is does not seem to have great influence on the transient behavior of the system, at least until it is not very large or very little, and the transients are not too rapid (the steady-state configuration does not depend on this parameter).

---

[1] The effect of this term is to prevent any quick variation in the system pressure. Suppose in fact that P has a tendency to rise, then this term will make X decrease because a part of the heat, which used to be spent into vaporization, has to be spent in rising the liquid temperature, and a decrease in X will decrease also P (see c)) and vice-versa: if P has a tendency to decrease, this term will increase X because some of the heat which was in the liquid is released.

We assume that the steam in the upper dome (which is sketched in Fig. 1.9.) could be either saturated or superheated, but never subcooled if not for a very short time. In the first case, the independent thermodynamic variables to be computed are reduced to one (in our model, we have assumed the pressure), but a new variable appears: the condensation mass flow rate; in the second case (superheated steam), this last variable is identically zero, while the independent thermodynamic variables become two (in our model, we have assumed the pressure and the steam density, the other being deduced by the state equation and the steam tables). The equations written are the mass conservation law and the energy conservation law, Fig. 1.14.

Referring to Fig. 1.14., the exact expression for the stored energy would be $V \frac{d}{dt} (R\emptyset.i+P/J)$ ($J=427$ kgm/Kcal), but it is very easy to see that term $V \frac{d}{dt} P/J$ is always very negligible.

Studying the steam characteristics, it turned out that the enthalpy, which is function of P and $R\emptyset$, can be very well approximated with an expression of the form

$$I = AI + BIPRO . \frac{P}{RO} \qquad (1.37.)$$

where AI and BIPRO are two constants whose values were deduced by trial fitting of the above expression to the steam curves of I against P for different values of RO (Fig. 1.15.). We further assume that ISAT, ILIQ and ROSAT can be approximated as follows:

$$
\begin{aligned}
ISAT &= AISAT+BISAT.P \\
ILIQ &= AIL+BIL.P \\
ROSAT &= AROS+BROS.P
\end{aligned}
$$

Where AISAT, BISAT, AIL, AROS and BROS are constant coefficients, the values of which have been determined imponing that the expressions (1.38.) fit at the best for $50 \leqslant P \leqslant 100$ kg/cm2, the corresponding functions of P, which can be deduced from the steam tables.

In Figs. 1.14., 1.16., 1.17., the real values of these functions are compared with the value computed with expressions (1.38.); as can be seen, this fitting is quite satisfactory.

By introducing the Eqs.(1.38.)and(1.37.)into the energy equation and combining it with the mass conservation (Fig. 1.10.), the energy equation can be reduced to the following form which is more suitable to the computer:

$$V \ BIPRO \ \frac{dP}{dt} = - \ AI.(X.(WR+WREQ)-WREQ-WC))$$
$$+ \ (AISAT+BISAT.P).(WR+WREQ))$$
$$- \ WREQ \ (AI+BIPRO.(P/RO))$$
$$- \ (AIL+BIL.P).WC$$

$$(1.39.)$$

Eq. (1.39.) together with the mass conservation eq.:

$$V \ . \ \frac{dRO}{dt} = X \ (WR+WREQ)-WREQ-WC \qquad (1.40.)$$

constitutes the set of equations which is to be integrated to compute RO and P in the upper dome. The only unknown left is WC which is computed as follows:

$$WC = \begin{cases} K \ . \ (RO-ROSAT) & RO > ROSAT \\ 0 & RO \leqslant ROSAT \end{cases} \qquad (1.41.)$$

The value of K must be chosen high enough to prevent RO to become greater than ROSAT for a long time, (how it happens can be understood replacing Eq. (1.41.) into (1.40.)); this is equivalent to assume that, as soon as the steam in the upper dome reaches the saturation conditions, the condensation prevents it from going deeply into the subcooled region, which seems reasonable as one regards a practical system.

Note that Eq. (1.39.) still represents fairly well the energy conservation law also when the steam in the upper

dome is at the saturation condition; in fact, in this case,
for what has been said, RO ≈ ROSAT ad Eq. (1.37) still gives an
acceptable approximation of the steam enthalpy, as it can be seen
in Fig. 1.18., where:

$$AI + BIPRO \cdot \frac{P}{ROSAT(P)}$$

is compared with ISAT(P) .

In practice, it seems that, at the frequencies
of the transients which have practical interest, the steam in
the upper dome is very near to the saturation condition being
always a little superheated, and this is the reason why the system
is not affected by the value of K.

d) Superheater

It has been supposed to make a negligible error
assuming to have the same mass flow rate of steam along the whole
superheater; this is true in steady state, while in transient,
according to the mass conservation law, there are local variations
due to the steam density variations in time:

$$\frac{\partial W}{\partial x} = - A \frac{\partial \rho}{\partial t} \quad .$$

It was nevertheless verified that, for cases
of practical interest, the maximum flow variation in the cell
due to density variation remains below 1% of the total flow.

The mass conservation law is thus reduced
to the trivial form $W(i) = WREQ$, where $W(i)$ is the mass flow rate
in the ith cell and WREQ the mass flow rate into the turbine.

The energy conservation law is reported in
Fig. 1.18., with the usual schemes and list of symbols. For
the steam density in the different cells, we have assumed the
steady-state value at full power.

1. Fig. 1.19., the values of the steam density in the different cells and at different powers have been plotted; from this figure, one cou'd have the impression that the error committed in neglecting the density variations due to pressure and temperature variations is not too small.

In reality, looking at the equations, it is clear that the only effect of an error over RO is to modify the time constant between the temperature of the wall and the temperature of the steam, and the effect on the primary side is still attenuated by the time constant between the organic temperature and the wall temperature.

Two transients done, assuming for RO values ten times greater and ten times smaller than the real ones, have shown no appreciable variations in the system behavior. This is due to the fact that, being always very near to the steady conditions, the error over RO is highly attenuated by the very little value of $\frac{d\ H(i)}{dt}$ (see Fig. 1.18.).

The energy conservation law has been written assuming, as thermodynamic independent variables, the pressure P and the steam enthalpy H(i). For the pressure, we assume that it is the same as in the upper dome (we neglect the pressure losses due to friction and acceleration). The error we do in this way effects the calculation of the temperature of the steam in the cell and can be estimated at approximately 0.5°C, as can be deduced from Fig. 1.20., assuming that the pressure losses over each cell can be evaluated to 0.5 kg/cm2.

The steam temperature which appears on the right hand side of the energy conservation law (Fig. 1.18.) has been considered a dependent variable whose value is deduced from the steam enthalpy I and pressure P with the following approximate formula:

$$T(°C) = 1.3333\ I + 1.0337\ P - 686.64 \qquad (1.42.)$$

where I must be expressed in Kcal/kg and P in Kg/cm2.

In Fig. 1.20., the values of the steam temperature against the steam enthalpy for different pressures have been plotted together with the values corresponding to Eq. (1.42.).

As it can be seen, the approximation is good, or at least comparable with the precision one can reach in computing the heat transfer coefficients, provided one remains in the region from 50 to 100 kg/cm2 for the pressure, and between 25% and 110% of nominal power.

1.4. The control and regulation system

1.4.1. Requirements

The automatic control and regulation system must stabilize the reactor which is instable with respect to temperature coefficients, and adjust its power level to the power demand according to a certain steady-state program.

1.4.2. Regulator equations and block diagram

Experiments on the analogue computer have shown that the regulation mechanism must be driven by an error term which should be a combination of two variables: the neutron power and the average temperature of the organic coolant:

$$\mathcal{E} = - R_1 \left[\frac{n-n_o}{n_o} - \frac{PW - PW_o}{PW_o} \right] - R_2 \frac{T_{av} - T_{avo}}{T_{avo}} \qquad (1.43.)$$

where:

$\mathcal{E}$ is the actuating error

n is the neutronic power

PW is the power demand at the turbine

T_{av} is the average temperature of the coolant

T_{av} = (temperature primary at the inlet of the heat exchanger + temperature primary at the outlet of the heat exchanger)/2

Note that T_{av} represents the average temperature only under steady-state conditions

R_1 and R_2 are arbitrary gains to be optimized

n_o, PW_o, T_{avo} are the values of N, PW, T_{av} at the nominal power of the reactor; they can be functions of the power

The terms $\dfrac{n-n_o}{n_o}$ and $\dfrac{PW-PW_o}{PW_o}$ allow to compare the extracted power of the reactor to the power supplied to the turbine and to adjust one to the other. The power demand PW is the product (WREQ.ΔH) where WREQ is the steam flow and ΔH the enthalpy span from the superheating steam temperature to the economizer water input temperature (which is assumed to be constant according to the reactor power). The power demand PW is changed by acting the steam throttle at the turbine input, which is identical to modifying the steam flow, but in a manner to verify the previous equality.

The term in n compensates the fast variations of the power, which are impossible to correct with temperature signals due to the important time delays (time delay in transferring the heat from fuel to coolnt: about 3 sec. and transport delay time to the mixing main collector: about 10 sec.).

The term in T_{av} corrects any variation of the average temperature; by definition, this is a low-frequency action and has little effect on the stability of the system, but influences greatly the variation of the thermodynamical quantities of the heat exchanger.

To the error term must be added a pressure term defined as $- R_3 \dfrac{p-p_o}{p_o}$ and intended to improve the pressure transient; this term presents a particular interest when p_o is a constant according to the power (for a constant pressure

regulation program). T_{avo} and p_o are two thermodynamical parameters connected so that the pressure term acts in the opposite direction of the term in T_{av}; therefore, its weight must be limited. This situation derives from the fact that a regulation program for a multiple-loop system is necessarily a compromise between contradictory requirements.

The <u>control-rod mechanism</u> is represented by the following transfer function:

$$\frac{\rho}{\epsilon} = \frac{R_4/S+R_5}{1+\tau S} \tag{1.44.}$$

where:

ρ is the reactivity introduced by the control mechanism

S   is the differential operator $\frac{d}{dt}$ (Laplace operator)

τ is the time constant due to the intertia of the mechanism

R_4 and R_5 are arbitrary gains to be optimized

Thus, the position of the control rod is changed in proportion to any error created by a power demand change or by an internal system transient. An on-off type control rod is inadequate, the reactor by itself being inherently instable; the presence of a dead zone in that discontinuous type system causes the control system to be in continuous oscillation.

The regulation is linear only within limits imposed by technology, which must be taken into account:

- the speed of the control rod has a sharp maximum limitation:

$$\frac{d\rho}{dt} \leqslant \text{max. speed of rods}$$

- the end-of-run limitations of the control rods must be considered as well:

$$\rho \leqslant \text{max. available reactivity}$$

$$\rho \geqslant \text{min. reactivity}$$

The law of variation of reactivity versus rod displacement is assumed to be linear for the computation, as it was verified on the computer that (within the limits mentioned above) any alternative (section of a sine function) does not change significantly the behavior of the control loop.

A separate mean to set the equilibrium point at any desired value between these limits must be avail - able.

It must be remembered that, if a reactivity disturbance greater than the above value occurs for any significant length of time, the regulator looses its ability to control the reactor.

The block diagram for the whole power plant control is reported on Fig. 1.21. The detail of the regulator is given in Fig. b. and Fig. c., which represent two possible servo mechanisms being mathematically equivalent. In Fig. b., the actuating error is integrated through an electronic integrator; its output and the error signal itself drive the control mechanism which acts here as a position servo. In Fig. c., the error signal and its derivative (damping term) drive a bar mechanism which is a rate servo.

Eliminating E between the relations (1.43.) and (1.44.), it appears that the proportional and integral terms are affected to the variables n, T_{av} and, eventually, p. Generally, the proportional terms are the stabilizing terms (the terms which improve the transients); the integral terms are the reset terms (refer to analogue and analytic results).

The regulator will be optimized with respect to the following parameters: R_1, R_2, R_3, R_4, R_5, and the speed and reactivity limits of control rods. The criteria for optimality are:

a) Minimum overshoot of all variables in transient response, in
   particular with respect to reactivity disturbances.

b) Minimum time for passing from one steady state to another
   when the power demand is varied.

c) Minimum time to return to steady state after any disturbance.

1.4.3. The steady-state program

In Fig. 1.21., a regulation program sets
the sum of the reference terms of the Eq. (1.43.): n_o and PW_o
are constants, while T_{avo} and p_o may vary according to a certain
predetermined law (steady-state program) as a function of PW;
it will be recalled that T_{avo} and p_o naturally will always remain
thermodynamically connected.   One of the possible steady-state
programs of the power plant is reported in Fig. 1.22. (program 1):

- From 100% to 75% of the power, the average temperature of the
  coolant remains constant;   the steam pressure rises from
  53,5 kg/cm2 to 67 kg/cm2.   This range of power is considered
  to be the normal working zone of the plant.

- From 75% to 25% of the power, the steam pressure is maintained
  constant;   the average organic temperature decreases from
  308°C to 289°C.

The inlet and outlet temperatures of the
coolant are represented on Fig. 1.22. in the same way as the
steam inlet temperature at the turbine.   Let us remember that
the assumed steam cycle taken into account for the dynamics
calculations is without reheating.

Experimentation made on computer has shown
that many alternatives, all stables, are possible;   in each
case, the regulation can be driven by T_{av} (R_3 = 0), assuming a
variable reference T_{avo} which depends on the power demand as in
Fig. 1.22.;   an additional term in p - p_o(R_3=0) where p depends
on the power demand as in Fig. 1.22. always improves the
regulator performance.

The regulator reference is setting to the
predetermined law (as a function of the power demand signal) by
a program (see Fig. 1.21a) which could be a set of relays,
comparators and constant gain amplifiers wired in a permanent
arrangement or, for more flexibility, a small on-line computer
(digital or analogue).

Other static programs studied are reported
in Fig. 1.23. The numerical differences between the two
programs 1 are explained by the fact that the dynamical studies
have been executed on two prototype variants where the coolant
organic span is, either 124°C (Fig. 1.22.), or 104°C (Fig. 1.23.);
in this last case, the steam pressure rises from 60 to 74 kg/cm2
when the power decreases from 100% to 75%. The results of the
study are modified in no way.

2. The analogue computation results

2.1. The instable core

2.1.1. Main characteristics of the channel

Bundle	19 rods
Fuel cross-section	31 cm2
Coolant cross-section	22 cm2
Moderator area/coolant area ratio	15,6
Length channel	400 cm
Fuel rod radius	1,45 cm
Cladding wall thickness	0,88 mm
Finning ratio	1,9
Thermal resistance between fuel & cladding	1,5°C/w/cm2
Maximum integral of conductibility	100 w/cm
Average velocity in the central channel	10 m/sec
Axial form factor	0,68
Radial form factor	0,85
Disadvantaged thermal flux factor	0,85

Characteristics of the "representative" channel (the power
of which being 0,89 the power of the central channel) at
nominal power

Removed power   4,65 MW

Input temperature   266°C

Output temperature   370°C

Average cladding temperature T_G 376°C

Average fuel temperature T_u 672,5°C

Temperature coefficients of the initial core:
- Fuel temperature coefficient: $\alpha_u = - 1,5$ pcm/°C
- Coolant temperature coefficient: $\alpha_c = - 0,25$ pcm/°C

Temperature coefficients of the equilibrium core:
- Fuel temperature coefficient: $\alpha_u = - 0,45$ pcm/°C
- Coolant temperature coefficient: $\alpha_c = + 5,6$ pcm/°C

Transport delays of coolant from
reactor to heat exchanger: 12 and 13 sec.

2.1.2. The reactor stability

The prototype stability situations have been
studied in the parametric plane $(+\alpha_{coolant}, -\alpha_{fuel})$, examining
the open loop transient response of the reactor to an initial
positive step disturbance of 50 pcm. If the second derivative
of neutron power versus time is negative, after a time of 100 sec.
longer than the longest time constant, the reactor is considered
to be stable.

The results are reported in Fig. 1.24. for
the two cases of a thermal resistance of 1.5°C/w/cm2 and
0.5°C/w/cm2 (the two curves are identical).

One can see that the irradiated reactor is
unstable. Thus the prototype requires an automatic external
control and regulating system.

2.1.3. Optimization of the regulator parameters

After experimentation, the following numerical values have been retained (if no speed limitation on control rod):

$$R_1 \quad\quad = 1$$
$$R_2 \quad\quad = 1$$
$$R_4 \quad\quad = 10^{-2} = 10 \text{ pcm/\% variation}$$
$$R_5 \quad\quad = 5.10^{-2} = 50 \text{ pcm/\% variation}$$
$$\tau_{inertia} \quad \leqslant 2 \text{ sec}$$

The regulator inertia $\tau_{inertia}$ = 2 sec. was used for computation as a worst case value.

Fig. 1.25. gives the stability domain of the control mechanism versus the gains R_4 and R_5, in the linear region of its transfer function (i.e. for disturbances which do not reach the reactivity speed and amplitude limitation). In the region to the left, the mechanism is stable and gives a damped response to a step input. In the central region, the mechanism is stable but gives a periodical response (overshot) to a step disturbance. In the right region, the loop is unstable.

The working point of the controller should be selected in the first region (damped). In fact, in order to avoid overshots in the non-linear region, systematic experimental investigation has shown that the working point of the mechanism should be about a decade to the left of the critical damping line as, for example, point 16 if the insertion speed of reactivity is limited to 10 pcm/sec.

Fig. 1.26. and 1.27. give the response of the system in case of a step disturbance of 50 pcm considered as a worst case for a small accident (like the drop of a cluster in the channel during the fuel handling), not requiring a scram.

The two figures give the neutron power response and the control rod reactivity (position and speed):

- Fig. 1.26. for a speed limitation of the
control rods of 10 pcm/sec (equivalent to
10 cm/sec) and a rod inertia time constant
of 2 sec.

- Fig. 1.27. for an unlimited speed of the
control rods.

During these transients, the temperatures
do not change significantly.

2.1.4. Ability of the regulator to control the reactor

The regulator optimized for values of
temperature coefficients corresponding to the irradiated reactor,
it is interesting to investigate up to which extreme limits the
regulator is capable to keep the reactor under control. The
quantities which affect significantly these limits are:

- The amplitude of the reactivity disturbance
(linked to the end-of-run limitations of the
control rods)[1].

- The maximum speed allowable for the control
rods.

- The temperature coefficients[2].

The limits of efficiency of the system control
are reported in Fig. 1.28. in the $(\alpha_{coolant}, \alpha_{fuel})$ plane for
the following values of the control system bounds:

---

(1) It is obvious that, if a reactivity disturbance greater than
the end-of-run values occurs for any significant length of time,
the regulator looses the ability to control the reactor.

(2) The temperature coefficients associated with the fuel and the
organic coolant are not easy to obtain, and there are always
some doubts on their accuracy. This fact justifies this
parametric study.

- Maximum rods speed: 15 cm/sec (e.g. 15 pcm/sec)

- Rod reactivity span from + 200 pcm to - 300 pcm with two sets of four rods: the negative reactivity end-of-run of the normal first set (-50 pcm) commands the release of the second group of rods (-250 pcm) (see Fig. 1.29.).

- The time constant of rods was taken = 1 sec. for this investigation.

Curves 1 and 2 give the limit above which a reactivity step disturbance of 100 and 50 pcm cannot be compensated by the regulator; curves 3 and 4 give the same limit for a step disturbance in the reactor inlet temperature of 10°C and 5°C respectively.

It turned out that the speed would be sufficient to control the system up to very high values of α_c, if the amount of reactivity supplied by the regulator is adequate. Beyond the limits of curves 1 to 4, the regulator looses its ability to control the reactor for the described disturbance.

2.1.5. Heat exchangers: accuracy of the dynamic computations - Steady-state checks

The steady-state results have been obtained for 100% and 75% of full power, as the equilibrium values of the dynamic equations. The steady-state temperature distribution for the heat exchanger is reported in Fig. 1.30. for 100% power, and Fig. 1.31. for 75% power. These results have been compared with those of a purely static digital computation (using thus a different mathematical representation. The agreement (within some degrees centigrades) between the results of the two computations represent a reliable validity (and accuracy) check for the complete analogue simulation.

2.1.6. Running at 100% of the power, handling of the fuel

The inserted reactivity law which simulates loading and unloading of a fuel element is given in curves 1L and 1U of Fig. 1.32. In these functions, horizontal segments have been abridged significantly to reduce computer time, as this does not affect the conclusions.

The curves 2U and 2L give the neutron power transient response, on a developed amplitude scale. It can be seen that the power level is virtually unaffected by the operation.

The curves 3U and 3L give the control rod position, which can be seen to compensate almost exactly (with negligible time lag) the introduced reactivity. During this transient, the temperature does not vary.

2.1.7. Changes in power

We cannot give all experiments achieved on the analogue computer; we will restrict ourselves to the essential:

a) **Regulation program 1: constant temperature/ constant pressure**
Changes in power from 100% to 75%

During this transient, the power demand to the turbine is varied from 100 to 75% and then it is kept constant; the rate of variation is **5% per minute.**

Figs. 1.33., 1.34. and 1.35 show the evolution of the reactor and secondary variables.

The coolant temperature and the average
cladding temperature reported are the same as those of the
central channel;   this is not the case for the average fuel
temperature: in transient state, that one of the central
channel differs from that one of the so-called representative
channel by a higher amplitude;   it will be determined knowing
that, in steady state, the span $(T_u - T_G)$ is proportional to
the channel power.

However, the two most significant variations
on the reactor side during all dynamical attempts are the
driving variables, i.e. the neutron power and the input coolant
temperature (for a constant coolant flow) which can be taken
as input data for a spatial-temporal code in order to
particularly determine the local variations of the cladding
and fuel temperatures.

Changes in power from 100% to 25%

Without pressure feedback:

The rate of variation is 5% per minute.
Fig. 1.36. shows the average organic temperature (T_{av}) evolution
and Fig. 1.37. the pressure transient;   it can be seen that,
even through the rate of change relatively slow, the pressure
overshot is far from being negligible.

The rate of variation is 0.5% per minute.
This transient can be considered as a sequence of equilibrium
states.   Fig. 1.38. gives the evolution of T_{av}, and Fig. 1.39.
gives the evolution pf pressure, both versus time.   Fig. 1.40.
and 1.41. show the T_{av} and pressure variation law versus the
power demand;   it can be easily observed that, on the analogue
computer (and, very likely in reality), it is very difficult to
maintain the pressure rigorously constant.   This situation is
due to the fact that there is no direct action of a pressure
measurement on the regulator $(R_3 = 0)$.   A definite improvement
on this situation can be obtained by introducing a term in R_3.

With pressure feedback:

The rate of variation is **5% per minute**.

Same regulation program with additional pressure feedback; R_3 is set to 0,5% and a pressure term in $\dfrac{p - p_0}{p_0}$ is added to error $\mathcal{E}$; p_0 is not a constant but follows the law expressed in Fig. 1.23., curve 1.

In Fig. 1.42., curve 1 gives the pressure transient without pressure feedback; curve 2 gives the same transient with the pressure feedback introduced in the regulator. The benefit of the pressure regulation clearly appears from the comparison between these two curves.

The rate of variation is **0,5% per minute**. Fig. 1.43. gives the pressure transient for a very slow power variation which can be considered as a sequence of steady states; comparing this curve with the one of Fig. 1.41., it can be seen that the pressure fluectuations are significantly reduced. The variation of T_{av} for the same case is given in Fig. 1.44.; it shows that the penalty in variation of the average temperature is quite acceptable.

A detailed investigation is given in Fig. 1.45. and 1.46. In these figures, the recorded variables are expressed as function of power and not of time, in order to facilitate comparison.

Curve 1 gives the evolution for $R_3=0$ and a rate of change of power of 5% per minute; in curve 2, $R_3=0,5$ with the same rate of change; in curve 3, $R_3=0,5$ and power varies of 10% per minute. Fig. 1.45. gives the steam pressure; Fig. 1.46. gives the average temperature of organic, the organic temperature at the primary inlet, the superheating temperature.

do not undergo significant variation.   It will be noted that,
in the case of a step change of 50 pcm, the power reaches 110%
in 14 sec., which is about the transport delay of coolant from
the reactor outlet to the boiler inlet.

2.1.9.   Scram

The scram is simulated by the instantaneous
insertion of a negative reactivity in the neighborhood of
8,000 pcm;   the neutron power then decreases from 100% to a
level equal to 5%, which represents the effect of photo neutrons
(see Figs. 1.62 to 1.65);   in the same time, in order to obtain
equality between the produced power and the extracted power, the
signal which has ordered the insertion of the scramming rods
closes the steam throttle of the turbine inlet, so that the
product PW = WREQ . ΔH (WREQ: steam flow, ΔH enthalpy span)
follows the variation of the supplied power;   the boiler being
at a fixed level, the water flow at the economizer input follows
the variation of WREQ, then, it decreases abruptly while the
boiler, because of the transport delay of the coolant from
reactor inlet and heat exchanger, receives always hot liquid
corresponding to the 100% power level;   these two facts explain
both the abrupt rise of the average coolant temperature on the
heat exchanger side and of the steam temperature, then of the
steam pressure.   After 12 sec., the cold coolant front comes
to the heat exchanger: all the heat exchanger temperatures
decrease, likewise the pressure;   finally, after some oscillations,
all the variables go to their steady state, which corresponds to
a power level and a water flow reduced to 5% and to a water
input temperature which has remained unchanged (190°C).

In order to reduce the pressure overshoot,
it is necessary to make the decrease of the water flow smaller,
i.e. to delay the closing of the steam throttle.   Figs. 1.66.
to 1.68. show this effect: the closing throttle is affected
with inertia, the time constant of this inertia being variable,
20 and 30 sec.;   it will be noted that the steady state is

2.1.8. Control loss and recovery

The following case of control loss has been studied:

- The reactor stabilized at the nominal power loses suddenly its control (the control rod is blocked) and, at the same time, is subjected to a step change in reactivity of 10 or 50 pcm.

- The control system recovers the reactor when its power reaches 130%.

Figs. 1.58., 1.59., 1.60. and 1.61 show the variation in the time of the neutron power, average coolant temperature on the reactor side, <u>average</u> cladding and fuel temperatures.

The temperature variations are larger in the case of a step change of 10 pcm as, the integrate power being larger, the energy exchanges are more important.

The event of control loss with simultaneous insertion of a step change in reactivity of 50 pcm is highly unlikely;   it presumes indeed two accidents in the same time:

- the rupture of the control system;

- the fall in the channel of a bundle during the fuel handling (fuel handling and coolant flow being in the same direction).

A more realistic event would be to consider a control loss simultaneously with the introduction of a bundle at a normal velocity (10 cm/sec), which corresponds to a step change in reactivity of 50 pcm in 25 sec. in the worse case.

During these control losses and recoveries, the variables on the boiler side and the input reactor temperature

Rate of power level variation from 100 to 75% in 5 min.		Coolant temperatures			Cladding temp.	Fuel temp.	Super-heating temp.	Steam pressure
		Input	Average	Output				
Constant average temperature program	g	+ 2,5	- 1	- 3	+ 4,5	- 16,5	- 2,5	+ 3
	a	+ 12	- 2,5	- 14,5	- 5	- 83	- 10	+ 16
Constant steam pressure program (with pressure term)	g	± 2,5	- 2,5	- 5	- 11,5	- 19	- 3,25	± 5,75
	a	+ 1,5 - 1	- 13	- 26	- 56	- 97	- 16	± 3,5
Program optimized for turbine	g	- 5	- 5	- 8	- 8,25	- 22,5	- 7	- 7,5
	a	+ 1,5 - 13	- 30	- 44	- 46	- 115	- 28	+ 2,5 - 20

The amplitudes are in °C or kg/cm2;   the gradients in °C/min. or kg/cm2/min.

b) Regulation program 2: constant pressure

Changes in power from 100 to 75%

The rate of variation is 5% per minute.   In Figs. 1.47., 1.48., 1.49. and 1.50 are reported the variations of the characteristic parameters.

Changes in power from 100 to 25%

The rate of variation is 5% per minute. Fig. 1.51. and 1.52. give the T_{av} and pressure transient with a parametric variation of R_3.   It can be seen that, because of the long time delays, gains of $R_3 > 0,5$ lead to excessive over-shots, thus $R_3 = 0,5$ has been retained as optimum.   This has been verified by more exchaustive computation with fastest transients. All these curves are not reported for the sake of brevity.

c) Other programs

It has been verified that many alternatives, all stable, are possible;   in particular, the pressure term can be introduced into other regulation programs, and computer investigation has shown its usefulness.   The following table gives the maximum amplitude and gradients of the characteristic variables on the reactor side and on the heat exchanger side for the three following regulation programs:

- the constant-average temperature program;

- the constant-steam pressure program;

- an optimized program for the conditions of the turbine inlet (for which the variations of the steam temperature at the turbine inlet are smallest;   the turbine efficiency is a maximum;   the steam moisture at the turbine outlet has the lowest possible value.

The steady state of this program is given with accuracy in Figs. 1.53., 1.54. and 1.55, where are also reported the corresponding variables of the two previous programs. The variation of some variables in transient state is given in Figs. 1.56. and 1.57.

reached much slowlier.   The large negative gradient of the steam
temperature is essentially due to the sudden decrease of the
coolant temperature at the reactor outlet after the step change
of power.   It might be reduced by changing the coolant flow
or by using a coolant by-pass, which was not possible to simulate
in the model used.

2.1.10. Remarks on the control system

The validity of the control system has been
verified by complementary experiments.

A possible simplification of this control
design is to set R_4 equal to zero (see the relations (1.43.) and
(1.44.)), on condition that, in the error term, the neutron
power and the average temperature are present together.   The
average temperature being an integral variable of the power, it
will indeed be verified that are rightly present a stabilizing
proportional term to the power and an integral term of this
power through the medium of the mean temperature which is the
reset term.   If in the reactor occurs an overpower in respect
to that absorbed in the heat exchanger, the average temperature
rises, which causes the regulator to decrease the power level.

The control system has been verified to be
stable;   the analogue computation shows however that the
transients are a little less good (see Figs. 1.69. to 1.71).
Besides, a defect in the measurement device of the average
temperature would lead to a more serious accident;   indeed,
nothing will offer opposition to a shift of the power supplied
by the reactor (whereas the integral term of the neutron power
will continue to oppose in the other case).   It will also be
noted that, for this control design, it is necessary to use a
position servo to move the control bar, what is generally not
the case for the proportional type of control systems (see
Fig. 1.21.).   On the other hand, taking always R_4 equal to zero,
but substituting now the average temperature term by a integral
term of the steam pressure:

$$\xi = - R_1 \left[\frac{n - n_o}{n_o} - \frac{PW - PW_o}{PW_o} \right] + R_2 \int \frac{p - p_o}{p_o} \, dt$$

we obtain a control design which is not able to control the reactor, the steam pressure being not a representative variable of the power.

2.2. The stable core

The interest of the study is to examine whether the stable reactor can use a simplified control system design.

2.2.1. Main characteristics of the channel

Bundle	18 rods
Fuel cross-section	50 cm2
Coolant cross-section	31 cm2
Moderator area/coolant area ratio	9 or 7
Channel length	400 cm
Fuel rod radius	0,915 cm
Cladding wall thickness	0,915 mm
Finning ratio	1,75
Thermal resistance between fuel and cladding	0,5 °C/w/cm2
Maximum integral of conductibility	80 w/cm
Average velocity in the central channel	10 m/sec.
Axial form factor	0,69
Radial form factor	0,86
Disadvantaged thermal flux factor	0,91

Characteristics of the so-called representative channel (assimilated with the mean channel) at its nominal power

Removed power	4,0 MW
Input temperature	293 °C
Output temperature	365 °C
Average cladding temperature	365 °C
Average fuel temperature	500 °C

Temperature coefficients for the equilibrium core

First case: α_{V} = 1,07 pcm/°C

α_{c} = + 1,83 pcm/°C

Second case: α_{V} = - 1,5 pcm/°C

α_{c} = - 1 pcm/°C

Time constants of the coolant circulation unchanged

2.2.2. Positive coolant temperature coefficient

a) On-off system

The simplest control system is an on-off control system where the position of the control rods is changed at a fixed velocity when the error signal exceeds a predetermined value (which thus defines a dead zone). The error signal is always formed at a neütron power-term and an average temperature-term.

This control design is actually able to control the reactor, but with a smaller accuracy and chiefly a rather weak safe margin in respect to the instability field.

The parametric study of the transients (see Figs. 1.72. to 1.76.) gives an optimum for:

Dead zone:	± 1%
Inertia time constant:	from 0,5 to 1 sec.
Velocity of the bar:	5 pcm/sec.

A dead zone of ± 0,25% or a bar velocity of 15 pcm/sec. lead to the instability, whereas a lower bar velocity (1 pcm/sec.) or a larger dead zone lead to a transient behavior which gives too large excursions to the thermodynamical variables of the heat exchanger.

In case of power change, the regulator follows the imposed program by a step curve (and not by a continous curve) (see Figs. 1.77. to 1.80.).

The circuit of the dead zone must be temporized to prevent a too frequent sollicitation by the reactor noise (see Fig. 1.81. where is reported the relay running).

In conclusion, the discontinuous-type regulator presents a stable running zone, but its suitability and its safe margin with respect to the instability lead to dissuade its practical use (on this subject, refer to pages 185-193 of /‾Ref. 1‾/ .

b) <u>Proportional-type system, but with error signal related to a thermal measurement of the power</u>

The error signal is thus

$$\varepsilon = -R_1 \left[\frac{(T_{out} - T_{in}) - \Delta T_o}{\Delta T_o} - \frac{PW - PW_o}{PW_o} \right] - R_2 \frac{\frac{T_{out} + T_{in}}{2} - T_{AV_o}}{T_{AV_o}}$$

where ΔT_o is the enthalpy span along the channel in steady state, and T_{in} and T_{out} are the input and output temperatures of the reactor.

This relation can be developed as follows:

$$- \varepsilon = K_1 T_{out} + K_2 T_{in} - \text{Ref } 1$$

where K_1, K_2 are numerical constants and Ref. 1 a reference which depends upon R_1, R_2, PW, PW_o and the eventual laws of variation which would be affected to T_{av}.

This control design is stable only for very weak gain values (see Figs. 1.82. and 1.83.). On the other hand, all parameters remain very critical with respect to the

instability, which would cause its realization to be difficult in practical conditions.

The optimum parameters are:

$$\begin{cases} R_1 = R_2 = 1 \\ R_5 = 1.10^{-3} \\ R_4 = 0,2.10^{-3} \end{cases}$$

c) Conclusions

It is practically necessary, in this case, to use the same control design as in the previous studied unstable case. In these conditions, the transient behavior is practically identical with the unstable case; the optimum values of the calculated parameters for the unstable case remain valid. However, the stable case presents a behavior highly favorable in the event of control-loss. It must also be noted that the reactor, though being intrinsically stable according to the usual definition, is unstable when attached to the heat exchanger because of the return of hotter coolant flow due to a perturbation (then a positive reactivity is sufficient to cause instability of the overall loop). This effect appears well in Fig. 1.85.: after about 40 sec., which is the whole coolant transport delay, the temperature rises more rapidly. A mean to evacuate the excess of energy in order to stabilize the reactor is a steam discharge into the atmosphere (see Figs. 1.84. to 1.88.); another solution would be to increase the secondary flow.

The stable reactor also allows a more important safe margin with respect to the zone where it is not possible to control the reactor, as it can be seen on Fig. 1.28.

2.2.3. Negative coolant temperature coefficient

a) On-off control system

The on-off control design with error signal related to the neutron power and the average temperature runs with a greater safe margin than in the case 2.2.2.a). The optimum parameters are here (see Fig. 1.89.):

Dead zone:	$\pm$ 1%
Inertia time constant:	from 0,5 to 1 sec.
Velocity of the bar:	10 pcm/sec.

The system is unstable for a velocity of 30 pcm/sec. and a dead zone of $\pm$ 0,25%.

b) On-off control system but with error signal related to the thermal measurement of the power

This control design runs (wrong) only for very low velocities; its practical use seems to be rejected because its parameters are very critical (see Figs. 1.90. to 1.92.).

c) Proportional-type control design but with error signal related to the thermal measurement of the power

This control design runs with a superior safe margin than in the case 2.2.2.b) (see Fig. 1.93.). The optimum parameters are:

$$\begin{cases} R_1 = R_2 = 1 \\ R_5 = 2,5 \cdot 10^{-3} \\ R_4 = 0,5 \cdot 10^{-3} \end{cases}$$

The gain values are larger than in the previous case.

d) **Conclusions**

Here, the reactor presents a more intrinsic
stability than in the previous case (the two temperature
coefficients are negative), which allows to consider the use of
regulators described in 2.2.3.a) and 2.2.3.c), also knowing that
lower operating velocities must be envisaged.   On the other
hand, the case 2.2.3.b) is to reject.

However, the control design described in
1.4. remains the one which gives the better performances in
transient and the more important safe margin for a variation of
the parameters towards the field of unstable gains.

The performances, in the event of control-
loss, are evidently more favorable than in the previous case.
It will however be noted that, because of the negative coolant
temperature coefficient, the steam discharge to a pre-fixed
value causes a new steady state of the neutron power to set up
at a superior level than the nominal one (Fig. 1.94.).   Indeed,
without steam discharge after the transient, the power would find
again its initial value of 100% (PW = 100% = WREQ . ΔH)..

2.3. General remarks on the regulator designs

In the regulator design as described in 1.4.,
the error term is independent of the transfer function of the
control mechanism.   Thus, the operations depending on time
(integration, derivation) are effected separately on certain
variables composing the error signal and not on others.   The
possible variants of the regulator are all described by the
general following diagram:

measured variables / references (programs of power level changes)	Summation Comparison Amplification	unique error signal	transfer function in S (derivations, integrations, poles, etc.) no-linearities	Control reactivity
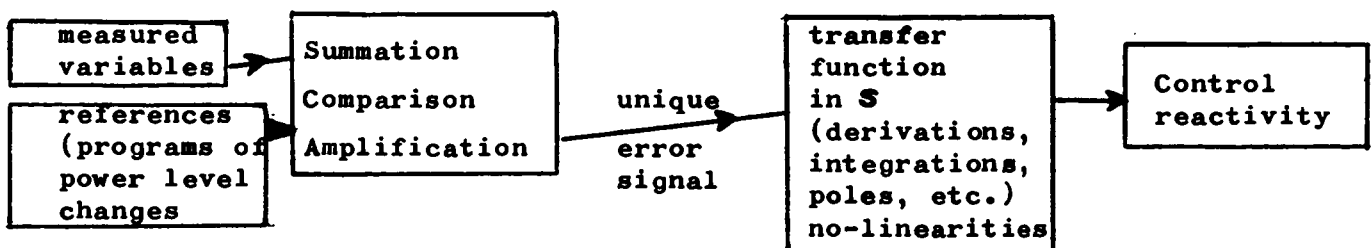
This gives the following advantages:

- simpler design;

- possibility to fit easily the regulator with
  different programs of power level changes,
  fixing thus various laws of variation of the
  temperatures, steam pressure, etc.;

- reduction of the effets due to the cut of
  one input in certain limits.

It will still be noted that the particular
formulation used in 1.4. allows still some freedom of choice in
the technological realization;   as it has been seen, the regulator
can be realized (see Fig. 1.21.):

- by a proportional-type amplifier, a forwards-
  phase compensation network (derivative),
  and a rate servo (i.e. with tachometer feed-
  back), excluding every integrative network
  in the electronic part;

- or by a proportional and integral-type circuit
  connected to a position servo (i.e. with
  potentio-meter feedback).

For the regulator described in 2.1.10., a
position servo is necessary.

The following table summarized the conclusions of the studies in the different cases:

	Unstable case $u = - 0.45$ $c = + 5.6$	Stable case 1 $u = - 1.07$ $c = + 1.83$	Stable case 2 $u = - 1.5$ $c = - 1$
Power coefficient* pcm/%	+ 0,55	- 2,2	- 4,3
1) Proportional-type regulator, neutron power signal and average temperature signal (pressure term in option)	yes	yes	yes
2) Proportional-type regulator, only temperature signal	no	insufficient performances	yes
3) On-off-type regulator, neutron power and temperature signals	no	insufficient performances	yes
4) On-off-type regulator, only temperature signal	no	no	insuff. perform.
5) Proportional-type regulator, pressure and/or integral pressure signals	no	no	no

Examining this table leads to envisage for the stable case 2 a regulator with the advantages of designs 1 and 2.

---

* Calculated from analytic relations

The configuration is:

- proportional-type servo;
- neutron power signal;
- thermal power signal;
- average temperature signal;

the reactor being able to be controlled in case of lack, by accident, of one of the error signal components.

The error signal is thus defined:

$$\xi = -R_1 \frac{(T_{out}-T_{in}) - \Delta T_o}{\Delta T_o} - R_2 \frac{\frac{T_{out}+T_{in}}{2} - T_{AV_o}}{T_{AV_o}} -$$

$$- K \frac{n - n_o}{n_o} + (K + R_1) \frac{PW - PW_o}{PW_o}$$

where ΔT_o, T_{AV_o}, n_o are the enthalpy span along the channel, the average temperature and the neutron power in steady state, T_{in} and T_{out} the input and output temperatures of the reactor.

This expression can be developed as follows:

$$-\xi = (+ k_1 T_{out} + k_2 T_{in} - \text{Ref 1}) + (k_3 n - \text{Ref2})$$

where k_1, k_2, k_3 are numerical coefficients and Ref 1 and Ref 2 are references depending on R_1, R_2, K, PW and PW_o, and on the eventual laws of variation which would be affected to T_{AV}.

By doing so, it can be verified on the analogue computer that, <u>if one of the two terms between brackets is removed, the regulator is always able to control the reactor</u> (Figs. 1.95. to 1.98.).

The analogue investigation gives the following optimum parameters:

$$R_1 = 1$$
$$R_2 = 1$$
$$R_4 = 0.5 \ 10^{-3}$$
$$R_5 = 2.5 \ 10^{-3}$$
$$K = 0.5$$

- servo-mechanism inertia time constant 0.5 ... 1 sec.
- velocity limit of the control bars 15 pcm/sec.
- delay in the measure of the temperatures 4 sec.

Fig. 1.95. gives the behavior of such a regulator for a step change in reactivity of 50 pcm in the case of a normal running, and in the other cases of running with one of the two measurement circuits cut.

Figs. 1.96. to 1.98. give the behavior and the operating of power change if one of the two measurement circuits is cut during the running.

The control design is the following:
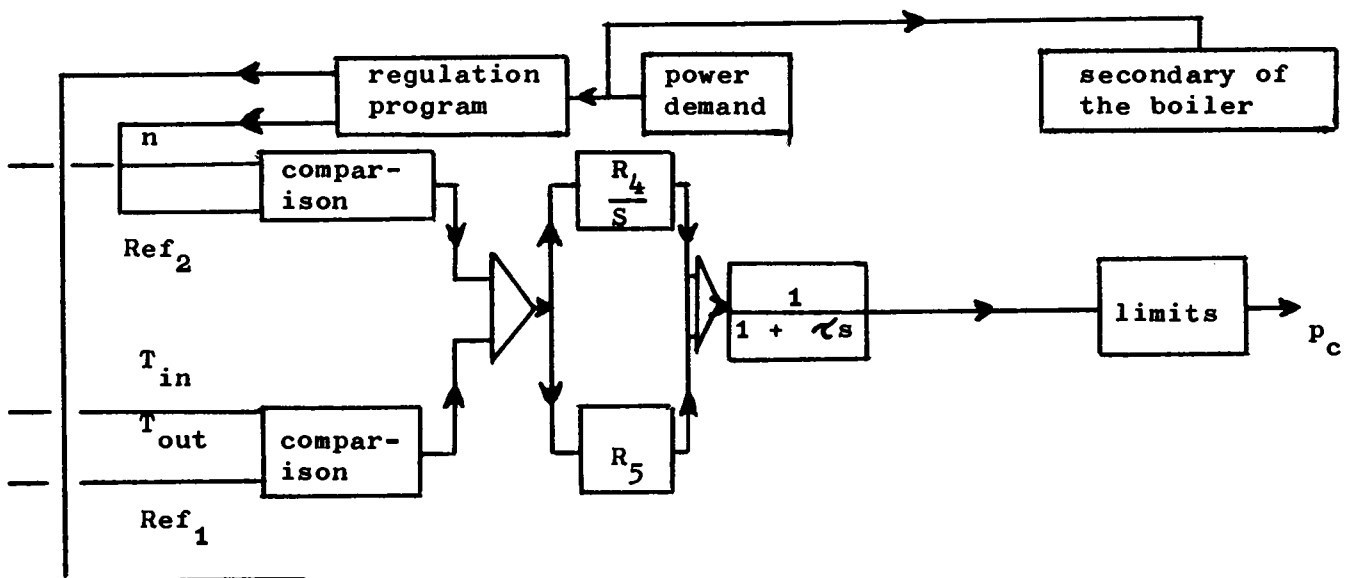
III. SECOND PART

1. The mathematical model

1.1. Introduction

In this second part, the model of reactor simulation has been taken again. However, as the representation of the whole plant appeared too heavy and led to minimize the number of operational amplifiers involved, all the groups of delayed neutrons have been lumped into a single group. This simple approximation is sufficient. Only one loop has been represented. It has been necessary to simulate the primary hydraulics because of the heat-exchanger by-pass and the secondary hydraulics because the pressure regulation by the water flow is not instantaneous; it will be recalled that, for a Benson heat exchanger in contrast with the drum boiler, the primary temperature and the steam pressure are not controlled independently because of the fitting of the economizer and boiler surfaces according to the power level.

The used Benson model is given afterwards; its original formulation has involved the reduction of differential equations to partial derivatives and variable limits into a system of ordinary time derivatives.

Only the main characteristics of the general control and regulating system defined by the industrial group will be reported.

2. Hydraulics of the loops

1.2.1. Primary loop

Fig. 2.1. gives a schematic drawing of the hydraulic loop; the power station of the prototype is composed of four identical loops, of which only one is represented.

Every loop includes a by-pass, the primary of
the Benson heat exchanger and the primary of the reheater.
The location of the pump circulation and the regulation values
must be noted. The numbers of the loops reported in Fig. 2.1.
correspond to the indexes of the equations expressing that the
sum of the pressure losses is equal to zero in every loop:

$$(2.1.) \sum_0 \frac{\ell_i}{A_i} \frac{d^F_o}{dt} + \sum_1 \frac{\ell_i}{A_i} \frac{d^F_1}{dt} + \sum_3 \frac{\ell_i}{A_i} \frac{d^F_2}{dt} = \Delta p - k_o F_o^2 - k_1 F_1^2 - k_3 F_3^2$$

$$(2.2.) \sum_0 \frac{\ell_i}{A_i} \frac{d^F_o}{dt} + \sum_1 \frac{\ell_i}{A_i} \frac{d^F_1}{dt} + \sum_2 \frac{\ell_i}{A_i} \frac{d^F_2}{dt} + \sum_3 \frac{\ell_i}{A_i} \frac{d^F_4}{dt} = \Delta p - k_o F_o^2 - k_1 F_1^2 - k_2 F_2^2 - k_4 F_4^2$$

$$(2.3.) \sum_0 \frac{\ell_i}{A_i} \frac{d^F_o}{dt} + \sum_1 \frac{\ell_i}{A_i} \frac{d^F_1}{dt} + \sum_2 \frac{\ell_i}{A_i} \frac{d^F_2}{dt} + \sum_5 \frac{\ell_i}{A_i} \frac{d^F_5}{dt} = \Delta p - k_o F_o^2 - k_1 F_1^2 - k_2 F_2^2 - k_5 F_5^2$$

where F_i is the flow in kg/sec.

Δp is the heat pump pressure in kg/m2

$\sum_i \frac{\ell_i}{A_i}$ is the sum of the ratios between the length and
the cross-area of the pipe sections into which
the circuits of Fig. (2.1.) can be divided

$k_i F_i^2$ are the pressure losses attached to these pipe
sections

The system (2.1.), (2.2.), (2.3.) must be
completed by the equations of flow conservation:

(2.4.) $F_o = F_1 + 3 \cdot F_1^*$

(2.5.) $F_2 = F_1 - F_3$

(2.6.) $F_5 = F_2 - F_4$

where F_1^* is the flow of the other not represented loops, running
in parallel.

In order to introduce the system (2.1.) to
(2.6.) on the computer, it is necessary to write it in a
transformed form which does not contain derivatives in the second

part of the equation. Therefore, auxiliary variables will be
defined, representing in fact the inertia strengths along the
three loops:

(2.7.) $\qquad V_1 = \alpha_o F_o + \alpha_1 F_1 + \alpha_3 F_3$

(2.8.) $\qquad V_2 = \alpha_o F_o + \alpha_1 F_1 + \alpha_2 F_2 + \alpha_4 F_4$

(2.9.) $\qquad V_3 = \alpha_o F_0 + \alpha_1 F_1 + \alpha_2 F_2 + \alpha_5 F_4$

$\qquad$ where $\alpha_i = \sum \dfrac{\ell_i}{A_i}$

Substituting gives:

(2.10.) $\qquad \dfrac{dV_1}{dt} = \Delta_p - k_o F_o^2 - k_1 F_1^2 - k_3 F_3^2$

(2.11.) $\qquad \dfrac{dV_2}{dt} = \Delta_p - k_o F_o^2 - k_1 F_1^2 - k_2 F_2^2 - k_4 F_4^2$

(2.12.) $\qquad \dfrac{dV_3}{dt} = \Delta_p - k_o F_o^2 - k_1 F_1^2 - k_2 F_2^2 - k_5 F_5^2$

(2.13.) $\qquad F_1 = \dfrac{\alpha_3 \alpha_4 V_3 + (\alpha_2 \alpha_4 + \alpha_2 \alpha_5 + \alpha_4 \alpha_5) \cdot V_1 + \alpha_3 \alpha_5 \cdot V_2}{(\alpha_4 + \alpha_5)(\alpha_1 \alpha_3 + \alpha_1 \alpha_2 + \alpha_2 \alpha_3) + \alpha_4 \alpha_5 (\alpha_1 + \alpha_3)}$

(2.14.) $\qquad F_2 = \dfrac{(\alpha_1 + \alpha_3) F_1 - V_1}{3}$

(2.15.) $\qquad F_5 = \dfrac{\alpha_4 / \alpha_3 (\alpha_1 + \alpha_3) \cdot F_1 - \alpha_4 / \alpha_3 V_1 - V_2 - V_3}{\alpha_4 + \alpha_5}$

(2.16.) $\qquad F_3 = F_1 - F_2$

(2.17.) $\qquad F_4 = F_2 - F_5$

$\qquad$ The Eqs. (2.10.) to (2.17.) are those actually
represented on the computer, and analogue investigation has shown
that the corresponding computation circuits are stable and give

about the same results as those obtained in numerically integrating the equations.

The pressure losses in the pipes being proportional to the squares of the flows, the k_i coefficients are constants (in newtons/m2)/(kg/sec.).

For the valves, the coefficients are variable and of the form:

$$k = \frac{\ell}{A(y)2}$$

where ℓ is a constant

A   is a characteristic function of the valve

y   is the opening in percentage

Fig. 2.2. gives the A functions used in computation.

If the operating range of the valve is limited, for example from 20% to 100%, Fig. 2.2. can be approximated by the following expression:

$$A(y) = a_1 + a_2 y^2 + a_3 y^4$$

which allows to use the parabolic function generators of the analogue computer.   (For Fig. 2.2., $a_1 = 4.36 \times 10^{-2}$, $a_2 = 2.961 \times 10^{-1}$, $a_3 = 6,54 \times 10^{-2}$;   the corresponding points are reported on the figure).   The pump characteristics are given in Fig. 2.3.

The temperature transfer functions of the pipes will be considered as pure time delays using a 5th order Padé's approximation to realize the delay operator.

1.2.2. Secondary loop

Fig. 2.4. is a schematic drawing of the secondary loop, where a common collector gathers the flows of the heat exchangers before distributing them towards the turbine. The feed pump is assumed to maintain the pressure independent of the value of the flows. For every heat exchanger, there is a regulation valve of the water flow. In the following, an unique heat exchanger will be represented, the others being assumed to be in the same conditions, then FD_{201} must be put equal to FD_{101}.

The flow entering into FD_{101} is deduced by the usual momentum equation:

$$\frac{Z}{A} \cdot \frac{dFD_{101}}{dt} = PD_{001} - PD_{002} - (16\ KD_{001} + KD_{001} + (\frac{Z}{A(YD_{101})})\ FD^2_{101}$$

The pressures and the temperatures in the collector are deduced by a mass and energy balance:

$$(2.19.) \quad VCOLL. \ \frac{d(RO_{002})}{dt} = 3.FD_{202} + FD_{102} - FD_{002}$$

$$(2.20.) \quad VCOLL. \ \frac{d(RO_{002} \cdot ID_{002})}{dt} = 3\ FD_{202}\left[EVSAT + CPS\ (TD_{202} - TSAT)\right]$$

$$+ FD_{102}\left[EVSAT + CPS\ (TD_{102} - TSAT)\right] - FD_{002}\ IR_{002}$$

$$- y_e \cdot \frac{GECO}{AS} - y_B\ \frac{GEVA}{AS}$$

taking

$$(2.21.) \quad ID_{002} = AIPRO + BIPRO \cdot (\frac{PD_{002}}{RO_{002}})$$

$$(2.22.) \quad TD_{002} = ATI \cdot (ID_{002}) + BTP \cdot (PD_{002}) + CT$$

where   VCOLL   is the collector volume

RD_{002} is the density of the steam in the collector

PD_{002} is the pressure of the steam in the collector

ID_{002} is the enthalpy of the steam in the collector

TD_{002} is the temperature of the steam in the collector

FD_{002} is the flow of the steam from the collector to the turbine

GECO and GEVA   represent the mass for unit of length for the economizer and the evaporator

Y_e and Y_B represent the heights of the economizer and the evaporator

AS   is the secondary cross-section of the boiler

Expressions (2.21.) and (2.22.) are linearizations of the steam characteristics, the precision of which can be judged by looking at Figs. 1.15. and 1.20.; the approximation (2.21.) has also been introduced into (2.20.). The mass flow and temperature of the steam exiting from the heat ex - changer (FD_{102}, TD_{102}) are output variables from the "Benson heat exchanger block"; FD_{202} and TD_{202} can be assumed equal to FD_{102} and TD_{102} as the four loops are working in the same conditions.

The flow into the turbine is calculated by:

(2.23.) $$FD_{002} = W_t \, PD_{002}$$

where W_t is proportional to the power demand; it is also possible to calculate the power delivered to the turbine by:

(2.24.) $$\dot{W}_{el} = (\,\Delta H_{ech} + \Delta H_{resurch}\, \beta)\, FD_l$$

where ΔH_{ech} and $\Delta H_{resurch}$ are the enthalpy spans on the secondary heat exchangers and reheaters

β the part of flow entering into the reheater

η the efficiency of the turbo-alternator group

1.3. Heat transfer equations in the Benson

1.3.1. Location of the phase-change zones

The primary and secondary fluids flow in opposite directions along a wall; the primary fluid (organic coolant) remains always liquid along its path, whereas the secondary fluid is changed from liquid state to wet steam and dry steam; the secondary circuit having a continuous structure, it results that the limits between the different thermodynamical states are variable in position. In the boiling zone, the same velocity will be assumed to the two phases.

The height of the economizer, of the evaporator and of the superheater is calculated from overall balances.

For **any** cross-element of the heat exchanger, the mass and energy balances give both for the primary and for the secondary:

$$(2.25.) \quad \frac{d}{dt} \int_{y_1}^{y_2} A \, \rho H \, dy = F_{in} H_{in} - F_{out} H_{out} + \int_{y_1}^{y_2} \propto (T_p - T) dy$$

$$(2.26.) \quad \frac{d}{dt} \int_{y_1}^{y_2} \rho A \, dy = \rho_{in} F_{in} - \rho_{out} F_{out}$$

where   A   is the cross-section for flow of fluid

       ρ is the density (kg/m3)

       H   is the fluid enthalpy (kcal/kg)

       F   is a mass flow (kg/sec.)

       $\propto$ is the heat transfer coefficient per unit length (kcal/°C/m)

       dy   is the height element

       y   is the height coordinate

       T   is the temperature

The indexes "in" and "out" refer to the entering and leaving fluid, and "p" to the wall.

Applying the relations (2.25.) and (2.26.) to the entire height of the economizer, the limit conditions are:

- the flow of input;
- the enthalpy of input;
- the enthalpy of saturation deduced from the pressure.

Assuming that the enthalpy distribution is changed along the heat exchanger according to a known law, Eqs. (2.25.) and (2.26.) allow to calculate the height of the economizer (y_e) and the exit flow (F_{out}). The following hypothesis must be introduced in order to resolve these equations for the economizer:

- the density is constant;
- the enthalpy is varied linearly according to the temperature:

$$H = H_o + C_p T$$

where C_p is the specific heat

- the temperature distribution is linear:

$$T = T_{in} + (T_{sat} - T_{in}) \frac{y}{y_e}$$

where T_{sat} is the saturation temperature.

The whole height of the economizer will be divided into NE cells, in order to quantify it according to the y axis. In these conditions, applying (2.25.) and (2.26.) to the secondary and on the whole economizer gives:

$$(2.27.) \quad \rho A C_p \frac{d}{dt} (y_e \cdot T) = C_p F_{in} T_{in} - C_p F_{out} \cdot T_{sat} + \alpha \sum_1^{NE} (T_{p_i} - T_i) \cdot y_e / NE$$

$$(2.28.) \quad \rho A \frac{d}{dt} y_e = (F_{in} - F_{out})$$

Then, after separating the variables and taking into account that $T = \frac{T_{in} + T_{sat}}{2}$:

$$(2.29.) \rho AC_p \cdot \frac{T_{in} + T_{sat}}{2} \frac{dy_e}{dt} = - \frac{\rho AC_p \, y_e}{2} \left(\frac{dT_{in}}{dt} + \frac{dT_{sat}}{dt}\right) +$$

$$+ C_p \, F_{in} T_{in} - C_p \, F_{out} T_{out} + \sum_{1}^{NE} (T_{p_i} - T_i) \, y_e / NE$$

$$(2.30.) \quad F_{out} = F_{in} - \rho A \frac{dy_e}{dt}$$

$$(2.31.) \quad T_i = T_{in} + (T_{sat} - T_{in}) \frac{y_e}{NE} \cdot i$$

where T_i is the average temperature of the cell indexed i. It must be noted that, if the pressure is constant, or is little varied, the term in $\frac{dT_{sat}}{dt}$ must be neglected in (2.29.).

Likewise, in most cases the variations of the input temperature will be very slow and the term in $\frac{d \, T_{in}}{dt}$ will also be neglected.

In the same manner, the evaporator will be quantified in NB sections, where the hypothesis are:

- linear distribution of the enthalpy

$$H = ELSAT + (EVSAT-ELSAT) \frac{y}{y_a}$$

$$T = TSAT$$

where

$$\rho = \rho(H) = \frac{1}{v' + (v'' - v') \frac{y}{y_B}}$$

$$\bar{\rho}' = \frac{1}{y_B \, H} \int_0^{y_B} \rho H \, dy$$

$$\bar{\rho}'' = \frac{1}{y_B} \int_0^{y_B} \rho \, dy$$

$$v' = \frac{1}{\rho'} = \text{specific volume of the saturated liquid}$$

$$v'' = \frac{1}{\rho''} = \text{specific volume of the saturated steam}$$

$$\bar{H} = (ELSAT+EVSAT)/2$$

Using Eqs. (2.25.) and (2.26.) still valid in the case of the evaporator, it results:

$$(2.32.) \quad A\bar{\rho H} \cdot \frac{dy_B}{dt} = \rho' F_{in} ELSAT - \rho'' F_{out} EVSAT + \sum_{1}^{NB} \alpha_i (T_{p_i} - T_{sat}) \frac{y_B}{NB}$$

$$(2.33.) \quad F_{out} = F_{in} - \rho A \frac{dy_B}{dt}$$

For these equations, the limit conditions are given by the output values of the economizer equations.

By integrating Eqs. (2.29.) and (2.33.), it is possible to determinate the heights of the economizer and evaporator in transient state; of course, the height of the superheater is deduced by difference.

1.3.2. Calculation of the temperature distributions

In order to obtain a rather accurate representation of the heat exchanger transient behavior, every zone previously determined has been subdivided into sections. **This is not a quantification of the space variable**, the zones being variable in the time, but it is a subdivision relative to these zones. This will define sections of finite differences with **variable dimensions and locations**.

Relations (2.25.) and (2.26.) remain valid for each of these sections. If the quantification is small enough (which must be determined by numerical computation), the output temperature T_i of the section i can be assimilated to its average temperature. For the same reason, the density and the specific heat C_p can be considered as constant in the interior of a section, which allows to take them outside the derivation operator.

The relations (2.25.) and (2.26.) become, for an indexed section i:

$$(2.34.) \quad \Delta y C_p \rho A \frac{dT_i}{dt} = C_p F_i (T_{i-1} - T_i) + \alpha \cdot \Delta T \cdot \Delta y$$

$$(2.35.) \quad F_i = F_{i-1} - A\rho \frac{dy}{dt}$$

where ΔT is the difference in temperature between the fluid and the wall and where Δy is the height of the section.

Eqs. (2.34.) and (2.35.) are used to represent the primary of the heat exchanger, in the same way as the secondary of the superheater. These equations are also available to represent the wall, when $\propto \Delta T$ includes the algrebraic sum of the exchanged heat amounts on both sides of the wall.

As the location of the sections is variable with respect to the heat exchanger, it is possible to take this movement into account by use of a fictive flow of the wall represented exactly as the real flows. In this case, Eq. (2.25.) will be completely defined if a fictive flow equal to zero at one of the ends of the heat exchanger is given as limit condition.

· The equation of the wall will be the following:

$$y \ C_p \ \rho A \ \frac{dT_i}{dt} = F_{i-1} \ C_p \ \rho (T_{i-1} - T_i) + \propto_p \ (T_p - T)_i \cdot y - \propto_s \ (T - T_s)_i \cdot y$$

$$F_i = F_{i-1} - A\rho \frac{dy}{dt}$$

In the following, we will find the complete set of the equations, as applied to the computer:

1.3.3. Set of the equations

a) Calculation of the heights

ECO) $\frac{1}{2}$ ROSE.AS.CSE.(TSAT-TSIN) $\frac{dYE}{dt}$ =

$$\text{CSE.FSIN.(TSAT-TSIN)} - \sum_{1}^{NE} {}_i \ \text{ALFAE(TP(i)-TS(i))} \ \frac{YE}{NE}$$

EVA) $\frac{1}{2}$ ROSB.AS.(EVSAT-ELSAT) $\frac{dYB}{dt}$ =

$$\text{FSE.(EVSAT-ELSAT)} - \sum_{NE+1}^{NE+NB} {}_i \ \text{ALFAB(i)(TP(i)-TSAT)} \ \frac{YB}{NB}$$

SUP) YS = LTPT - YE - YB

b) Calculation of the flows

Secondary

ECO) $FSE = FSIN - ROSE \cdot AS \cdot \dfrac{dYE}{dt}$

EVA) $FSB = FSE - ROSB2 \cdot AS \cdot \dfrac{dYB}{dt}$

SUP) $FS(i) = FS(i-1) - \dfrac{ROSS \cdot AS}{NS} \cdot \dfrac{dYS}{dt}$

$i = NE+NB+1, NE+NB+NS$

$FS(o) = FSB$

Wall

ECO) $FP(i) = FP(i+1) - \dfrac{ROP \cdot AP}{NE} \cdot \dfrac{dYE}{dt}$ $i = 1, NE$

EVA) $FP(i) = FP(i+1) - \dfrac{ROP \cdot AP}{NB} \cdot \dfrac{dYB}{dt}$ $i = NE+1, NE+NB$

SUP) $FP(i) = FP(i+1) - \dfrac{ROP \cdot AP}{NS} \cdot \dfrac{dYS}{dt}$ $i = NE+NB+1, NE+NB+NS$

$FP(NE+NB+NS+1) = o$

Primary

ECO) $FOL(i) = FOL(i+1) - \dfrac{ROOL \cdot AOL}{NE} \cdot \dfrac{dYE}{dt}$ $i = 1, NE$

EVA) $FOL(i) = FOL(i+1) - \dfrac{ROOL \cdot AOL}{NB} \cdot \dfrac{dYB}{dt}$ $i = NE+1, NE+NB$

SUP) $FOL(i) = FOL(i+1) - \dfrac{ROOL \cdot AOL}{NS} \cdot \dfrac{dYS}{dt}$ $i = NE+NB+1, NE+NB+NS$

$FOL(NE+NB+NS+1) = FOLIN$

c) Calculation of the temperatures

Primary

ECO) $COL.ROOL.AOL. \dfrac{dTOL(i)}{dt} =$

$= COL.FOL(i+1).(TOL(i+1)-TOL(i))/YE+ALFP.(TOL(i)-TP(i))$

$i = 1, NE$

EVA) $COL.ROOL.AOL. \dfrac{dTOL(i)}{dt} =$

$= COL.FOL(i+1).(TOL(i+1)-TOL(i))/YB+ALFP.(TOL(i)-TP(i))$

$i = NE+1, NE+NB$

SUP) $COL.ROOL.AOL. \dfrac{dTOL(i)}{dt} =$

$= COL.FOL(i+1).(TOL(i+1)-TOL(i))/YS+ALFP(TOL(i)-TP(i))$

$i = NE+NB+1, NE+NB+NS$

$TOL(NE+NB+NS+1) = TOLIN$

Wall

ECO) $CP.AP.ROP. \dfrac{dTP(i)}{dt} =$

$= CP.FP(i+1).(TP(i+1)-TP(i))/YE+ALFP(TOL(i)-TP(i)) -$

$- ALFSE.(TP(i)-TS(i))$

$i = 1, NE$

EVA) CP.AP.ROP. $\dfrac{dTP(i)}{dt}$ =

CP.FP(i+1).(TP(i+1)-TP(i))/YB(+ ALFP(TOL(i))-TP(i)) -

- ALFSB(i)(TP(i)-TSAT)

i = NE+1, NE+NB

SUP) CP.AP.ROP. $\dfrac{dTP(i)}{dt}$ =

= CP.FP(i+1).(TP(i+1)-TP(i))/YS+ALFP.(TOL(i)-TP(i))-

- ALFSS(TP(i)-TS(i))

i = NE+NB+1, NE+NB+NS+1

Secondary

ECO) TS(i) = TSIN + (TSAT-TSIN) $\dfrac{2.i-1}{2.NE}$

EVA) TSI = TSAT

SUP) CSS.AS.ROSS. $\dfrac{dTS(i)}{dt}$ = CSS.FS(i-1).(TS(i)-TS(i-1))/YS +

+ ALFSS.(TP(i)-TS(i))

SYMBOLS

AOL, AL, AP	Area of heat transfer surface of the primary, of the wall and of the secondary,(m2).
COL, CP, VSE, CSS	Specific heat of the primary, of the wall and of the secondary on economizer and superheater sides (kcal/kg °C).
ROOL, ROP, ROSE, ROSS	Average densities of the primary, of the wall and of the secondary on economizer and super-heater sides (kg/m3).
ROSB	Density of the secondary on the evaporator side (kg/m3).

$$\text{ROSB1} = \frac{2}{\text{EVSAT+ELSAT}} \int_{0}^{1} \text{ROSB.HSB } dx$$

ROSB2 =	ROSB dx =
ROSB =	$1/(\ v'+(\ v''-v').x)$ kg/m3
HSB	Enthalpy of the evaporator on secondary side (kcal/kg) = ELSA+(EVSAT−ELSAT)x
ELSAT, EVSAT	Specific heats of the liquid and of the saturated steam (kcal/kg)
v', v"	Specific volumes of the liquid and of the saturated steam (m3/kg)
TSAT	Temperature of saturation (°C)
YE, YB, YS	Heights of the economizer,evaporator and superheater (m)
NE, NB, NS	Number of sections for the quantification of the economizer, of the evaporator and of the superheater
LTOT	Total height of the heat exchanger (m) = YE + YB + YS
ALFAE, ALFAB(i), ALFAS	Heat transfer coefficient between wall and secondary for the economizer, the evaporator and the superheater (kcal/sec m2 °C)
ALFP	Heat transfer coefficient between wall and primary (kcal/sec m2 °C)
FSIN, FOLIN	Flows to the secondary and primary inlets (kg/sec)
FSE, FSB, FS(i)	Exit flows of the economizer, of the evaporator and of the superheater (kg/sec)
FOL(i)	Organic flow (kg/sec)
FP(i)	Fictive flow of the wall (kg/sec)
TSIN, TOLIN	Temperature at the secondary and primary inlets (°C)
TOL(i), TP(i), TS(i)	Organic, wall and secondary temperatures (°C)

1.4. The control and regulating system

We will restrict ourselves to give the general principles.

The control and regulating scheme is already given in Fig. 2.5., where the reheater has been removed by simplification. The general regulation scheme is reproduced in Fig. 7., where, by simplification, the reheater has been omitted.

The regulation must hold to the set values:

- the neutron power
- the power to the turbine
- the reactor output temperature
- the steam output temperature
- the steam pressure
- the coolant flow in the reactor

Moreover, the control system must allow the power level changes from the low powers (10 ... 25%) to the nominal power of the power station. The power station must be stable at any power level.

The mathematical simulation of the components of the control system presents no difficulties and will not be retaken here.

The representation of the effect of the valves on the hydraulic loop has been given in 1.2. The transient response of a valve is the same as the one due to a one pole transfer function, but it is necessary to represent also on the computer the velocity limit of their operating mechanism.

The control rods are made of neutron-absorptive gas; with respect to mechanical control rods, their inertia is very weak.

In the regulator, proportional and integral terms are necessary; the analogue computation has showed that the

addition of a derivative term does not improve the control-rod performances.

2. ANALOGUE COMPUTATION RESULTS

2.1. Transient reponses of the primary loop

Because of the non-linearities of the primary loop, it is necessary to check the static characteristics before designing a regulating system.

Fig. (2.6.) gives the flow variations as function of heat exchanger throttle opening Y_2, for a constant value of by-pass-valve opening.

Fig. (2.7.) shows the range of Y_2 variation (heat exchanger valve) when it is necessary to maintain the flow F_1 constant (the indexes refer to Fig. 2.1.). The different values of F_1 are reported as parameters. This figure shows that, for the large flows ($F_1 \geqslant$ 1400 kg/sec.), the efficiency of the regulation becomes unreliable because of the neighborhood of the limits for valves motion travel stoppages, and that it is not possible for the flow regulation (which maintains constant F_1) to run with the by-pass valve too near to its stoppage. It will also be noted that the effect of the regulation valve is the same as the one due to a variable gain in the regulation loop.

According to the present data (June, 1968) of the 250-MWe prototype, it is necessary to set up a flow F_2 (primary heat exchangers and reheaters) equal to 1340 kg/sec. for a temperature span of about 50°C. In these conditions, in order to obtain a good running of the F_1 regulation, it is necessary to hold the set value of F_1 at least at 1400 kg/sec. (which has been confirmed on the computer). Then, in Fig. (2.7.), it must be shown that are necessary a heat exchanger valve opening of about 90% and a by-pass valve opening of about 45%.

Fig. (2.8.) shows that F_2 must be modulated (i.e. that the regulation of the temperature or of the steam pressure can operate) for different values of F_1, maintained constant by a regulation. This curve shows clearly that the regulations cannot run with a too weak value of F_1, which justifies afterwards the value of 1400 kg/sec. obtained from the prototype data.

Fig. (2.9.) shows that it is possible to modulate the reheater flow F_5 in the same conditions.

All the previous considerations show clearly that the choic e of the set points of the regulating system is not indifferent, but it is practically imposed by the static characteristics of the hydraulic loop.

In the following are summarized the set points determined on the computer:

Reactor flow (for one loop): F_1 = 1425 kg/sec.

By-pass flow: : F_3 = 85 kg/sec.

Primary heat exchangers flow: F_2 = 1340 kg/sec.

Benson flow : F_4 = 1150 kg/sec.

Reheaters flow: : F_5 = 190 kg/sec.

The pressure loss coefficients being imposed, these values allow to determine the pressure which is necessary to the pump and the pressure losses of the loop reported in the following table:

Head pressure: 21 kg/cm2

Pressure loss in the reactor: 16.2 kg/cm2

Pressure loss in pipes: 1.0 kg/cm2

Pressure loss in the by-pass: 3.8 kg/cm2

Pressure loss in the primary heat exchanger: 1.3 kg/cm2

Pressure loss in the heat exchanger valve: 2.1 kg/cm2

Pressure loss in the heat exchanger pipes: 0.4 kg/cm2

2.2. Stability of the secondary loop

On the secondary hydraulic loop (see Fig. 2.4.),
the steam flow FD_2 is imposed by the power demand, whereas the
input water flow FD_1 is determined by the pressure at the feed
pump and by the position of the secondary regulation valve.
At the equilibrium, the feed water flow must be equal to the
steam flow, but, for a certain frequency (of about 0,5 Hz), the
phase angle is 180° between these flows and, in these conditions,
instabilities can arise.

Fig. 2.10. gives a recording which shows how the
instabilities settle.   The recording is done in the following
conditions:

At the partial opening of the feed valve (50%),
the pressure at the pump is 86 kg/cm2, whereas the steam
pressure at the collector is 70 kg/cm2, which gives an overall
pressure loss on the loop of 16 kg/cm2.   There is no regulating
system operating on the secondary.   Under these conditions, the
loop is stable, as can be shown in the figure.   Then the feed
valve opening is stepped, which involves the pressure losses in
the loop to decrease.   At a certain moment, the oscillation
arises (it goes to a limit cycle) (the last right-hand part of
the figure has an expanded scale in time, which allows to examine
the phase relations).

We conclude that, first, sufficient pressure losses
must be introduced into the loop in order to stabilize it and,
secondly, any designed regulating system must suppress the
oscillations involved.

2.3. Heat exchanger behavior

2.3.1. Accuracy of the mathematical model

The dynamic behavior of the heat exchanger involves that one of the whole power station; the accuracy of the heat exchanger simulation on the computer is capital. We have seen that this representation is based on the quantification of the three zones of the heat exchanger. The question then arises: into how many sections must be subdivided each zone? The problem can only be carried out experimentally, by examining the asymptotic convergency of the results as function of the increase of the sections number.

Fig. (2.11.) shows how converge the steady state values of temperatures and dimensions of the heat exchanger zones as function of the number of the sections by zone. Finally, the chosen subdivision is a compromise between the accuracy and the bounds of the computer. In this case, have been used:

- 1 section for the economizer
- 4 sections for the evaporator
- 2 sections for the superheater.

The results referring to this subdivision are reported to the right-hand side of Fig. (2.11.).

2.3.2. Steady-state performances.

As for the hydraulic behavior, it is necessary to take the thermal steady-state equilibriums into account, in order to set up the set points of the regulating system, which must maintain the steam characteristics (pressure, temperature) constant at different power levels.

The power level is changed by varying the secondary flow. On the primary side, several regulating programs are

possible as a principle:

a) constant input temperature and variable flow (using a by-pass);
b) constant flow and variable input temperature (case without by-pass);
c) variable temperature and flow (using a by-pass).

For the case c), an infinity of solutions is possible. For the same power conditions, the options a), b) and c) lead to significative differences in the temperature distributions and then in the location of the heat exchanger phase changes. The search of a determined shape of temperature distribution will be able to be a criteria of choice between the solutions a), b) and c) in order to change the power level.

Figs. (2.12.) to (2.17.) give the state of the heat exchanger in various cases, for the base data of the prototype, for a steam temperature of 345°C and a steam pressure of 67 kg/cm2.

Fig. (2.12.) gives the heat exchanger subdivision in case a). It can be shown that, for the low power levels, the evaporator fills nearly all the heat exchanger, whereas the economizer and the superheater become very small. Thus, a little variation of the primary flow involves a large variation of the steam temperature, which must cause the regulating system to be instable (at 25% of the power, a variation of 2.8°C on the steam temperature involves a variation of 1 kg/sec. on the primary flow, which is to compare with 0.033°C for 1 kg/sec. at 100% of the power). This fact makes difficult the regulation at the power levels inferior to 70% ... 50%.

Fig. (2.13.) gives the variation of the flow and of the output primary temperature for the same case a), as function of the power level.

Fig. (2.14.) gives the subdivision of the heat exchanger for case b) (no by-pass): at the low power levels, the evaporator diminishes, whereas the superheater increases. Variations on the primary will have a less important influence with respect to the previous case.

Fig. (2.15.) shows the variations of the coolant input and output temperatures in case b). This figure shows that, in case of regulation without by-pass, it is not possible to hold the reactor output temperature constant as function of the power level. The set point of this temperature must vary necessarily according to Fig. (2.15.), which involves a decrease of about 8°C for a variation of the power level from 100% to 25%. It can be seen that, at the low power levels, the heat exchanger pinch-point decreases (whereas it was constant in case a)).

Examining Figs. (2.12.) and (2.14.), it appears that it is possible to find an intermediate scheme (case c)) which allows to maintain about constant the height of the heat exchanger zones (Fig.(2.16.)) (and also the temperature distributions), this by varying the primary flow and the coolant input temperature as reported in Fig. (2.17.). This solution requires the use of a by-pass, but eliminates the defect of scheme a), which we have pointed out previously; it allows to find easier the conditions for a regulating system being stable at the low powers.

Figs. (2.12.), (2.14.) and (2.16.) would deserve a careful examination by the builder of the heat exchanger, who would have to indicate what configuration gives the better opera ing conditions at part loads.

2.3.3. Transient responses of the heat exchanger

The variation of the heat exchanger transient behavior as function of the power level determines essentially the performances of the regulating system (or even determines the possibility or not to regulate).

Now, we have ssen in the previous chapter that the power can be varied by modifying either the primary flow or the primary input temperature, or both. As for the static cases, the transient behavior is very different and we will examine each one of these cases. It will be recalled that the output steam characteristics must be maintained independent of the power level.

The input variables of the heat exchanger are the temperature and the flow. The output variables which are of interest (because they must be regulated) are the steam output temperature and the steam pressure. As the steam pressure mainly depends on the characteristics of the secondary loop, the responses of the steam temperature to the input variables in step function will be of interest. Besides, these computations would allow to derive the heat exchanger transfer functions.

Fig. (2.18.) shows the response of the steam temperature as a result of a step-like variation of the input coolant temperature at 100% of the power level. (In this attempt, as in the next one, are reported the responses, either for a positive or for a negative variation in step function).

Figs. (2.19.) and (2.20.) give the same attempt for 75% and 50%, the power being varied according to case a) (by-pass, constant input coolant temperature). It can be shown that the transfer function is substantially modified in amplitude and phase; furthermore, the dissymetry of the responses as a result of the positive and negative variations in step function increases. We can conclude that the running of a control system according to scheme a) will be difficult, which has been actually pointed out on the computer. In other words, according to the regulation, it is not recommended to maintain the reactor output temperature constant when the power level of the plant is varied. It will be noted that this conclusion, based on transient considerations, strengthens the one of the previous chapter which was set up on static considerations.

Fig. (2.21.) gives the response of the output temperature as a result of a step -like variation of the input flow.

Figs. (2.22.) and (2.23.) give the same attempt at 75% and 50% of the power level, always for scheme a). The comparison of the three figures between themselves involves the same conclusions (for the response to a variation of flow in step function) which we had expressed for the response to a variation

temperature in step function: i.e., the variation of the transfer
function is such that the regulation will be always difficult to
stabilize at the low powers. Incidentally, the examination of the
six last figures shows also that an approach of stability based on
a transfer function representation (i.e. on a linearization of the
problem) cannot give sure results.

Figs. (2.24.) and (2.25.) give the response of the
steam temperature as a result of a step-like variation of the
input   coolant temperature, at 75% and 50% of the power level
and for scheme b) (constant flow, no by-pass). It is important
to note how these curves differ from those of Figs. (2.19.) and
(2.20.). Here, the amplitude and phase characteristics change
little with the power level and this scheme allows immediately to
consider a regulator being stable at any power. This regulator
might however follow the   set points as indicated in chapter 2.3.2.
(steady-state performances).

Fig. (2.26.) shows the response to a variation in
step function of the flow, for scheme c), at 75%, 50% and 25% of
the nominal power (case where the input flow and the input
temperature are both varied in order to maintain the location of
the phases water-steam constant in the heat exchanger secondary).
This gain in amplitude decreases at the low powers, which would
made stable but unefficient a regulation of the steam temperature
by regulating the primary flow. In this case, the power station
might be better regulated by simply holding the primary heat
exchanger flow as function of the operating power of the plant
(the by-pass ensuring always the regulation of the flow in the
reactor) and regulating the steam temperature by means of the
fixed output reactor temperature.

2.3.4. Internal transient variations

Independently of the study of the heat exchanger
as a control element, the mathematical model can yield information
on the transient behavior of the internal heat exchanger variables.
We will not extend ourselves over this point of view, but, for
illustrative purposes, we give the following figures;   these

attempts are less accurate than the previous ones; indeed, they have been set up by taking a quantification of two sections by cell into account (see (Fig.2.11.)); all refer to the case of the nominal power.

Fig. (2.27.) gives the variations as result of a positive step in input secondary temperature.

Fig. (2.28.) gives the responses to a positive step in input primary organic temperature.

Fig. (2.29.) gives the responses to a positive step in feed water flow.

Fig. (2.30.) gives the responses to a positive step in primary organic flow.

2.3. Conclusions

In this study of the heat exchanger transient behavior, it has been searched to set up the basis knowledge being necessary to design a regulating system. As usual, in this kind of study, the control engineer can choose between several arrangements for the control devices and points of measurement and each one of them, well studied, involves a suitable design. The study of the regulation must - above all - be founded on a complete investigation of the steady state operating at all power levels. Without this, it would be possible to choose criteria incompatible between themselves.

The simulation also yields information which can be useful to the design engineer or the builder, like the distribution of the pressures along the hydraulic loop or the repartition of the water-steam phases in the heat exchanger.

If several control designs, also suitable for the control engineer, are balanced, the features reported previously will allow to fix a choice based on technological considerations (thermal stresses, charges, etc...).

Another, more general, conclusion is that the dynamic study of a power plant similar to the one studied here must rest on an accurate mathematical heat exchanger representation both for the heat transfers and for the hydraulic behavior. For the reactor, a on-point model is sufficient.

Fig. 1-1

GO-1922
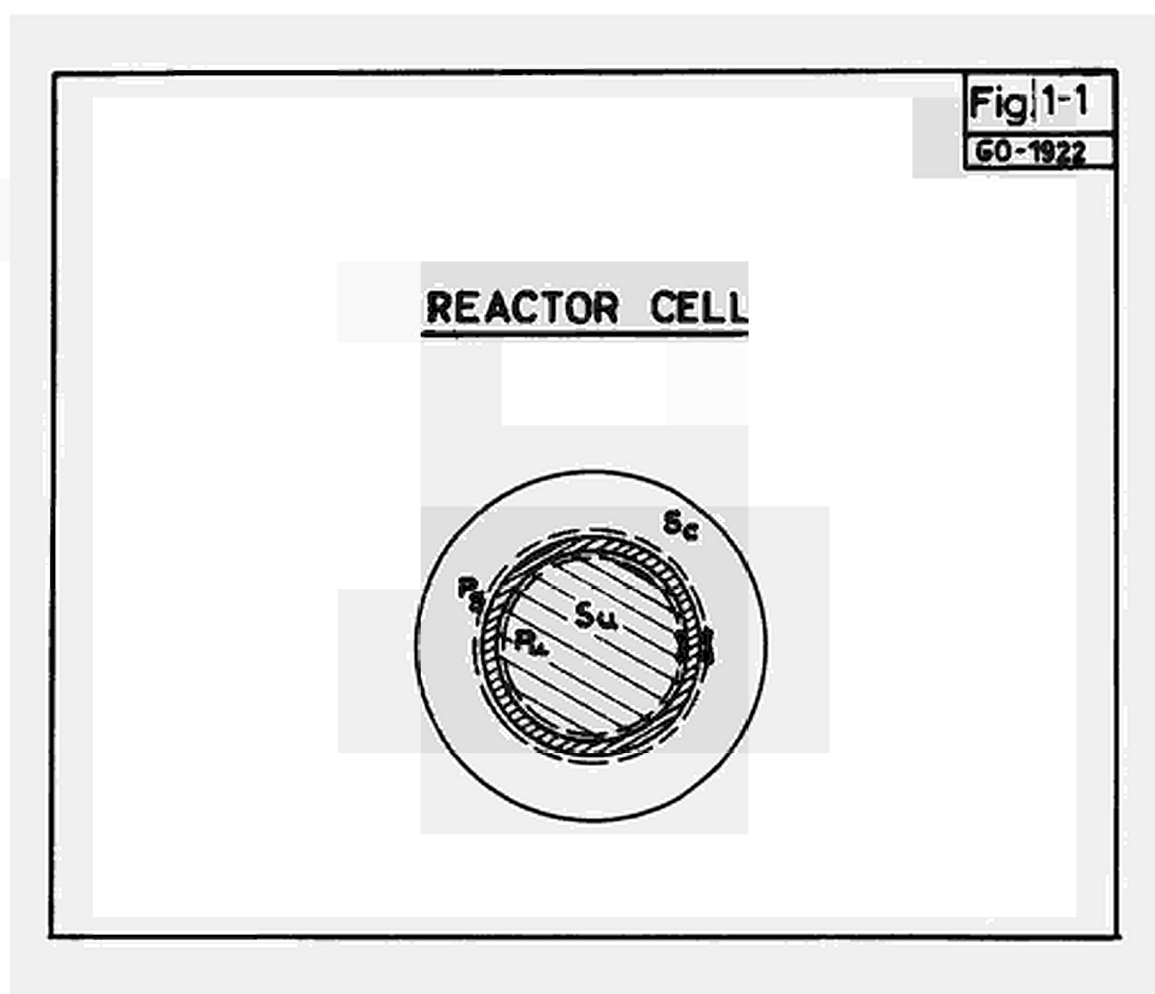
REACTOR CELL

Fig. 1-2
60 - 1804

SCHEME OF THE CELLS INTO WHICH THE
HEAT EXCHANGER HAS BEEN DIVIDED

FROM THE REACTOR
WOL kg / sec.

TOL °C

TO THE TURBINE
WREQ kg/sec.
P kg/cm²

TLVEC (3) °C

SUPER HEATER

UPPER DOME

BOILER

ECONOMIZER

TO THE REACTOR
WOL kg/sec
TOLEC (1) °C
ORGANIC SIDE
O.L.

WALL
P.A.

FROM THE RIGENERATORS
WREQ kg/sec
TF °C
SECONDARY SIDE
L.V.

WOL (kg/sec.)
TOL °C

SUPERHEATER L.O.

GO - 1806
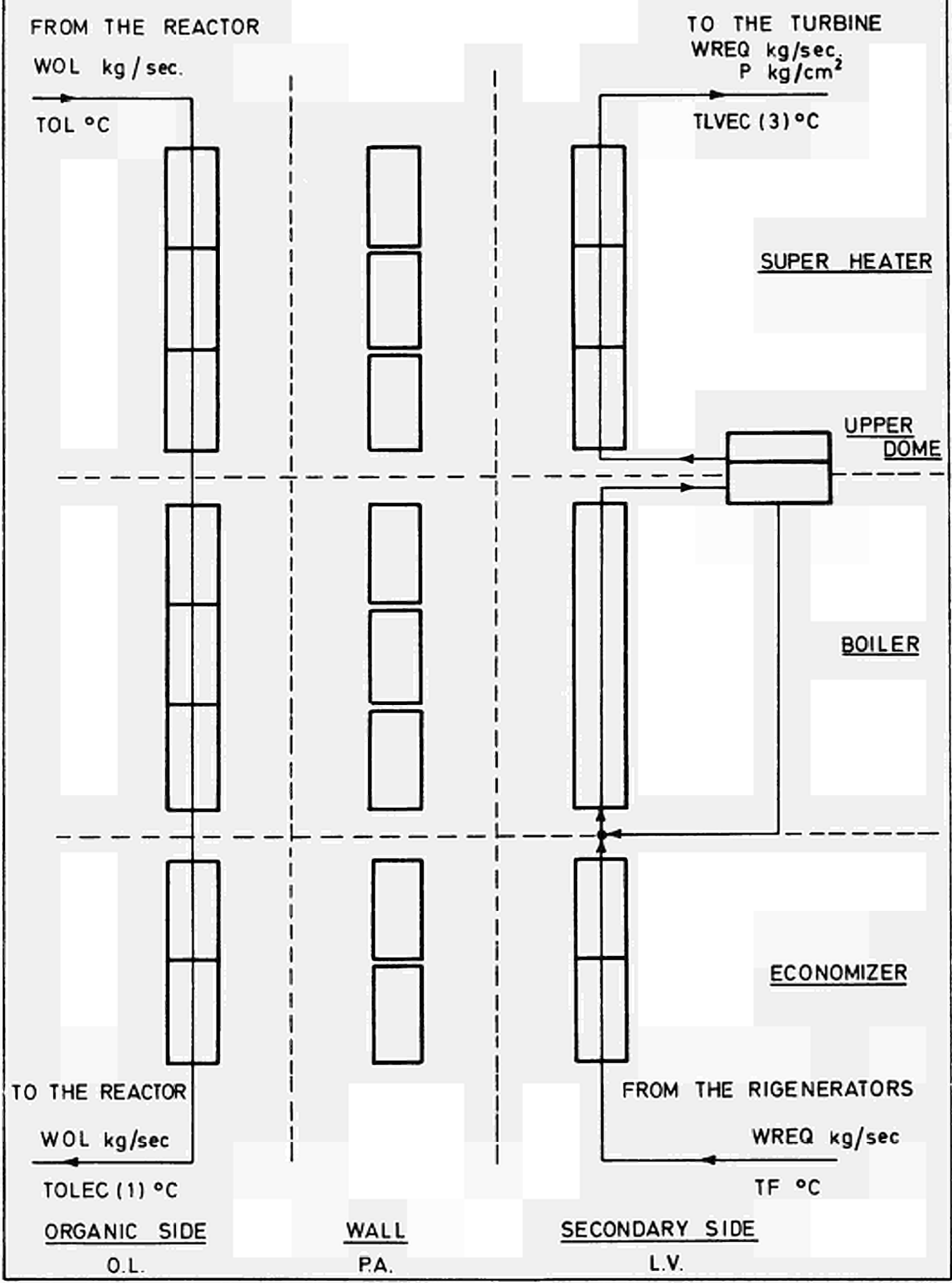
ENERGY TRANSPORTED IN
BY THE O.L. INCOMING

WOL.CLOS.TOL.

STORED ENERGY $ALOS.LSUR.CLOS.ROLOS.\dfrac{d\,TOLSU^{(3)}}{dt}$ **3** $HLOS.PLOS.LSUR.(TOLSU^{(3)}-TPASU^{(3)})$

ENERGY TRANSFERRED TO THE WALL   ③

ENERGY TRANSPORTED OUT FROM 3
INTO 2 BY O.L. $WOL.CLOS.TOLSU^{(3)}$

$ALOS.LSUR.CLOS.ROLOS.\dfrac{d\,TOLSU^{(2)}}{dt}$ **2** $HLOS.PLOS.LSUR.(TOLSU^{(2)}-TPASU^{(2)})$ ②

$WOL.CLOS.TOLSU^{(2)}$

$ALOS.LSUR.CLOS.ROLOS.\dfrac{d\,TOLSU^{(1)}}{dt}$ **1** $HLOS\ PLOS\ LSUR\ (TOLSU^{(1)}-TPASU^{(1)})$ ①
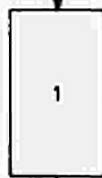
$WOL.CLOS.TOLSU^{(1)}$

TO THE BOILER

ENERGY CONSERVATION LAW

$$ALOS.LSUR.CLOS.ROLOS.\frac{d\,TOLSU^{(3)}}{dt}=WOL.CLOS.(TOL-TOLSU^{(3)})-HLOS.PLOS.LSUR.(TOLSU^{(3)}-TPASU^{(3)})$$

$$ALOS.LSUR.CLOS.ROLOS.\frac{d\,TOLSU^{(2)}}{dt}=WOL.CLOS.(TOLSU^{(3)}-TOLSU^{(2)})-HLOS.PLOS.LSUR.(TOLSU^{(2)}-TPASU^{(2)})$$

$$ALOS.LSUR.CLOS.ROLOS.\frac{d\,TOLSU^{(1)}}{dt}=WOL.CLOS.(TOLSU^{(2)}-TOLSU^{(1)})-HLOS.PLOS.LSUR.(TOLSU^{(1)}-TPASU^{(1)})$$

SYMBOLS

TOL   O.L. INLET TEMP. °C.

$TOLSU^{(i)}$ O.L. TEMP. IN THE ith CELL °C

$TPASU^{(i)}$ WALL TEMP. IN THE ith CELL °C

WOL = O.L. MASS FLOW   kg/sec

CLOS = O.L. SPECIFIC HEAT   kcal/kg

ROLOS = O.L. DENSITY kg/m^3

HLOS = HEAT TRANSFER COEFF. $kcal/m^2\,sec\,°C$

ALOS = CELL CROSS SECTION m^2

LSUR = CELL LENGHT   m

PLOS = CELL WETTED PERIMETER L.O.   m

Fig. 1-4
GO-1807

FROM THE SUPERHEATER
WOL(kg /sec.)
$TOESU^{(1)}$ °C

BOILER L.O.

ENERGY TRANSPORTED IN
BY THE O.L. COMING FROM
THE SUPERHEATER

$WOL.CLOS.TOLSU^{(1)}$

STORED ENERGY $\quad ALOB.LEVA.CLOB.ROLOB \dfrac{d\,TLOBO^{(3)}}{dt}$

3

$HLOB.PLOB.LEVA.(TOLBO^{(3)} - TPABO^{(3)})$
ENERGY TRANSFERRED TO THE WALL

③

ENERGY TRANSPORTED
FROM 3 TO 2 BY O.L.

$WOL.CLOB.TLOBO^{(3)}$

$ALOB.LEVA.CLOB.ROLOB, \dfrac{dTLOBO^{(2)}}{dt}$

2

$HLOB.PLOB.LEVA.(TOLBO^{(2)} - TPABO^{(2)})$

②

$WOL.CLOB.TLOBO^{(2)}$

$ALOB.LEVA.CLOB.ROLOB.\dfrac{dTLOBO^{(1)}}{dt}$

1

$HLOB.PLOB.LEVA.(TOLBO^{(1)} - TPABO^{(1)})$

①

$WOL.CLOB.TLOBO^{(1)}$

TO THE ECONOMIZER

ENERGY CONSERVATION LAW

$$ALOB.LEVA.CLOB.ROLOB.\dfrac{d\,TOLBO(3)}{dt} = WOL.(CLOS.TOLSU^{(1)} - CLOB.TLOBO^{(3)}) - HLOB.PLOB.LEVA.(TOLBO^{(3)} - TPABO^{(3)})$$

$$ALOB.LEVA.CLOB.ROLOB.\dfrac{d\,TOLBO(2)}{dt} = WOL.CLOB.(TLOBO^{(3)} - TLOBO^{(2)}) - HLOB.PLOB.LEVA.(TOLBO^{(2)} - TPABO^{(2)})$$

$$ALOB.LEVA.CLOB.ROLOB.\dfrac{d\,TOLBO(1)}{dt} = WOL.CLOB.(TLOBO^{(2)} - TLOBO^{(1)}) - HLOB.PLOB.LEVA.(TOLBO^{(1)} - TPABO^{(1)})$$

SYMBOLS

$TOLSU^{(1)}$ O.L. INLET TEMPERATURE ° C

$TOLBO^{(i)}$ O.L. TEMP. IN THE ith CELL°C

$TPABO^{(i)}$ WALL TEMP IN THE ith CELL°C

WOL = O.L. MASS FLOW kg /sec

CLOB = O.L. SPECIFIC HEAT kcal/kg °C

ROLOB = O.L. DENSITY kg /m³

HLOB = HEAT TRANSFERT COEFF kcal/m² sec °C

ALOB = CELL CROSS SECTION ·m²

LEVA = CELL LENGHT m

PLOB = CELL WETTED PERIMETER L.O. m

Fig. 1-5
GO - 1808

ECONOMIZER L.O.

FROM THE BOILER
WOL (kg/sec.)
TOLBO$^{(1)}$ °C

ENERGY TRANSPORTED IN
BY THE O.L. COMING
FROM THE BOILER

WOL . CLOB . TOLBO$^{(1)}$

STORED ENERGY   ALOE . LECO . CLOE . ROLOE $\dfrac{d\,TOLEC^{(2)}}{dt}$ |2| HLOE . PLOE . LECO . $(TOLEC^{(2)} - TPAEC^{(2)})$
ENERGY TRANSFERRED TO THE WALL   ②

ENERGY TRANSPORTED
FROM 2 TO 1 BY O.L.   WOL . CLOE . TOLEC$^{(2)}$

ALOE . LECO . CLOE . ROLOE . $\dfrac{d\,TOLEC^{(1)}}{dt}$ |1| HLOE . PLOE . LECO . $(TOLEC^{(1)} - TPAEC^{(2)})$ ①

WOL . CLOE . TOLEC$^{(1)}$

TO THE REACTOR

ENERGY CONSERVATION LAW

$$ALOE . LECO . CLOE . ROLOE . \frac{d\,TOLEC^{(2)}}{dt} = WOL \cdot (CLOB . TOLBO^{(1)} - CLOE . TOLEC^{(2)}) - HLOE . PLOE . LECO . (TOLEC^{(2)} - TPAEC^{(2)})$$

$$ALOE . LECO . CLOE . ROLOE . \frac{d\,TOLEC^{(1)}}{dt} = WOL . CLOE . (TOLEC^{(2)} - TOLEC^{(1)}) - HLOE . PLOE . LECO . (TOLEC^{(1)} - TPAEC^{(1)})$$

SYMBOLS

TOLBO$^{(1)}$ O.L. INLET TEMP °C

TOLEC$^{(i)}$ O.L. TEMP. IN THE i$^{\underline{th}}$ CELL

TPAEC$^{(i)}$ WALL TEMP. IN THE i$^{\underline{th}}$ CELL

WOL = O.L. MASS FLOW kg / sec

CLOE = O.L. SPECIFIC HEAT kcal / kg °C

ROLOE = O.L. DENSITY kg / m^3

HLOE = HEAT TRANSFER COEFF kcal / m^2 sec °C

ALOE = CELL CROSS SECTION m^2

LECO = CELL LENGHT m

PLOE = CELL WETTED PERIMETER L.O. m

Fig. 1-6
GO-1809

O.L.

WALL

$LSUR.APS.ROPS.CPS.\dfrac{dTPASU^{(3)}}{dt}$

SUPERHEATER

3   $HLOS.PLOS.LSUR.(TOLSU^{(3)}-TPASU^{(3)})$ ③ $HLVS.PLVS.LSUR.(TPASU^{(3)}-TLVSU^{(3)})$ 3   L.V

$LSUR.APS.ROPS.CPS.\dfrac{dTPASU^{(2)}}{dt}$

2   $HLOS.PLOS.LSUR.(TOLSU^{(2)}-TPASU^{(2)})$ ② $HLVS.PLVS.LSUR.(TPASU^{(2)}-TLVSU^{(2)})$ 2

$LSUR.APS\;ROPS\;CPS\dfrac{d\,TPASU^{(2)}}{dt}$

1   $HLOS.PLOS.LSUR.(TOLSU^{(1)}-TPASU^{(1)})$ ① $HLVS.PLVS.LSUR.(TPASU^{(1)}-TLVSU^{(1)})$ 1

BOILER

$LEVA.APB.ROPB.CPB.\dfrac{dTPABO^{(3)}}{dt}$

3   $HLOB.PLOB.LEVA.(TOLBO^{(3)}-TPABO^{(3)})$ ③ $HLVB.PLVB.LEVA(TPABO^{(3)}-TSAT)$

$LEVA.APB.ROPB.CPB.\dfrac{d\,TPABO^{(2)}}{dt}$

2   $HLOB.PLOB.LEVA.(TOLBO^{(2)}-TPABO^{(2)})$ ② $HLVB.PLVB.LEVA.(TPABO^{(2)}-TSAT)$

$LEVA.APB.ROPB.CPB.\dfrac{d\,TPABO^{(1)}}{dt}$

1   $HLOB.PLOB.LEVA.(TOLBO^{(1)}-TPABO^{(1)})$ ① $HLVB.PLVB.LEVA.(TPABO^{(1)}-TSAT)$

$TSAT(p)$

ECONOMIZER

$LECO.APE.ROPE.CPE.\dfrac{dTPAEC^{(2)}}{dt}$

2   $HLOE.PLOE.LECO.(TOLEC^{(2)}-TPAEC^{(2)})$ ② $HLVE.PLVE.LECO(TPAEC^{(2)}-TLVEC^{(2)})$ 2

$LECO.APE.ROPE.CPE.\dfrac{d\,TPAEC^{(1)}}{dt}$

1   $HLOE.PLOE.LECO.(TOLEC^{(2)}-TPAEC^{(2)})$ ① $HLVE.PLVE.LECO.(TPAEC^{(1)}-TPAEC^{(1)})$ 1

WREO, TF

Fig. 1-7

GO-1810

SUPERHEATER

$$APS \cdot ROPS \cdot LPS \cdot \frac{d\,TPASU(i)}{dt} = HLOS \cdot PLOS \cdot (TOLSU(i) - TPASU(i)) - HLVS \cdot PLVS \cdot (TPASU(i) - TLVSU(i))$$

$$i = 1,2,3$$

BOILER

$$APB \cdot ROPB \cdot CPB \cdot \frac{d\,TPABO(i)}{dt} = HLOB \cdot PLOB \cdot (TOLBO(i) - TPABO(i)) - HLVB \cdot PLVB \cdot (TPABO(i) - TSAT(p))$$

$$i = 1,2,3$$

ECONOMIZER

$$APE \cdot ROPE \cdot CPE \cdot \frac{d\,TPAEC(i)}{dt} = HLOE \cdot PLOE \cdot (TOLEC(i) - TPAEC(i)) - HLVE \cdot PLVE \cdot (TPAEC(i) - TLVEC(i))$$

$$i = 1,2$$

SYMBOLS

$TPASU(i)$ = WALL. TEMP IN THE ith CELL OF THE SUPERHEATER °C

$TPABO(i)$ = WALL TEMP. IN THE ith CELL OF THE BOILER °C

$TPAEC(i)$ = WALL TEMP. IN THE ith CELL OF THE ECONOMIZER °C

$TLVSU(i)$ = STEAM TEMP IN THE ith CELL OF THE SUPERHEATER °C

$TSAT(p)$ = SATURATION TEMPERATURE AT PRESSURE P °C

$TLVEC(i)$ = WATER TEMP. IN THE ith CELL OF THE ECONOMIZER °C

$TOLSU(i)$ = O.L. TEMP. IN THE ith CELL OF THE SUPERHEATER °C

$TOLBO(i)$ = O.L. TEMP. IN THE ith CELL OF THE BOILER °C

$TOLEC(i)$ = O.L. TEMP. IN THE ith CELL OF THE ECONOMIZER °C

APS = WALL CROSS SECTION IN THE SUPERHEATER   ROPS = ROPB = ROPE = WALL DENSITY kg/m^3

APB = WALL CROSS SECTION IN THE BOILER

APE = WALL CROSS SECTION IN THE ECONOMIZER   CPS = CPB = CPE = WALL SPECIFIC HEAT $\frac{KCAL}{kg\,°C}$

PLOS = WETTED PERIMETER IN THE SUPERHEATER , PRIMARY SIDE m

PLVS = WETTED PERIMETER IN THE SUPERHEATER , SECONDARY SIDE m

PLOB = WETTED PERIMETER IN THE BOILER , PRIMARY SIDE m

PLVB = WETTED PERIMETER IN THE BOILER , SECONDARY SIDE m

PLOE = WETTED PERIMETER IN THE ECONOMIZER , PRIMARY SIDE m

PLVE = WETTED PERIMETER IN THE ECONOMIZER , SECONDARY SIDE m

HLOS = HEAT TRANSF. COEFF BETWEEN THE O.L. AND THE WALL IN THE SUPERHEATER $KCAL/m^2 sec \,°C$

HLVS = " " " " THE WALL AND THE SECONDARY IN THE SUPERHEATER   "

HLOB = " " " " THE O.L. AND THE WALL IN THE BOILER   "

HLVB = " " " " THE WALL AND THE SECONDARY IN THE BOILER   "

HLOE = " " " " THE O.L. AND THE WALL IN THE ECONOMIZER   "

HLVE = " " " " THE WALL AND THE SECONDARY IN THE ECONOMIZER   "

Fig. 1-8

ECONOMIZER L.V.

60 - 1812

TO THE BOILER

WALL

$WREQ \cdot CLVE \cdot TLVEC^{(2)}$

STORED ENERGY

② $HLVE \cdot PLVE \cdot LEVA \cdot (TPAEC^{(2)} - TLVEC^{(2)})$

HEAT TRANSFERRED FROM THE WALL

2   $ALVE \cdot LEVA \cdot CLVE \cdot ROLVE \cdot \dfrac{dTLVEC^{(2)}}{dt}$

$WREQ \cdot CLVE \cdot TLVEC^{(1)}$

ENERGY TRANSPORTED
FROM 1 TO 2 BY SECONDARY
FLUID

① $HLVE \cdot PLVE \cdot LEVA (TPAEC^{(1)} - TLVEC^{(1)})$

1   $ALVE \cdot LEVA \cdot CLVE \cdot ROLVE \cdot \dfrac{dTLVEC^{(1)}}{dt}$

$WREQ \cdot CLVE \cdot TF$

$\dfrac{WREQ}{TF}$ FROM THE RIGENERATORS
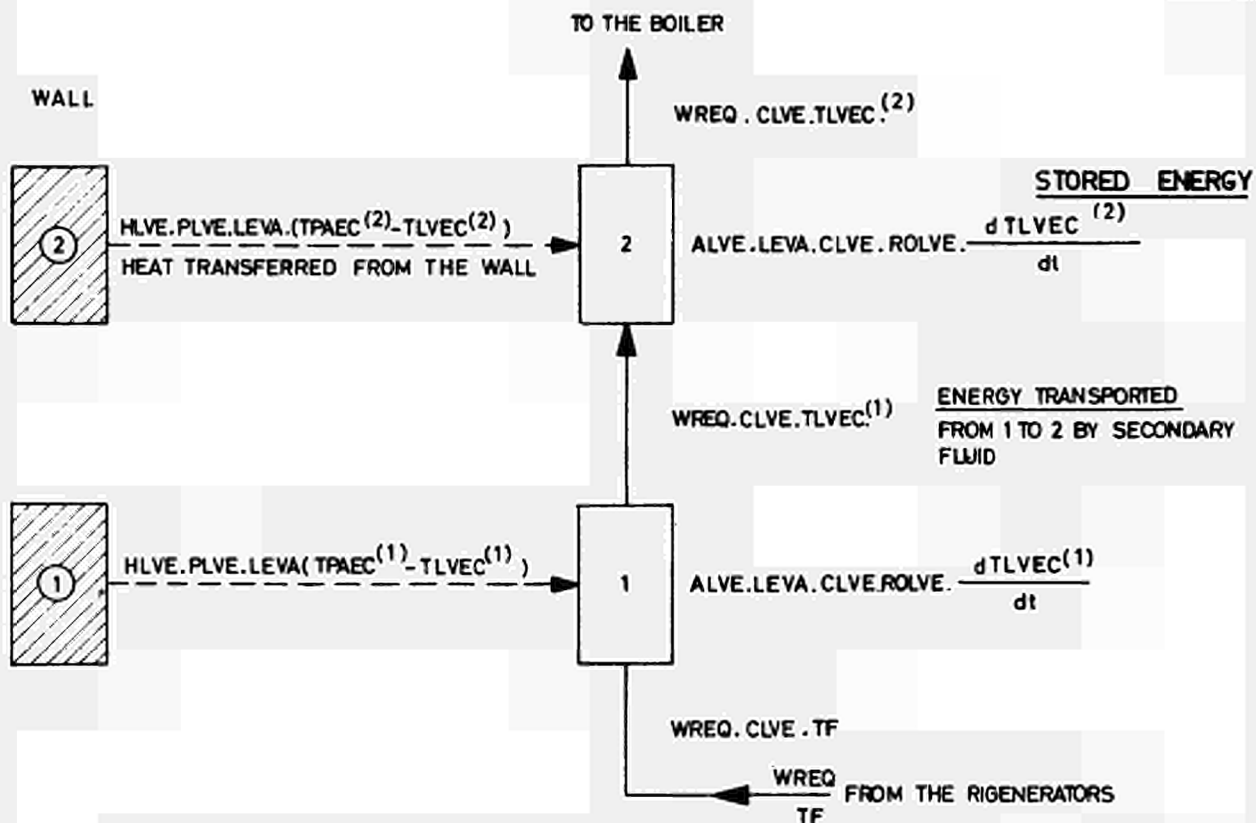
ENERGY CONSERVATION LAW

$$ALVE \cdot LEVA \cdot CLVE \cdot ROLVE \cdot \frac{dTLVEC^{(2)}}{dt} = WREQ \cdot CLVE \cdot (TLVEC^{(1)} - TLVEC^{(2)}) + HLVE \cdot PLVE \cdot LEVA \cdot (TPAEC^{(2)} - TPAEC^{(1)})$$

$$ALVE \cdot LEVA \cdot CLVE \cdot ROLVE \cdot \frac{dTLVEC^{(1)}}{dt} = WREQ \cdot CLVE \cdot (TF - TLVEC^{(1)}) + HLVE \cdot PLVE \cdot LEVA \cdot (TPAEC^{(2)} - TPAEC^{(1)})$$

SYMBOLS

TF   FEED WATER TEMPERATURE °C

$TLVEC^{(i)}$ WATER TEMPERATURE OF THE ith CELL

$TPAEC^{(i)}$ WALL TEMPERATURE OF THE ith CELL

WREQ   WATER MASS FLOW RATE kg/sec.

CLVE =   kcal/kg°C   WATER SPECIFIC HEAT

ROLVE = kg/m^3 WATER DENSITY

HLVE = $kcal/m^2 sec °C$ HEAT TRANSF. COEFF.

ALVE = m^2 CELL CROSS SECTION

LEVA =   m CELL LENGHT

PLVE =   m CELL WETTED PERIMETER

PRIMARY AND SECONDARY FLOW PATHS IN THE BOILER

Fig. 1-9
GO-1813

Fig. 1-10
GO – 1815

X.WOUT STEAM TO THE UPPER DOME

BOILER L.V.

$(1-X) \cdot$ WOUT WATER TO THE DOWNCOMER

WOUT . IM OUTCOMING ENERGY

③ HLVB.PLVB.LEVA.$(\text{TPABO}^{(3)} - \text{TSAT})$

② HLVB.PLVB.LEVA.$(\text{TPABO}^{(2)} - \text{TSAT})$

① HLVB PLVB LEVA $(\text{TPABO}^{(1)} - \text{TSAT})$

TSAT, X, P, ρ, WR + WREQ, IM

$\text{AR} \cdot \text{LR} \cdot \dfrac{d}{dt}(\rho \cdot \text{IM})$ STORED ENERGY

WR . ILIQ + WREQ . CLVE . $\text{TLVEC}^{(2)}$ INCOMING ENERGY

WR (kg/sec.) FROM THE DOWNCOMER

WREQ (kg/sec.) FROM THE ECONOMIZER

CONSERVATION LAWS

MASS $\text{WOUT} = \text{WR} + \text{WREQ} - \text{AR.LR} \dfrac{d\rho}{dt}$

ENERGY $\text{AL.LR} \cdot \dfrac{d}{dt}(\rho \cdot \text{IM}) = \text{WR . ILIQ} + \text{WREQ . CLVE . TLVEC}^{(2)} - \text{WOUT . IM} + Q$

$Q = \text{HLVEB . PLVEB.LEVA.}(\text{TPABO}^{(3)} + \text{TPABO}^{(2)} + \text{TPABO}^{(1)} - 3.\text{TSAT})$

SYMBOLS

WR = DOWNCOMER MASS FLOW RATE (kg/sec.)

WREQ = ECONOMIZER MASS FLOW RATE (kg/sec.)

WOUT = MASS FLOW RATE FROM THE BOILER

ILIQ = SATURATED LIQUID HEAT CONTENT (kcal/kg.)

IM = RISER HEAT CONTENT (kcal/kg.)

ρ = RISER MEAN DENSITY (kg/m^3)

X = RISER MEAN QUALITY (kgsteam/kg.)

AR = RISER CROSS SECTION m^2

LR = 3.LEVA = RISER LENGHT m

PLVB = RISER WETTED PERIMÈTER m

VS FUNCTION

True values
Fitting curve

AVS = 0.069968
BVS = 0.60926.10³
Max error = 2.045 %
At P = 70 kg/cm²

Fig. 1-11

CLAT FUNCTION

True values
Fitting curve

ALAT = 472.701
BLAT = -1.59255
Max error = 0.1338 %
At P = 50 kg/cm²

Fig. 1-12

ILIQ FUNCTION

True values

Fitting curve

AIL = 217.718

BIL = 1.33676

Max error = 0.1664 %

At X = 50 kg/cm²

Fig. 1-13

60 - 1818

Fig.1-14
GO-1819

UPPER DOME

P, RO, I

→ TO THE SUPERHEATER

WREQ
I

STORED MASS $V \cdot dRO/dt$

STORED ENERGY $V \cdot d(RO \cdot I)/dt$

STATE EQ. $I = AI + BIPRO \cdot (P/RO)$

FROM THE RISER   WC

ILIQ   FREE LEVEL

$X \cdot (WR + WREQ)$

ISAT   TO THE DOWNCOMER

MASS CONSERVATION LAW

$$V \cdot \frac{dRO}{dt} = X \cdot (WR + WREQ) - WREQ - WC$$

ENERGY CONSERVATION LAW

$$V \cdot \frac{d(RO \cdot I)}{dt} = X \cdot (WR + WREQ) \cdot ISAT - WREQ \cdot I - WC \cdot ILIQ$$

STATE EQUATION

$$I = AI + BIPRO \cdot (P/RO)$$

CONDENSATION LAW

$$WC = \begin{cases} K \cdot (RO - ROSAT) & FOR \quad RO > ROSAT \\ 0 & FOR \quad RO \leqslant ROSAT \end{cases}$$

SYMBOLS

$V = 1\ m^3$ UPPER DOME VOLUME

$P\,(kg/cm^2)$ UPPER DOME PRESSURE

$RO\,(kg/m^3)$ DENSITY OF THE STEAM IN THE UPPER DOME

$ROSAT\,(kg/m^3)$ DENSITY OF SATURATED STEAM AT P

$I\,(KCAL/kg)$ ENTHALPY OF THE STEAM IN THE UPPER DOME

$ISAT\,(KCAL/kg)$ ENTHALPY OF SATURATED STEAM AT P

$ILIQ\,(KCAL/kg)$ ENTHALPY OF SATURATED WATER AT P

$WC\,(kg/sec)$ CONDENSATION MASS FLOW RATE

$AI = 460.456$

$BIPRO = 103.25$

STEAM ENTHALPY V.S. PRESSURE AT CONSTANT DENSITY

I - KCAL/KG

Ro = 25 kg/m³
Ro = 30
Ro = 35
Ro = 40
Ro = 45

Saturation curve

True values
AI + BIPRO·($\frac{P}{RO}$)

P (kg/cm²)

GO·1820

Fig. 1-15

ISAT FUNCTION

True values
Fitting curve

AISAT = 681.472
BISAT = 0.272078

Max error = 0.02522 %
At P = 50 kg/cm²

Fig. 1-16

ROSAT FUNCTION

True values
Fitting curve

AROS = _2.68174
BROS = 0.548355

Max error = 0.2613 %
At P = 50 kg/cm²

Fig. 1-17

Fig. 1-18
GO - 1824

WALL   **SUPERHEATER L.V.**
TO THE TURBINE

$WREQ \cdot H(3)$

③	$HLVS \cdot PLVS \cdot LSUR \cdot (TPASU(3) - TLVSU(3))$ →	**3**

$ALVS \cdot LSUR \cdot RO(3) \cdot \dfrac{dH(3)}{dt}$ **STORED ENERGY**

$P,\ TLVSU(3)$

$WREQ \cdot H(2)$

②	$HLVS \cdot PLVS \cdot LSUR \cdot (TPASU(2) - TLVSU(2))$ →	**2**

$ALVS \cdot LSUR \cdot RO(2) \cdot \dfrac{dH(2)}{dt}$

$P,\ TLVSU(2)$

$WREQ \cdot H(1)$

①	$HLVS \cdot PLVS \cdot LSUR \cdot (TPASU(1) - TLVS(1))$ →	**1**

$ALVS \cdot LSUR \cdot RO(1) \cdot \dfrac{dH(1)}{dt}$

$WREQ \cdot i$

ENERGY CONSERVATION LAW

$$ALVS \cdot LSUR \cdot RO(1) \cdot \frac{dH(1)}{dt} = WREQ \cdot (i - H(1)) + HLVS \cdot PLVS \cdot LSUR \cdot (TPASU(1) - TLVSU(1))$$

$$ALVS \cdot LSUR \cdot RO(2) \cdot \frac{dH(2)}{dt} = WREQ \cdot (H(1) - H(2)) + HLVS \cdot PLVS \cdot LSUR \cdot (TPASU(2) - TLVSU(2))$$

$$ALVS \cdot LSUR \cdot RO(3) \cdot \frac{dH(3)}{dt} = WREQ \cdot (H(2) - H(3)) + HLVS \cdot PLVS \cdot LSUR \cdot (TPASU(3) - TLVSU(3))$$

STEAM TEMPERATURE : $TLVSU(i) = 1.3333\ H(I)\ (kcal/kg) + 1.0937 \cdot P(kg/cm^2) - 686.64$

SYMBOLS

$TPASU(i)$	WALL TEMP. IN THE ith CALL	°C
$TLVSU(i)$	STEAM TEMP. IN THE ith CALL	°C
$H(i)$	STEAM ENTHALPY IN THE ith CALL	KCAL/kg.
i	ENTHALPY OF THE STEAM IN THE UPPER DOME	KCAL/kg
P	SYSTEM PRESSURE	kg/cm^2
$RO(1)$ =	STEAM DENSITY IN CELL 1	kg/m^3
$RO(2)$ =	STEAM DENSITY IN CELL 2	kg/m^3
$RO(3)$ =	STEAM DENSITY IN CELL 3	kg/m^3
$ALVS$ =	CELL CROSS SECTION	m^2
$LSUR$ =	CELL LENGHT	m
$PLVS$ =	CELL WETTED PERIMETER	m
$HLVS$ =	HEAT TRANSF. COEFF.	$KCAL/m^2 sec\ °C$

Fig. 1-19
GO·1825

STEAM TEMPERATURE VS DENSITY AT DIFFERENT PRESSURES
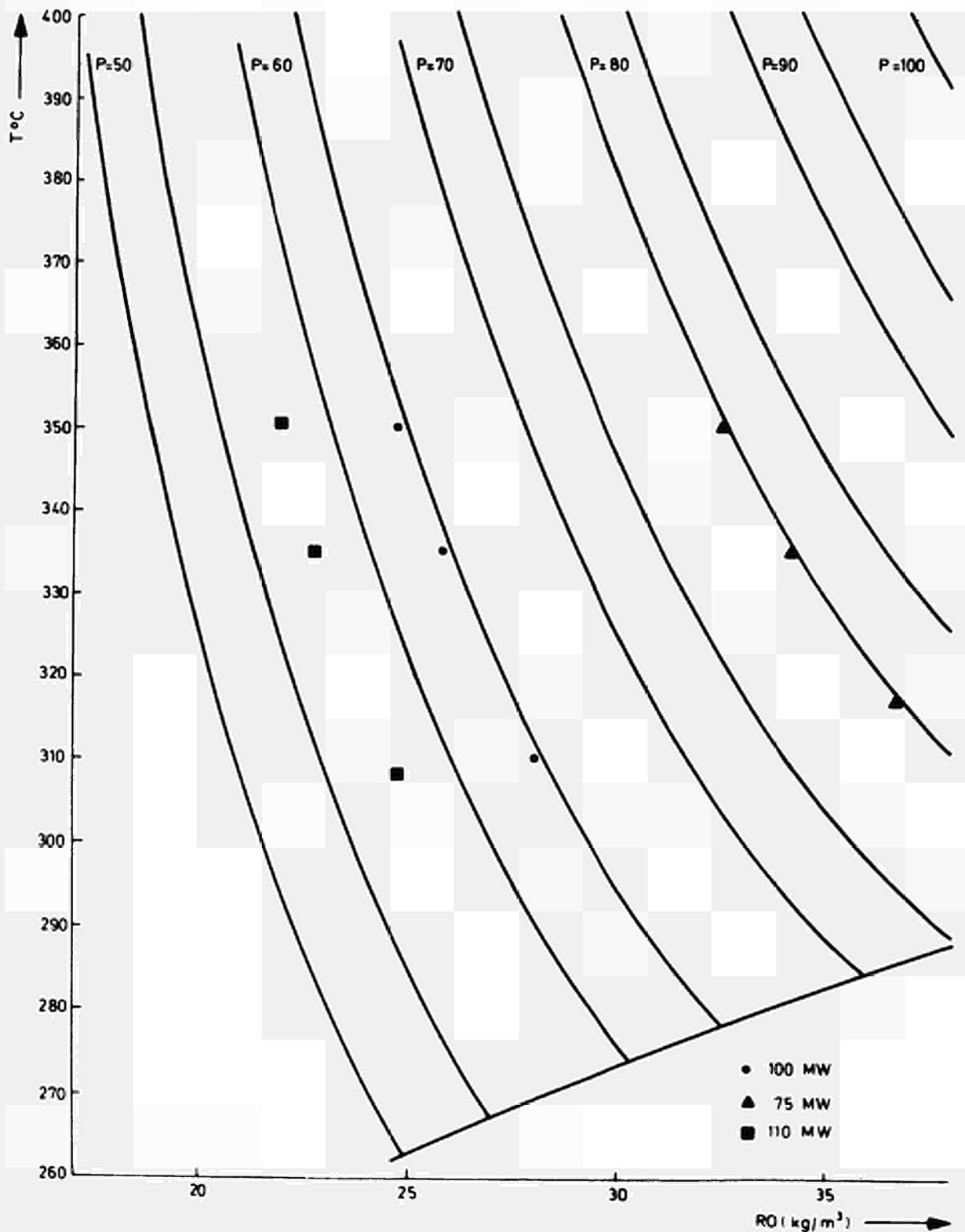
STEAM TEMP. VS. ENTHALPY AT DIFFERENT PRESSURES. ----- T = 1.3333 i + 1.0937 P - 686.64

Fig. 1-20
60-1826

Fig. 1.21
GO 1852

Fig. a

Regulation programme — Power — Power demand

Variable reference

Regulator — ε — Σ — Act. error

$\rho_{contr.}$

Reactor — n — T_{av} — Σ

Ion chamber

Thermocouple

Heat exch. — Sup. — Boil. — Eco.

Manometer

T_S — Throttle

p

Turbine

Thermocouple

Fig. b

ε

$R_4 \int \varepsilon \, dt$ — Integrator

R_5 — Proportional gain — Damping term

Σ

POSITION SERVO

$\dfrac{1}{1+\tau s}$ — Inert — Inertia and speed limitation

Non linearities

$\rho_{Control}$ (Rod position)

Fig. c

ε

R_4 — Proportional gain

$s\,R_5$ — Damping term — Derivator

Σ

RATE SERVO

$\dfrac{1}{s(1+\tau s)}$ — Inert — Inertia and speed limitations

Non linearities

$\rho_{Control}$

STATIC PROGRAMME OF THE 250 MW POWER PLANT (VERSION 1)

Fig 1·22

STATIC PROGRAMMES 1,2,3.

Fig 1·23
GO 1853

$\beta_c = 0.5$ AND $1.5°C/(W/cm^2)$ STABILITY ORGEL 250 MWe.
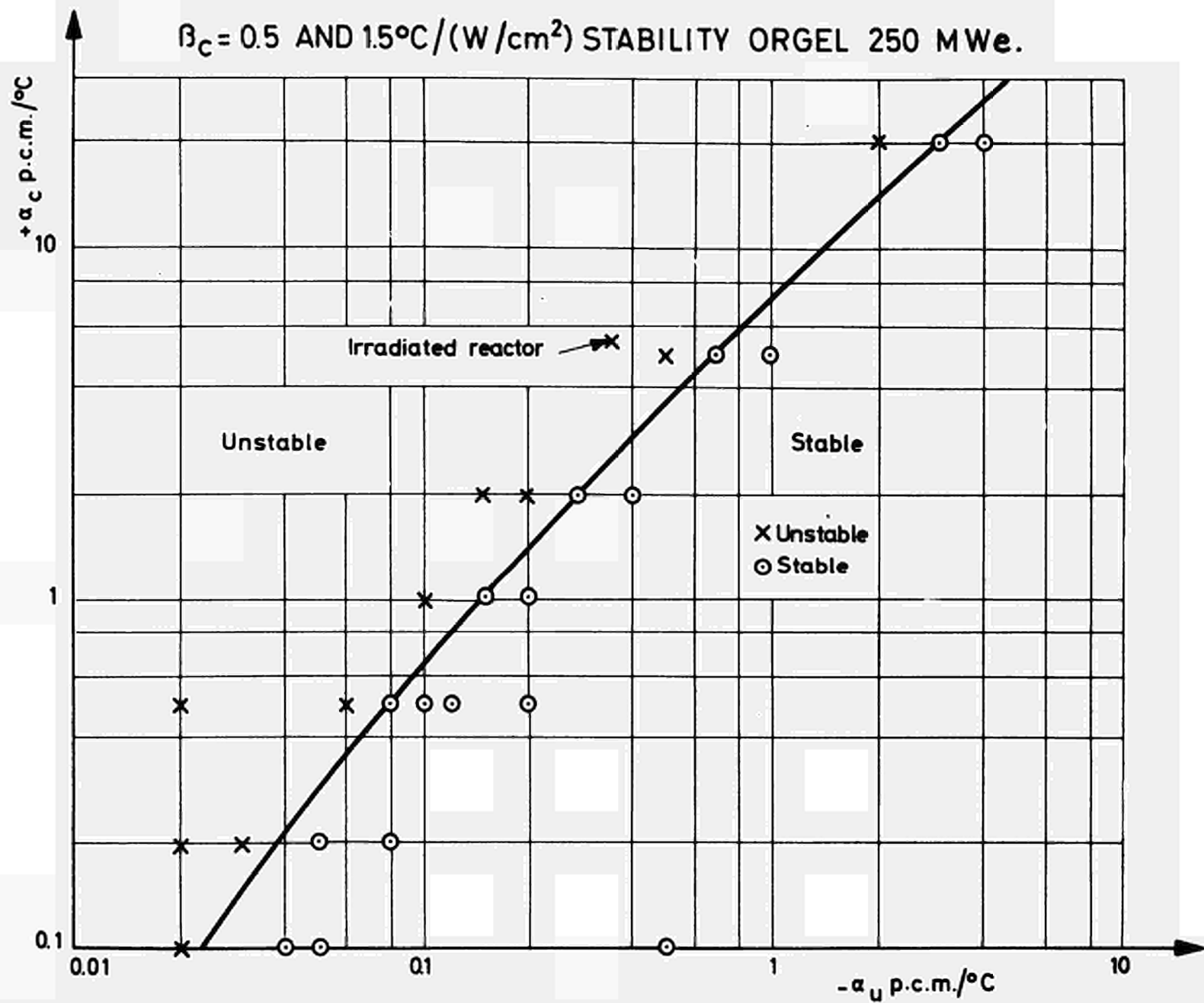
Fig.1·24
GO 1815

STABILITY DOMAIN OF THE CONTROL MECHANISM

Fig.1-25
GO.1818

107

RESPONSE TO A STEP OF 50 P.C.M.
BAR SPEED LIMITED TO 10 P.C.M./sec.

Fig. 1-26
GO-1819

RESPONSE TO A STEP OF 50 P.C.M. WITHOUT SPEED LIMITATION

$R_4 = 10^{-2}$ $R_5 = 2.5 \cdot 10^{-2}$
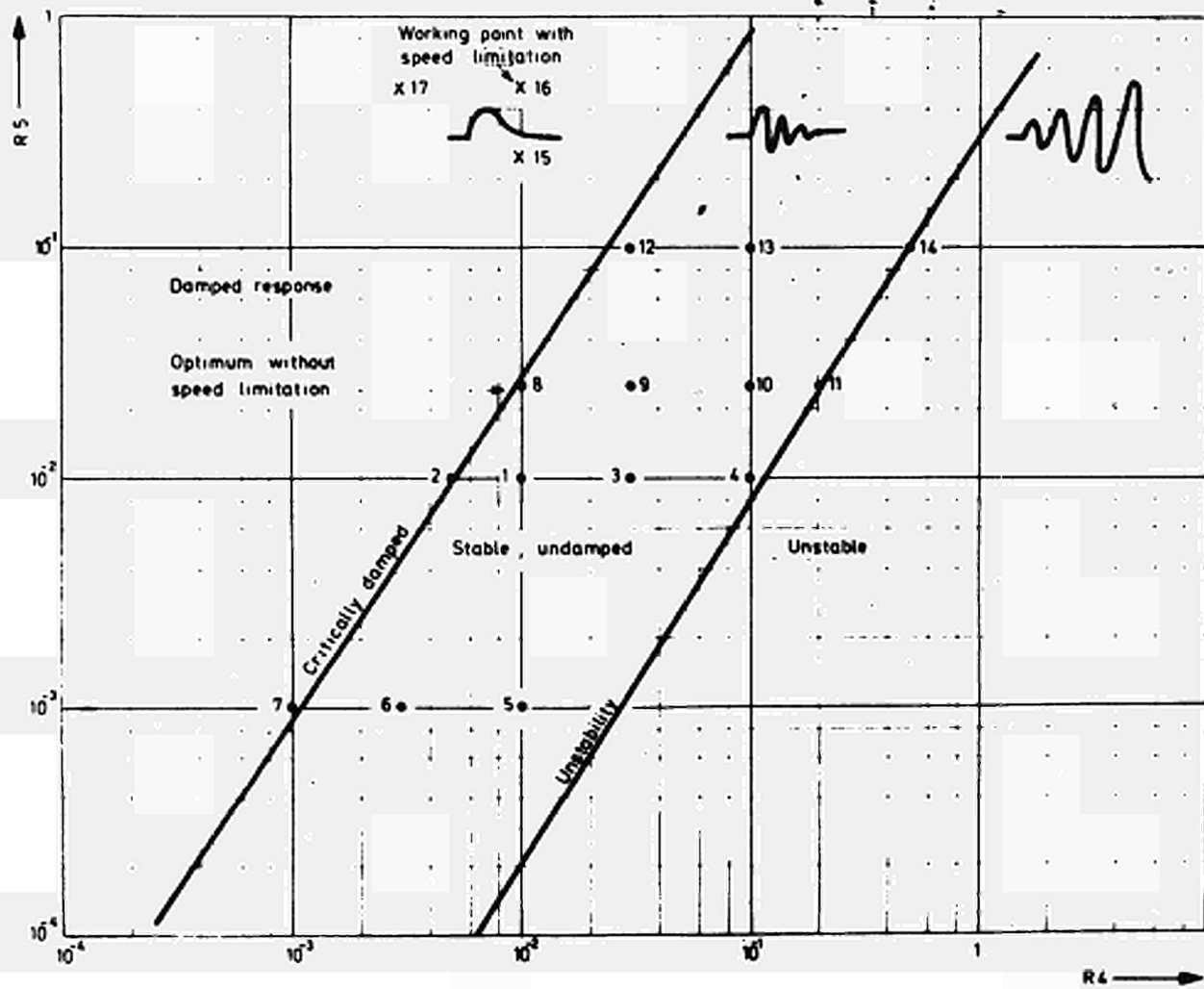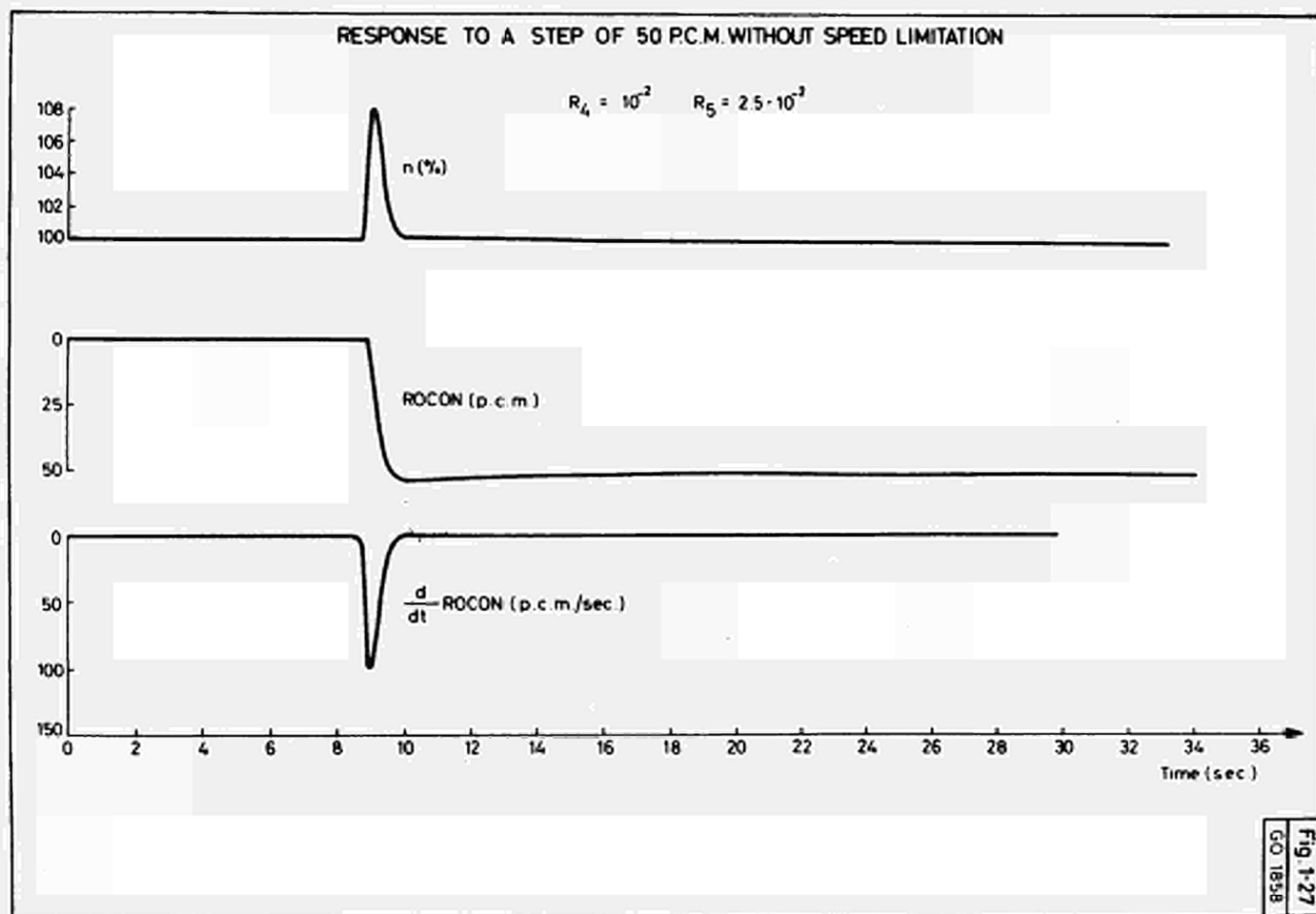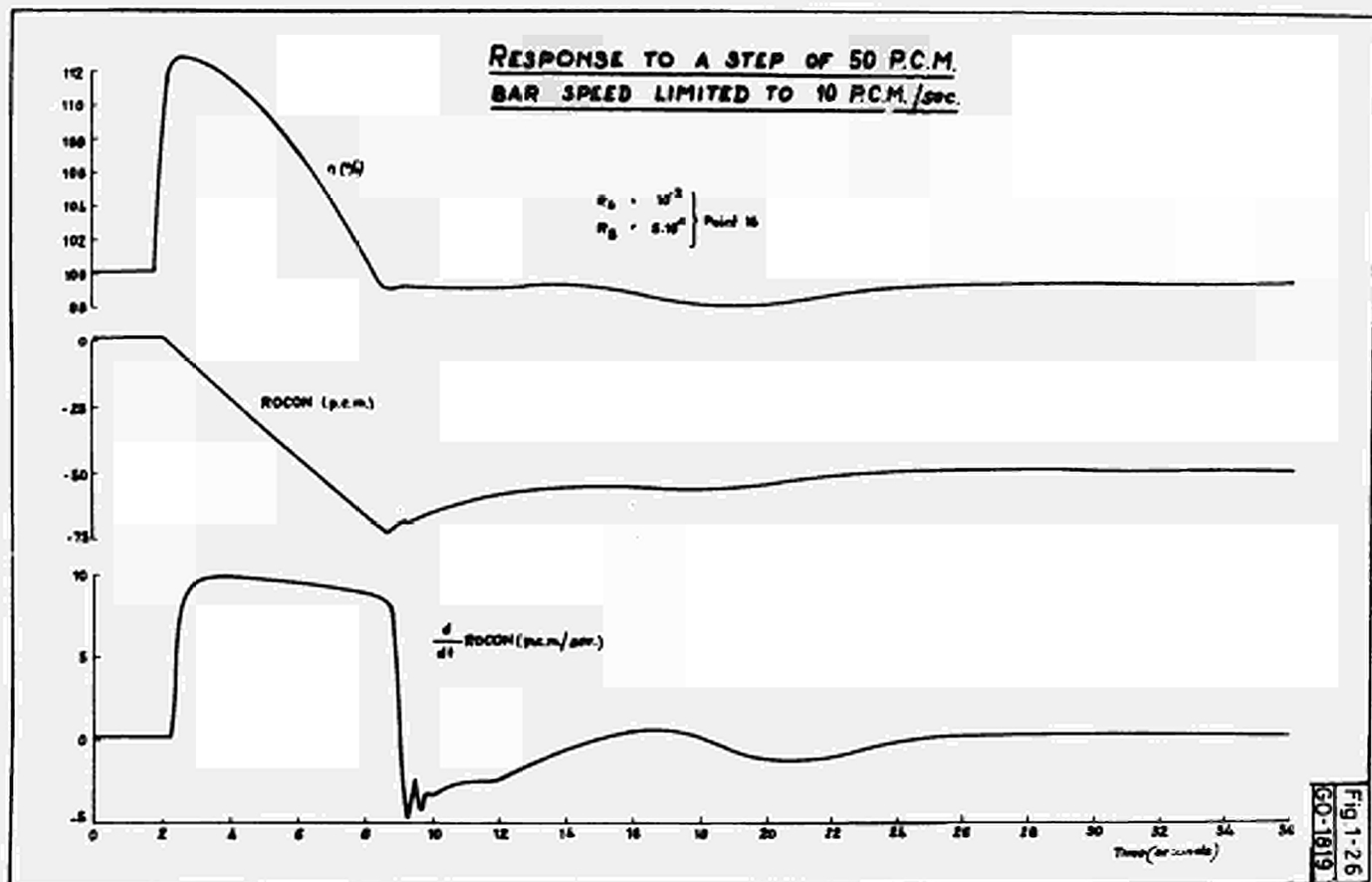
Fig. 1-27
GO-1858

Fig.1-28
GO-1820

LIMITS OF EFFICIENCY OF THE SYSTEM CONTROL

Rod reactivity span : +200 p.c.m. , -300 p.c.m.

Maximum rod speed : 15 cm./sec.

Time constant of rods : 1 sec.

1. 100 p.c.m. step disturbance
2. 50 p.c.m. step disturbance
3. 10 °C step disturbance
4. 5 °C step disturbance

Uncontrollable

Controllable

Irradiated reactor

Temperature stability limit

Stable

α_c p.c.m./°C

$-\alpha_u$ p.c.m./°C
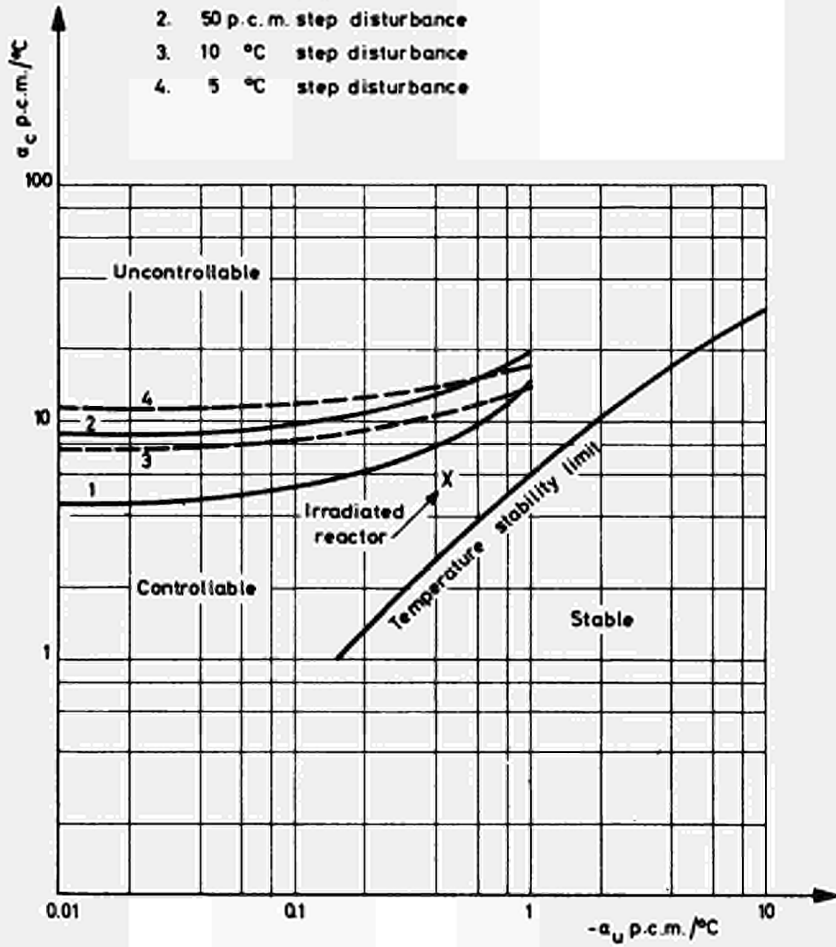
Fig.1-29
GO-1859

CONTROL AND REGULATION RODS

The end-of-run B commands the release in the core of the second set of four rods.

Nominal position

Working range

Total antireactivity of 4 rods

p.c.m.

insertion into the core

(m)

111

Power 100% ⎣⎯⎯ 173.51 MW
P   =   61.69 kg/cm²
TSAT = 275.35 °C
R   =   13.84
x   =   Wall temp.

Fig.1-30
GO-1860

Power 75% ⎣⎯⎯ 130.855 MW
P   =   78.38 kg/cm²
TSAT = 290.91 °C
R   =   15.35
x   =   Wall temp.
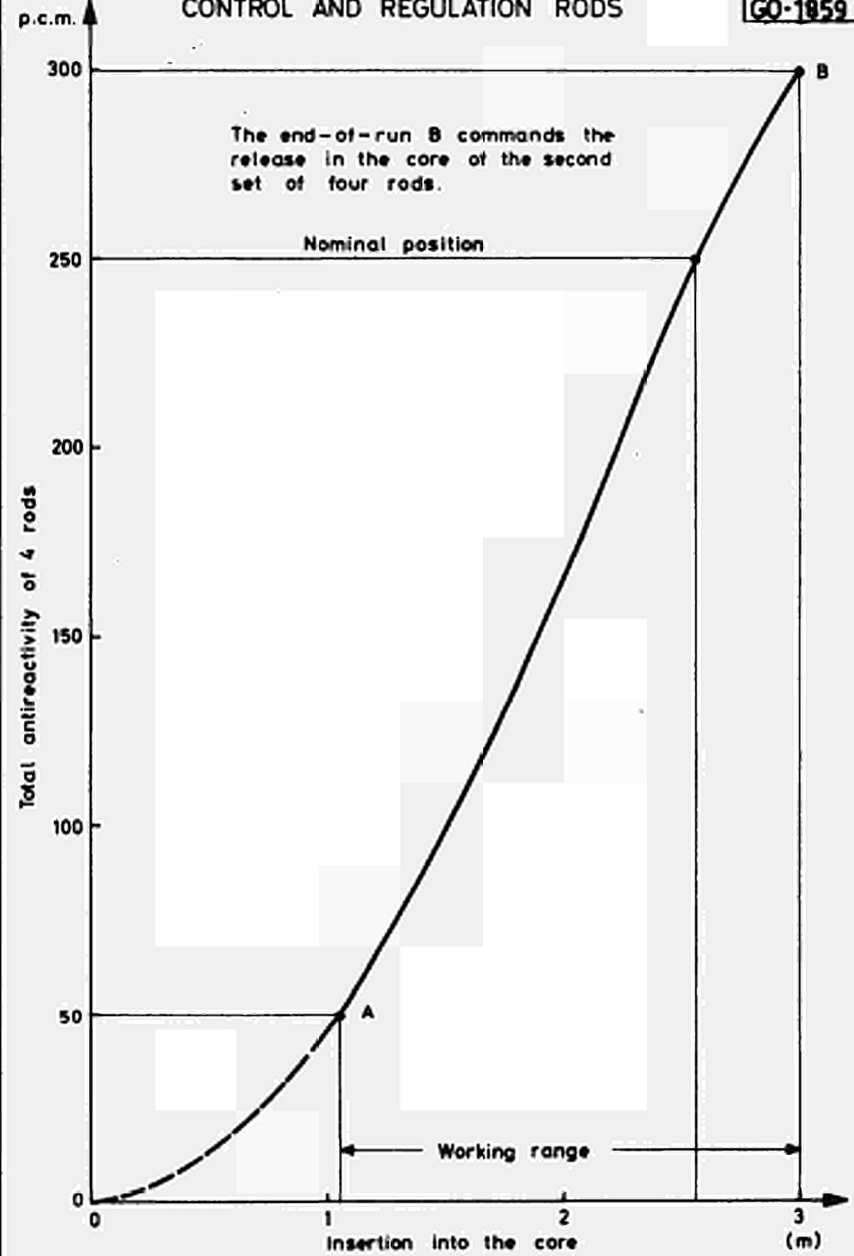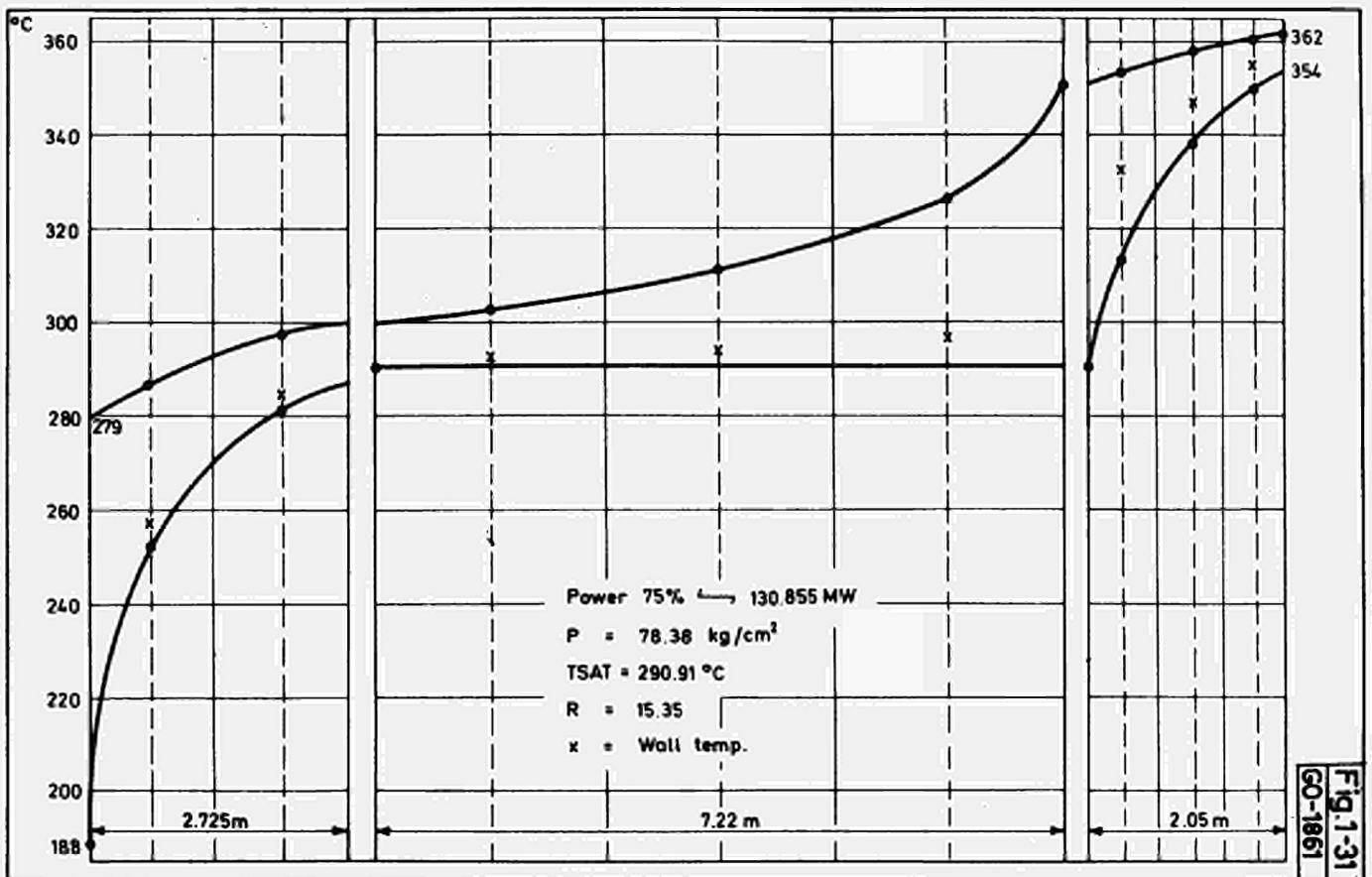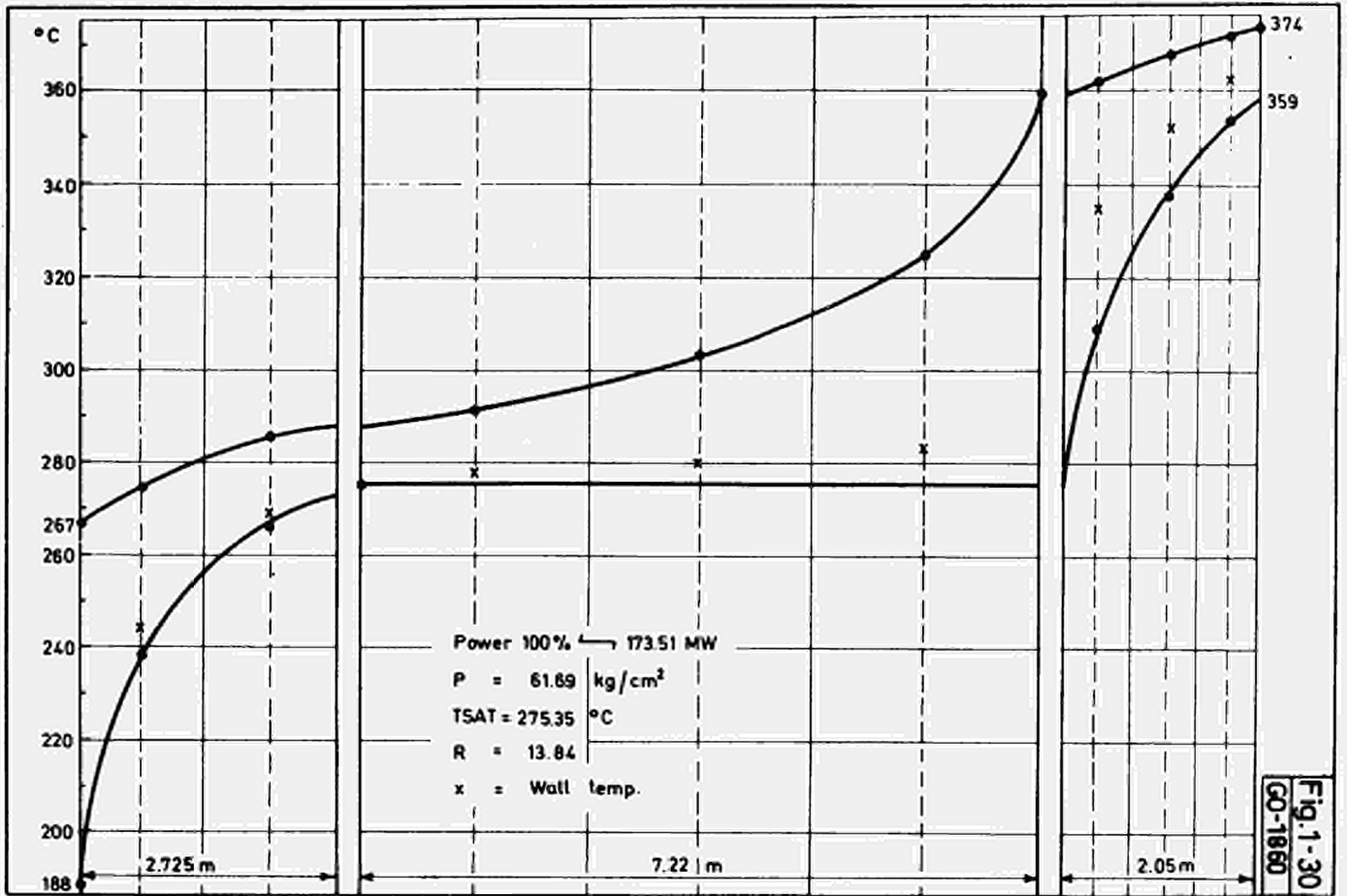
Fig.1-31
GO-1861

UNLOADING AND LOADING OF A CENTRAL FUEL ELEMENT
THE BAR SPEED IS LIMITED TO 10 P.C.M. /sec.
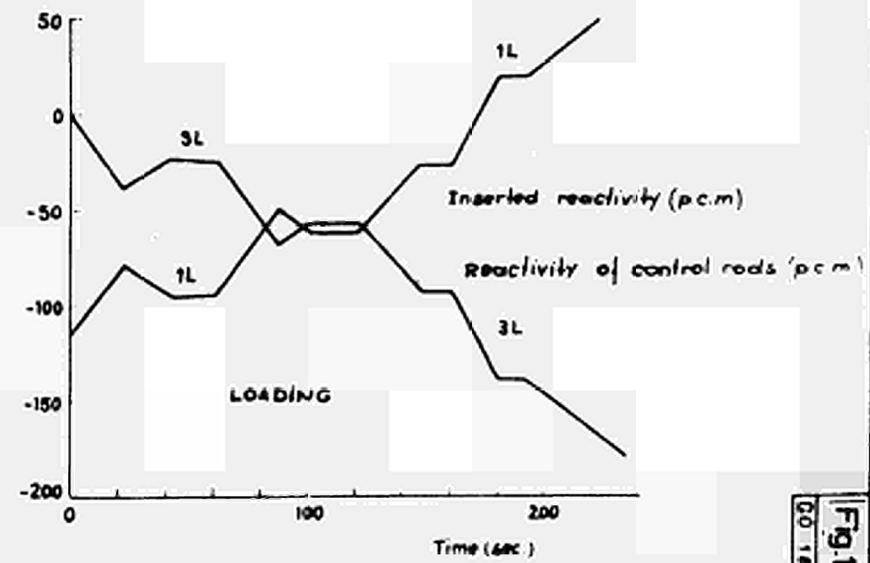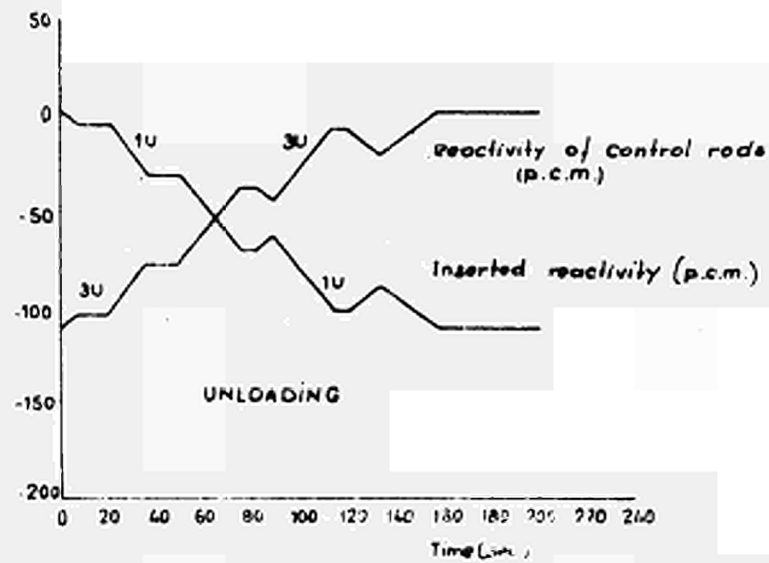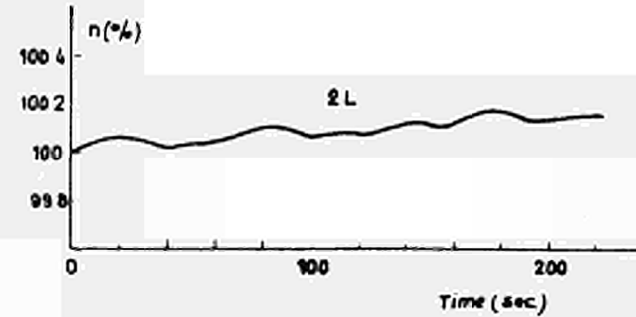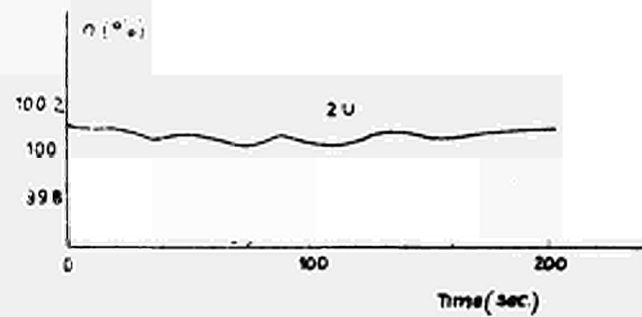
Fig.1·32

VARIATION OF POWER 100 - 75, 5 % PER MINUTE (PROGRAMME 1)

Cladding temperature — T_g (°C)

Fuel temperature — T_u (°C)

Control-bar reactivity — ROCON (p.c.m)

Neutron power — n (%)

Time (minutes)
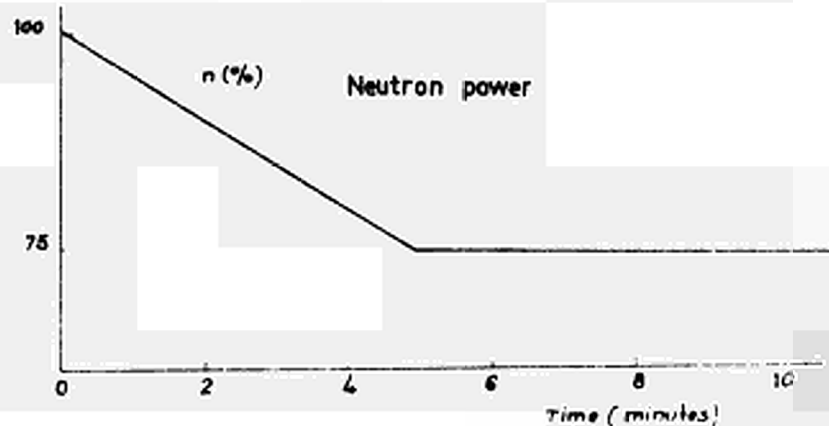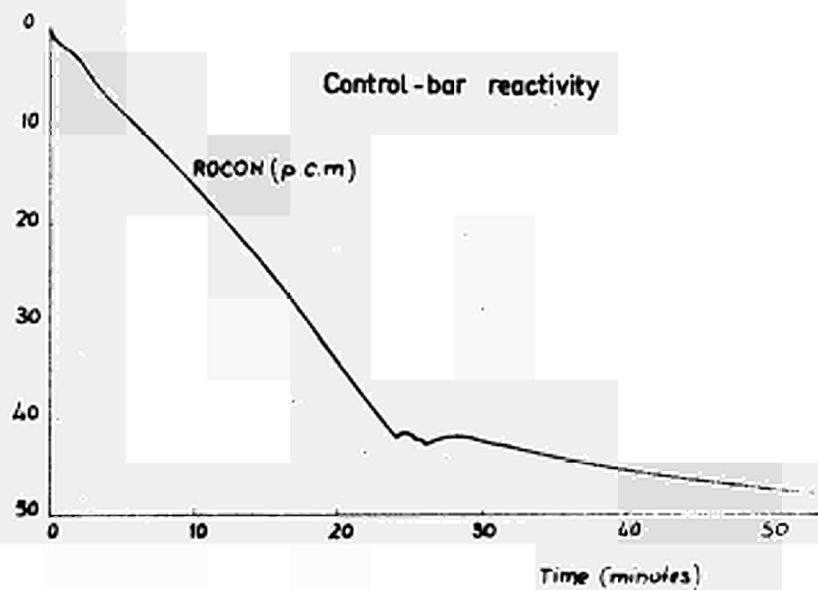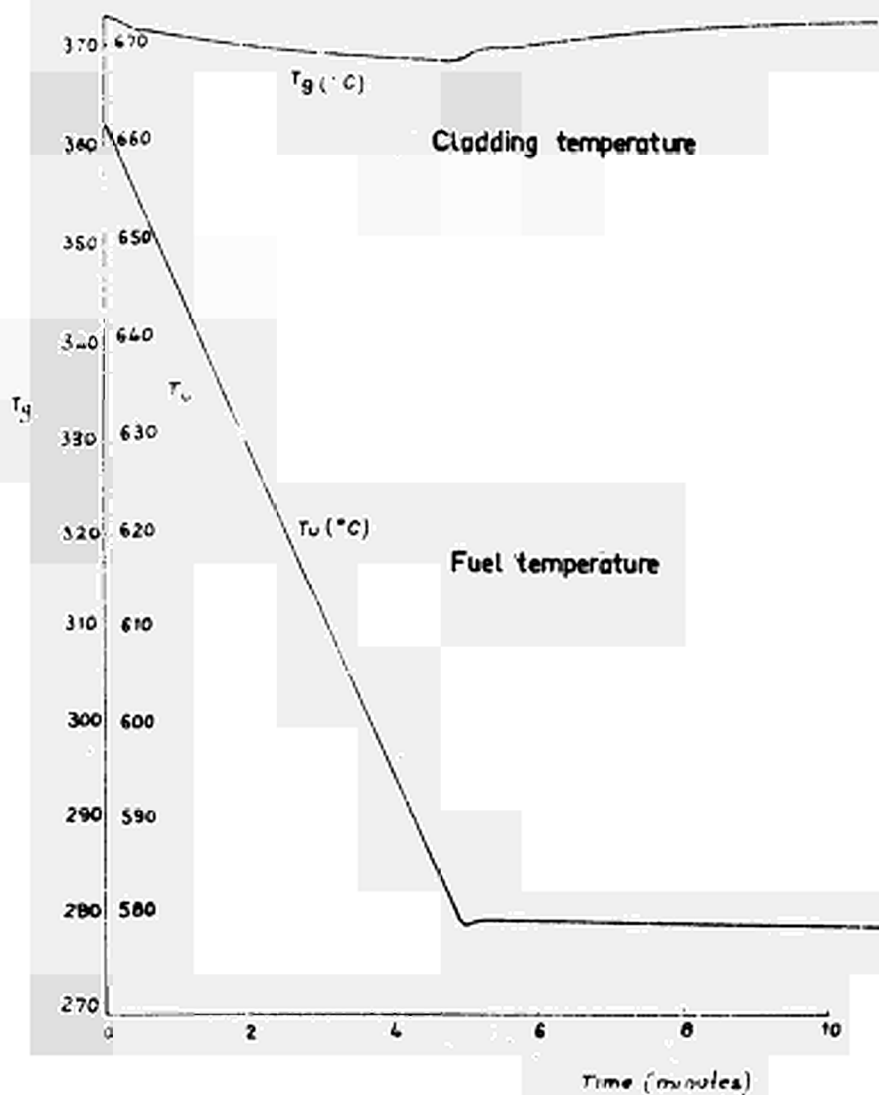
Fig.1-33
GD-18-22

II2

Fig. 1·34
GO-1823

VARIATION OF POWER FROM 100% TO 75% : 5% PER MINUTE
(PROGRAMME 1)

Organic temperature
H. Exch. inlet
T. Average
H. Exch. outlet

Time (minutes)
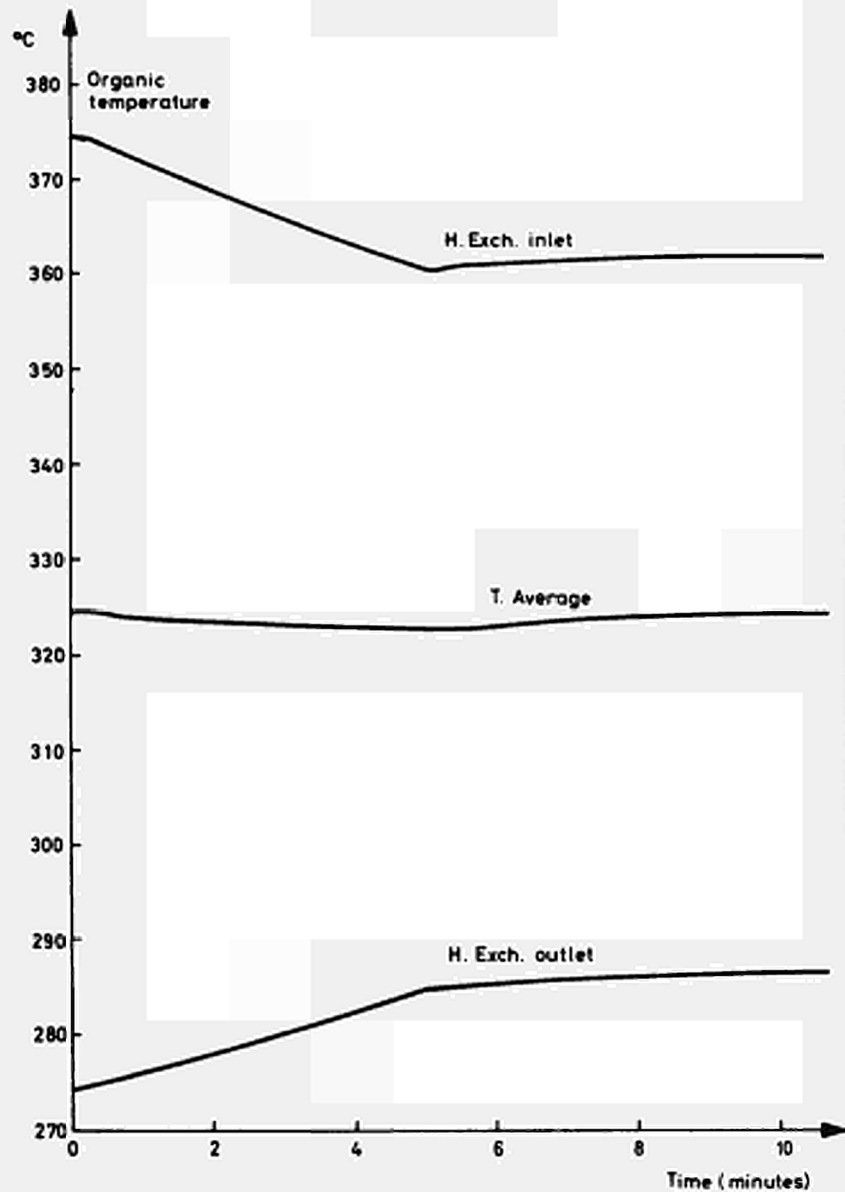
Fig. 1·35
GO-1824

VARIATION OF POWER FROM 100% TO 75% : 5% PER MINUTE
(PROGRAMME 1)

Average vapour title
X

Recirculation flow
WR (kg/sec)

WREQ (kg./sec.)
Steam outlet flow

Steam pressure
P (atm.)

Time (minutes)

113
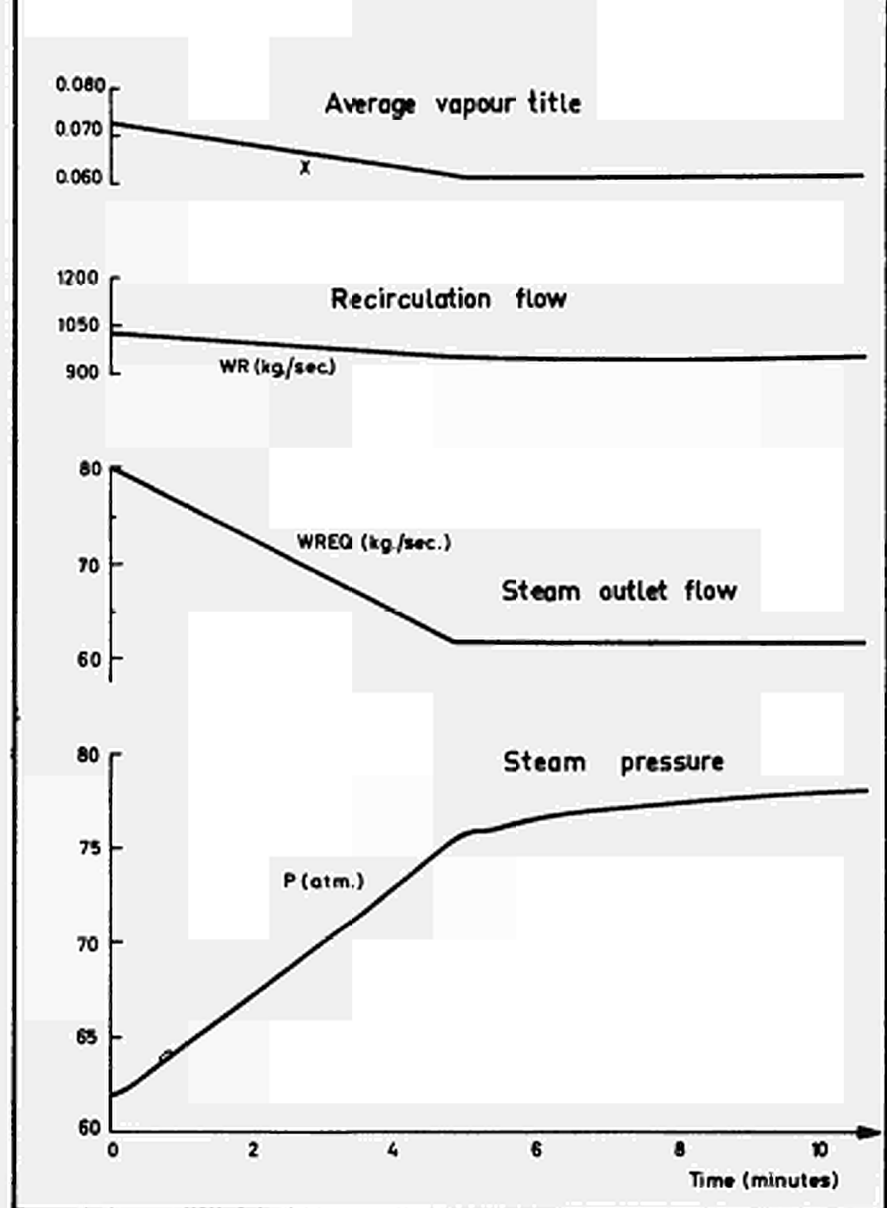
VARIATION OF POWER FROM 100% TO 25%
(PROGRAMME 1)
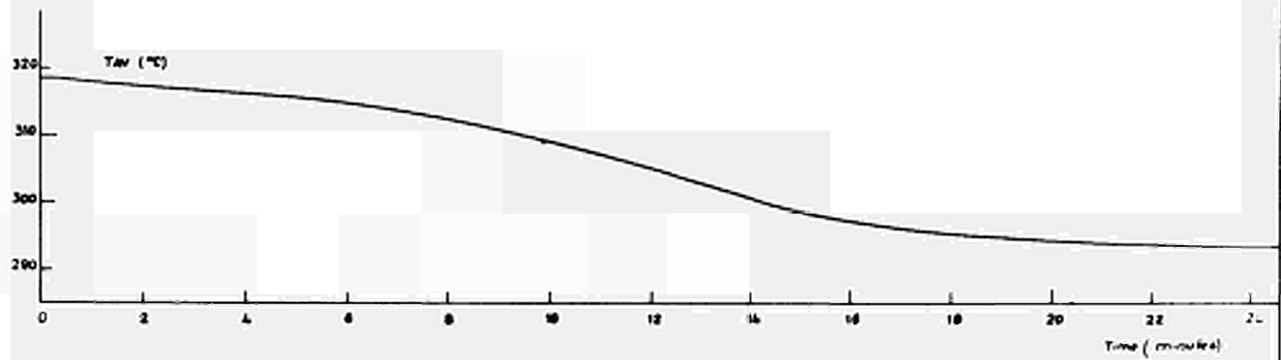
Fig.1-36
GO-1825

VARIATION OF POWER FROM 100% TO 25% : 5% PER MINUTE
(PROGRAMME 1)

Fig.1-37
GO-1852

VERY SLOW VARIATION OF POWER FROM 100% TO 25% : 5% PER MINUTE
(PROGRAMME 1)

Fig.1-38
GO 1863

VERY SLOW VARIATION OF POWER FROM 100% TO 25% : 0.5% PER MINUTE
(PROGRAMME 1)
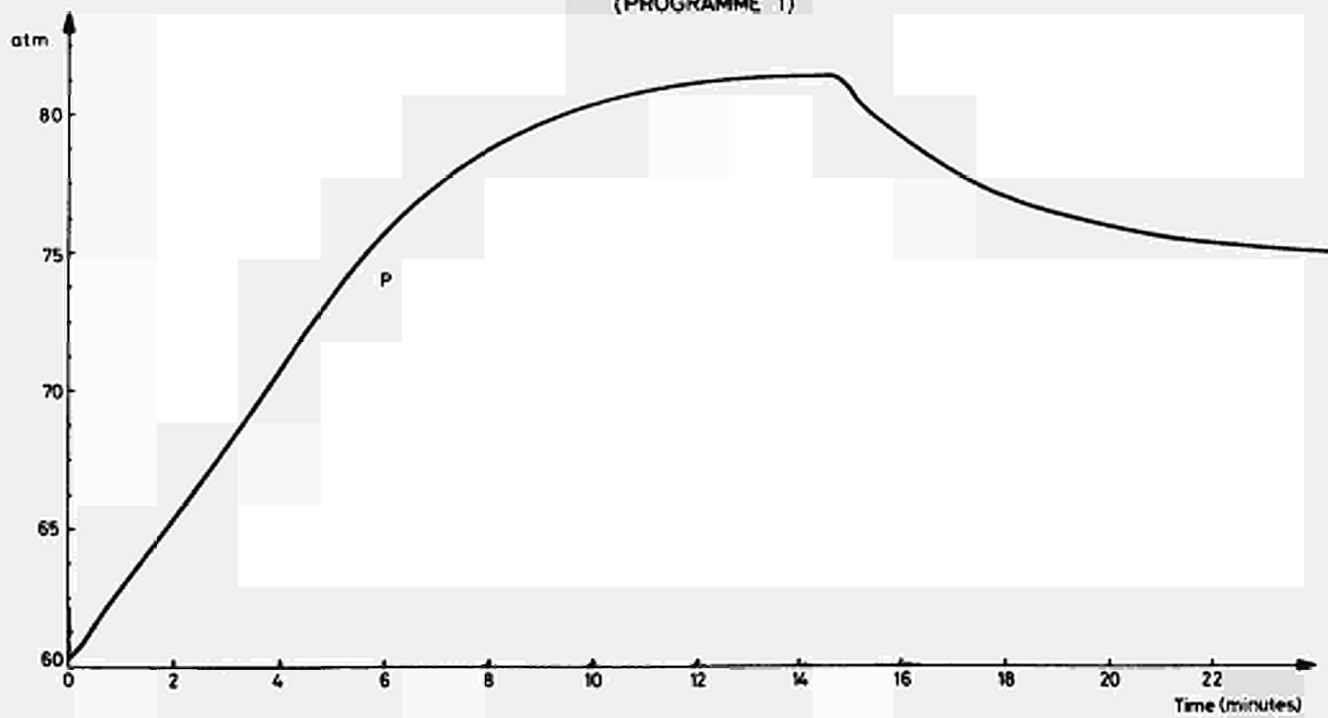
Fig.1-39
GO 1864
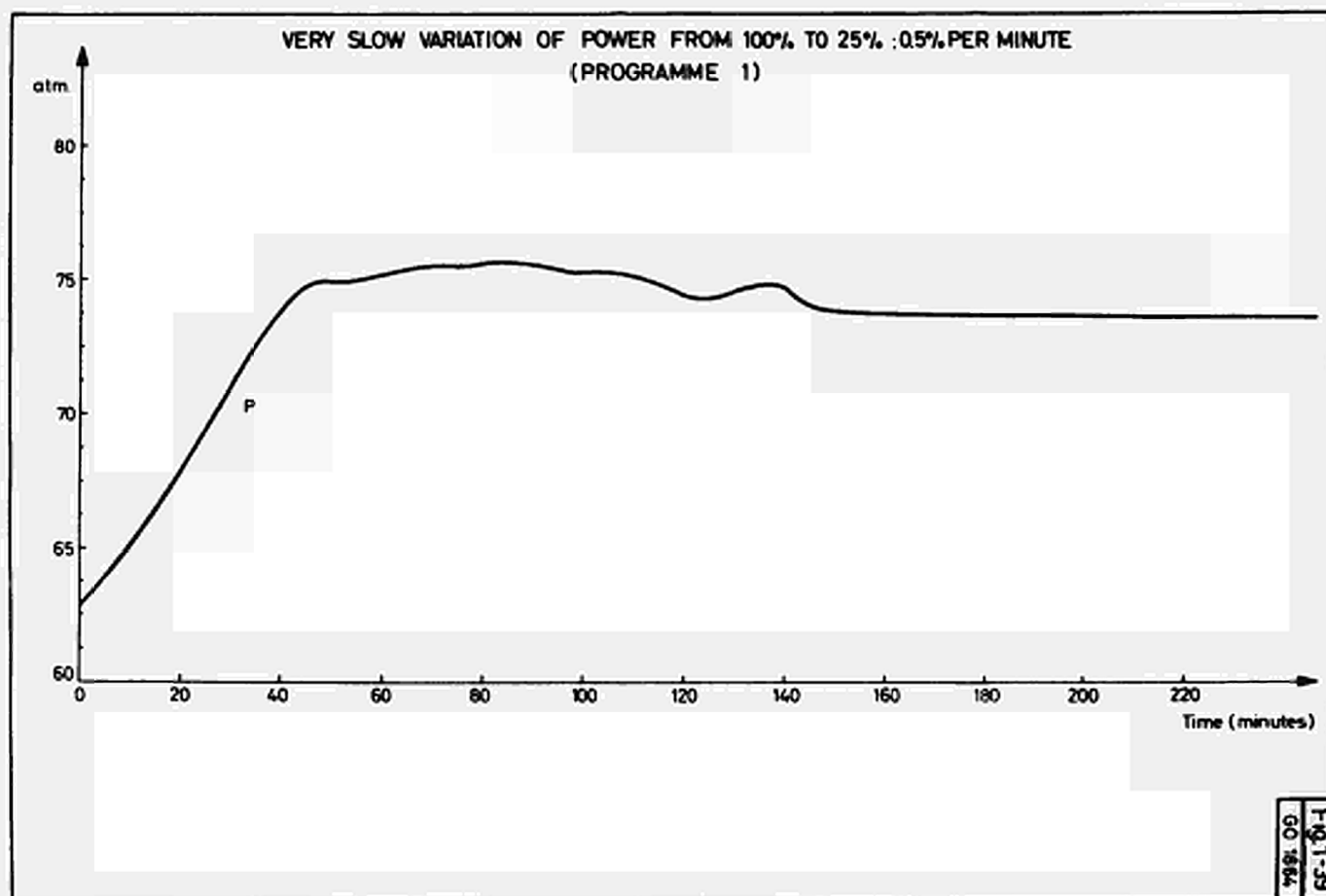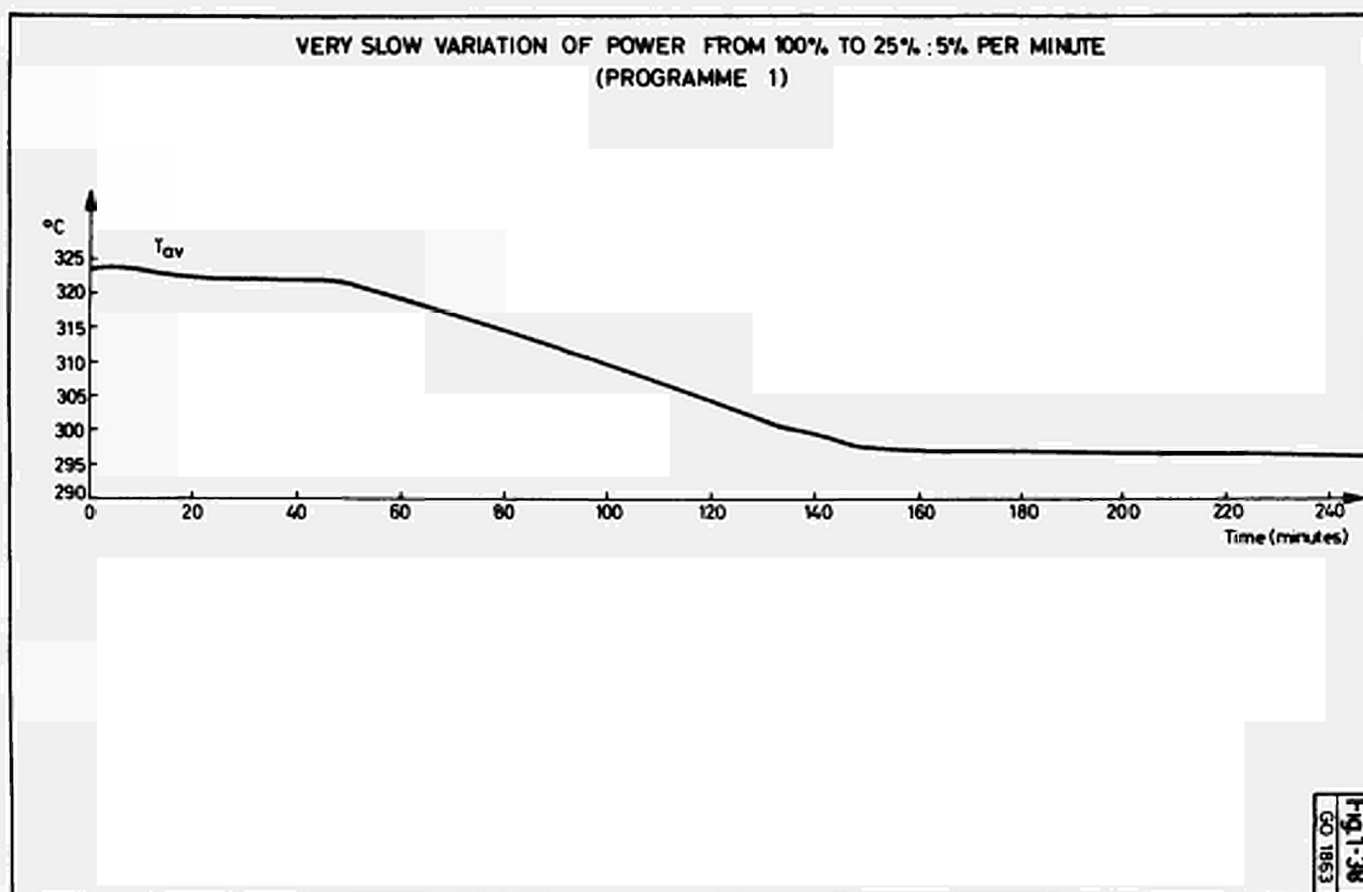
VERY SLOW VARIATION OF POWER FROM 100% TO 25% : 0.5% PER MINUTE
(PROGRAMME 1)

Fig.1-40
GO 1865

VERY SLOW VARIATION OF POWER FROM 100% TO 25% : 0.5% PER MINUTE
(PROGRAMME 1)

Fig.1-41
GO 1865

VARIATION OF POWER FROM 100% TO 25%, 5% PER MINUTE
(PROGRAMME 1)

Curve 1 (without additional pressure term)

Curve 2 (with additional pressure term)

Fig. 1-42
GO-1826

VERY SLOW VARIATION OF POWER FROM 100% TO 25% : 0.5% PER MINUTE
(PROGRAMME 1)

Fig. 1-43
GO-1868

VERY SLOW VARIATION OF POWER FROM 100% TO 25% : 05% PER MINUTE
(PROGRAMME 1)
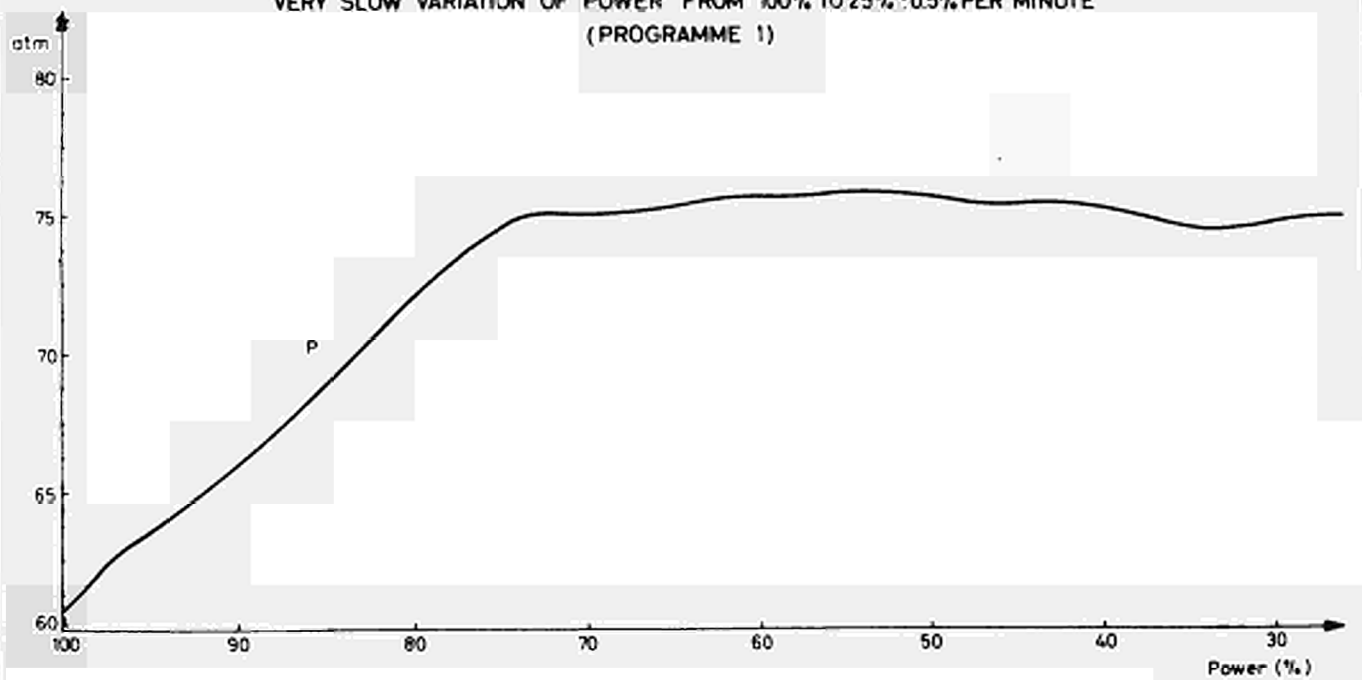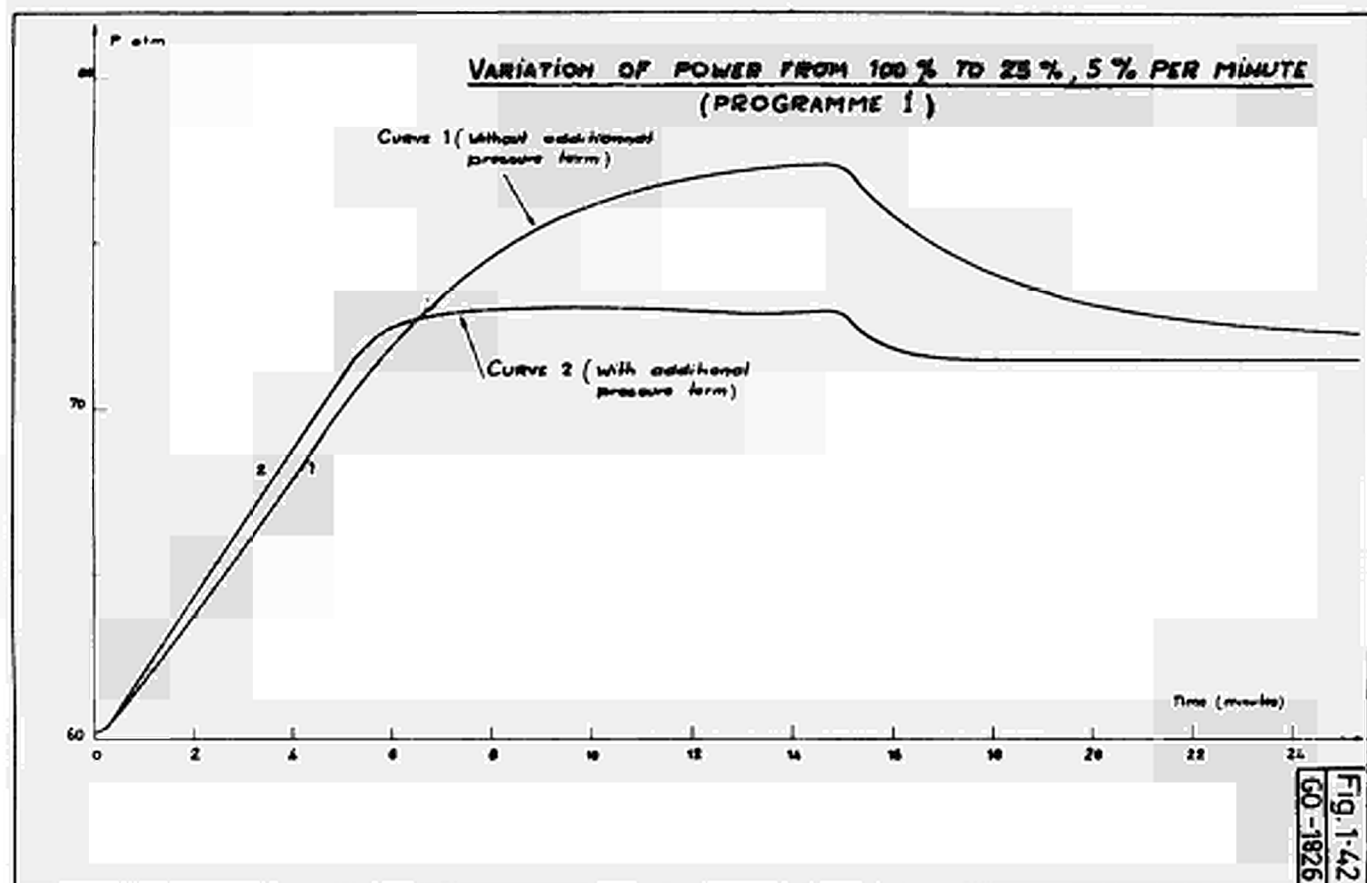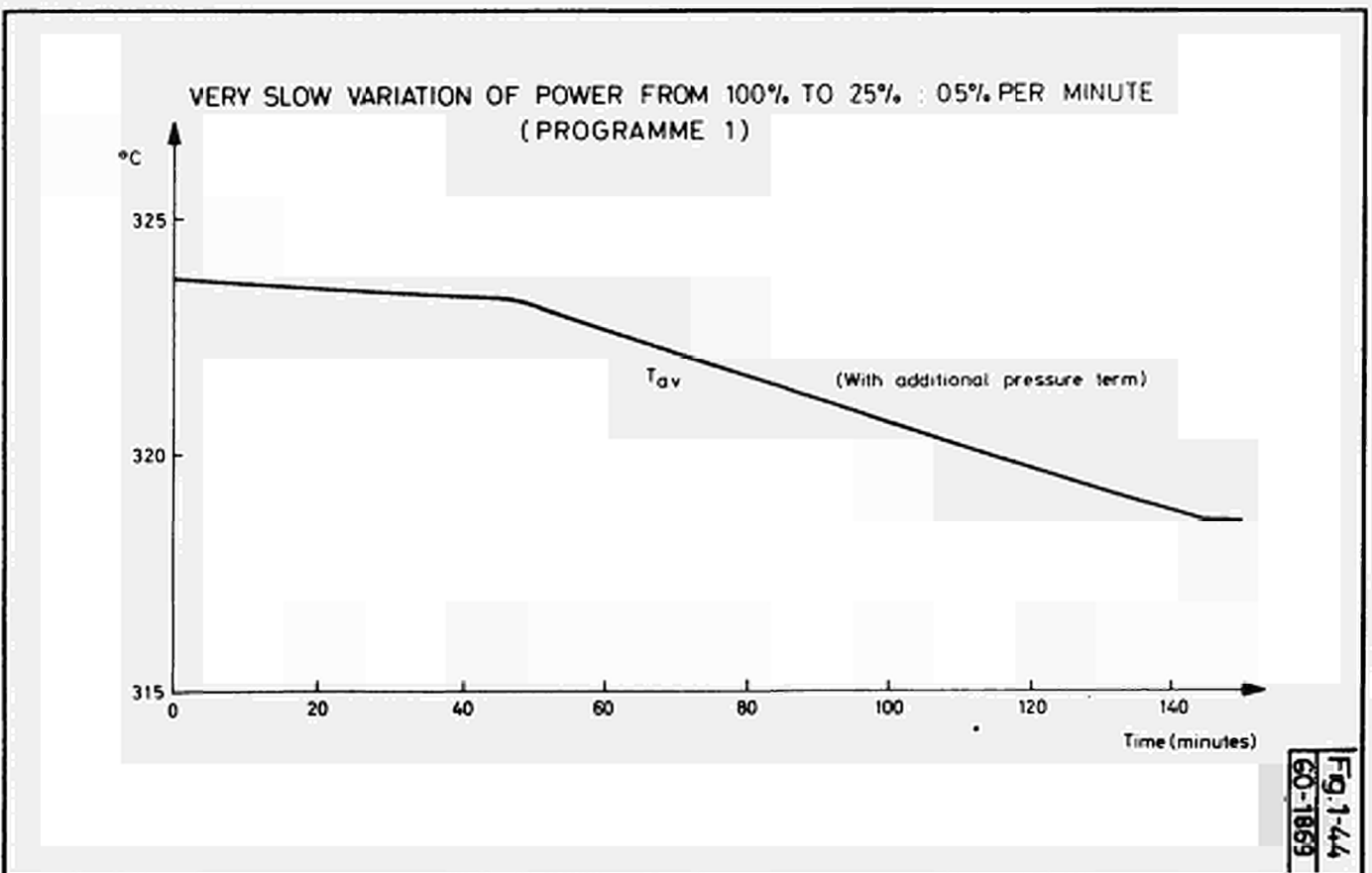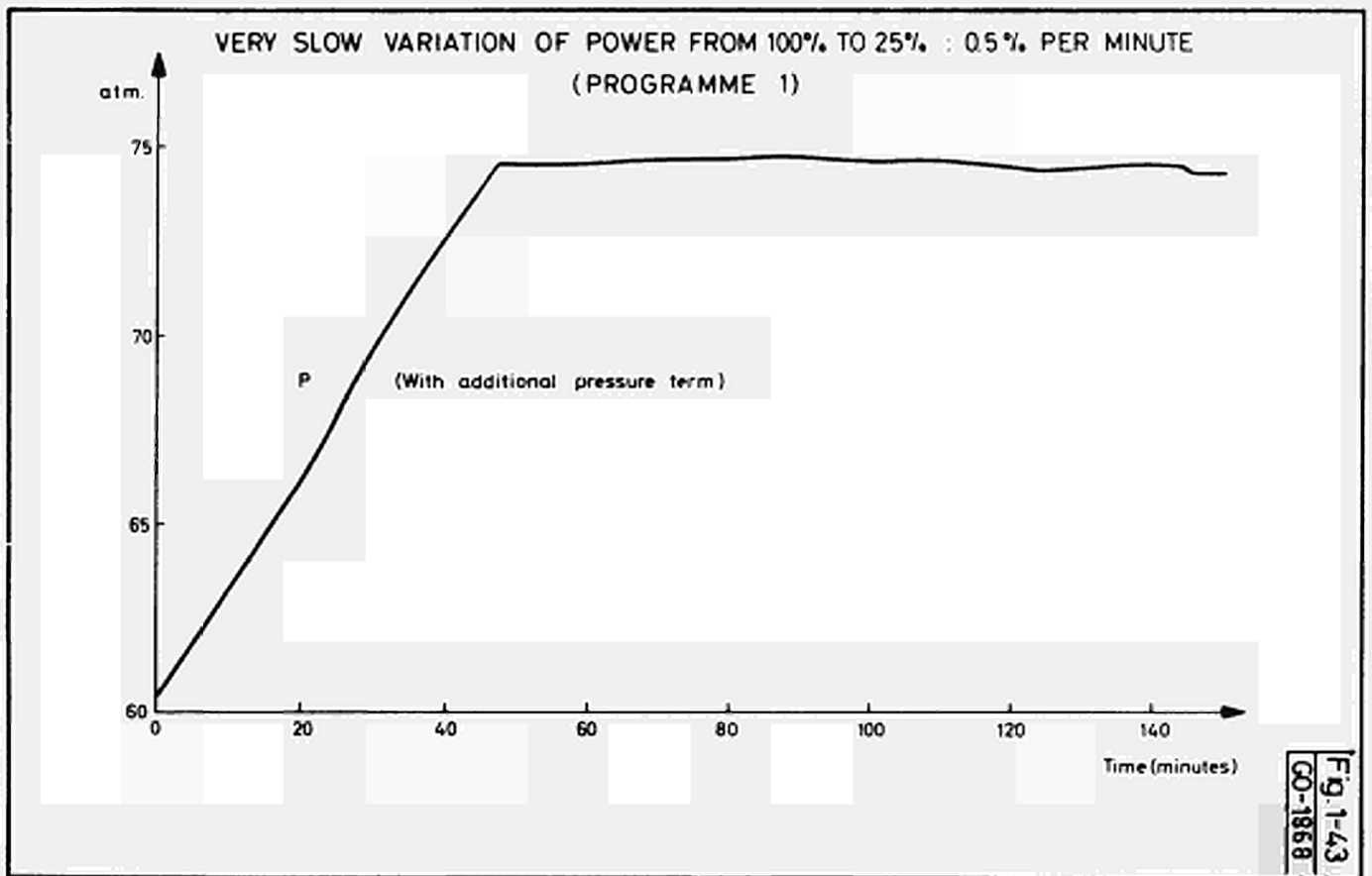
Fig. 1-44
GO-1869

Fig. 1-45 / GO-1870

VARIATION OF POWER FROM 100% TO 25%
(PROGRAMME 1)

Curve 1 : 5% per minute, $R_3 = 0$
Curve 2 : 5% per minute, $R_3 = 0.5$
Curve 3 : 10% per minute, $R_3 = 0.5$
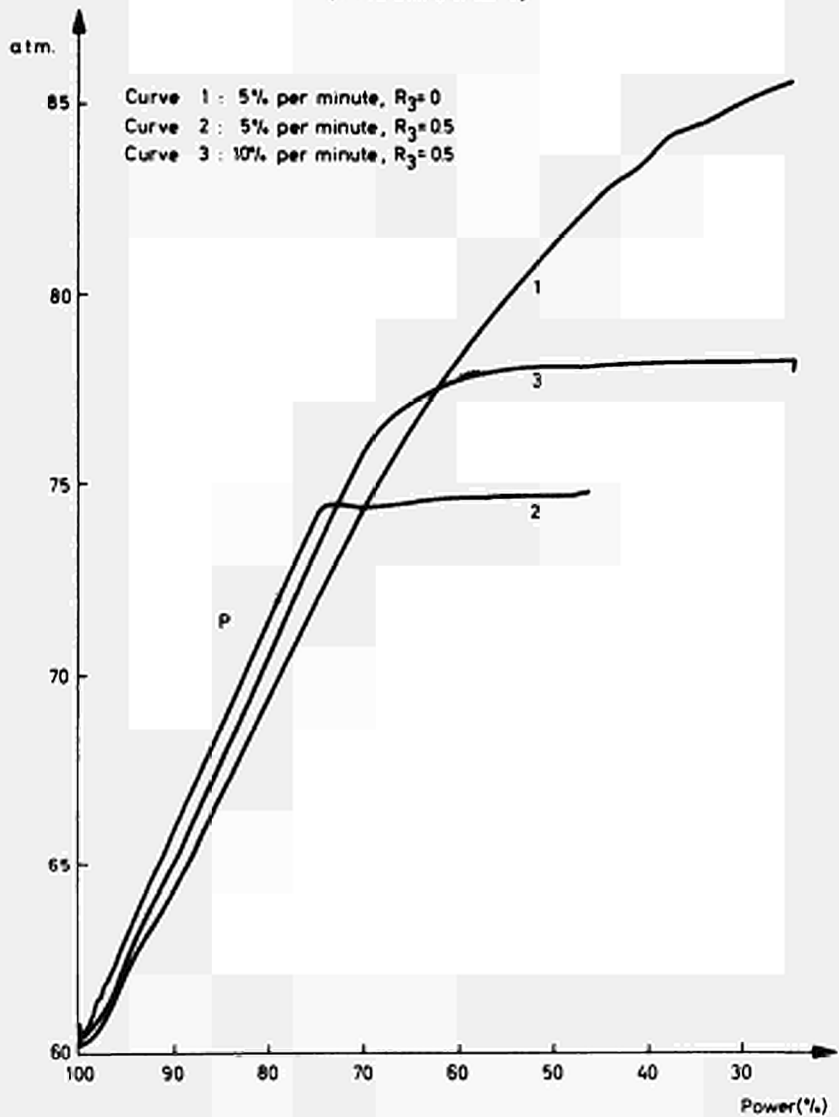
Fig. 1-46 / GO-1871

VARIATION OF POWER FROM 100% TO 25%
(PROGRAMME 1)

Curves 1 : 5% per minute, $R_3 = 0$
Curves 2 : 5% per minute, $R_3 = 0.5$
Curves 3 : 10% per minute, $R_3 = 0.5$

119
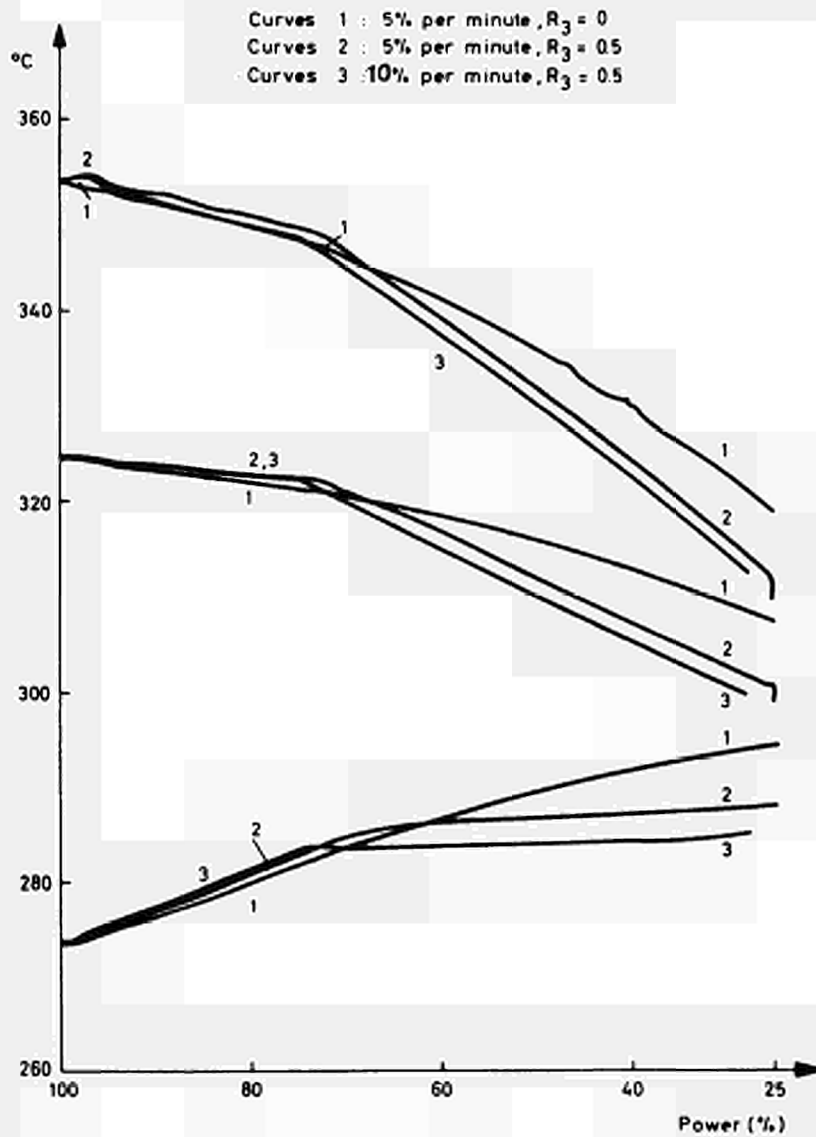
CONSTANT-STEAM PRESSURE PROGRAM

POWER CHANGE BETWEEN 100 AND 75% (5%/min.)

WITH PRESSURE TERM ($R_2 = 0.5$)
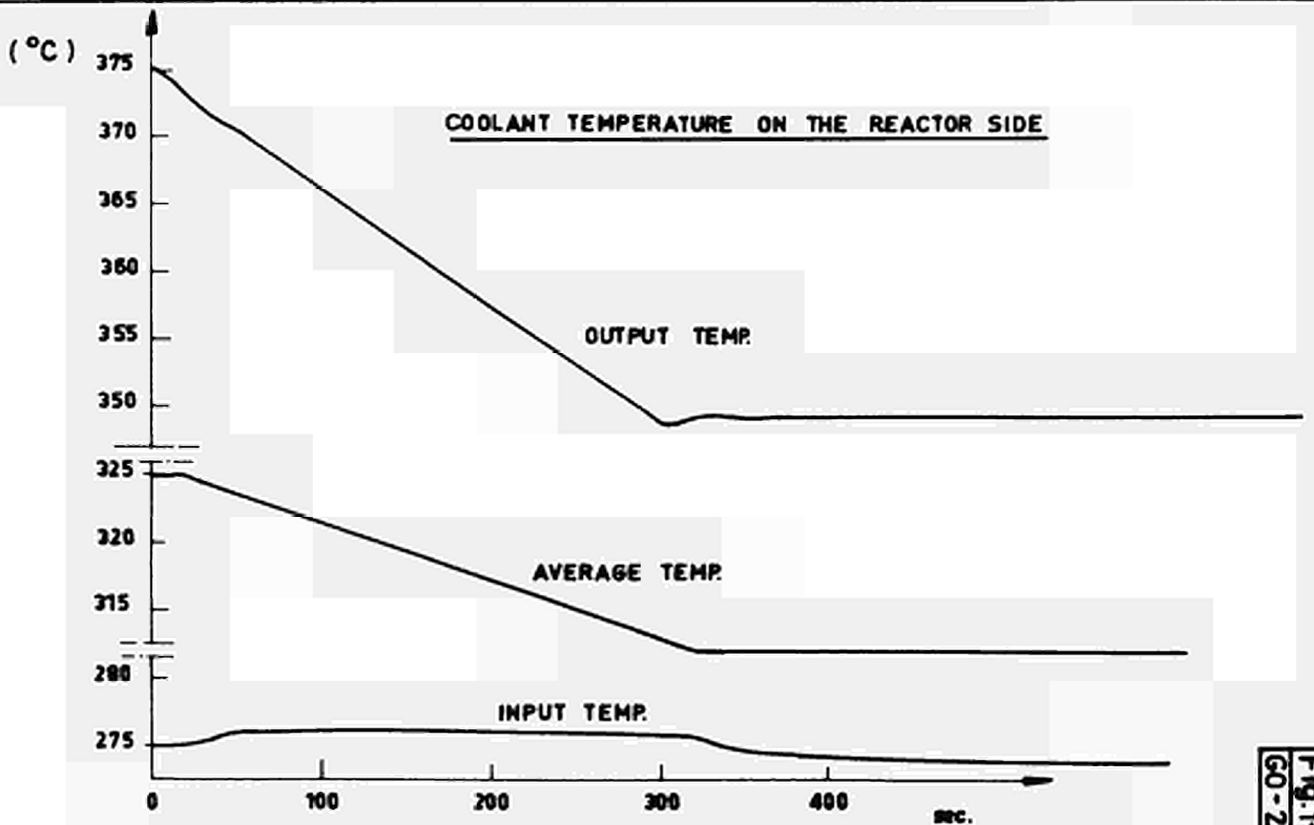
(%)

NEUTRON POWER

Fig.1-47
GO-2059

(°C)

COOLANT TEMPERATURE ON THE REACTOR SIDE

OUTPUT TEMP.

AVERAGE TEMP.

INPUT TEMP.

Fig.1-48
GO-2055

STEAM PRESSURE

(kg/cm²)

Fig.1-49
GO-2065

SUPERHEATING STEAM TEMPERATURE

(°C)

Fig.1-50
GO-2066

Fig.1-51
GO-1878

VARIATION OF POWER FROM 100% TO 25% : 5% PER MINUTE
(PROGRAMME 2)

Fig.1-52
GO-1879

Fig.1-53

Fig.1-54
(GO-1171)

Steam temperature turbine inlet

T turb. (°C)

350

300

250

P/Po (%)
100 90 80 70 60 50 40 30 20 10 0
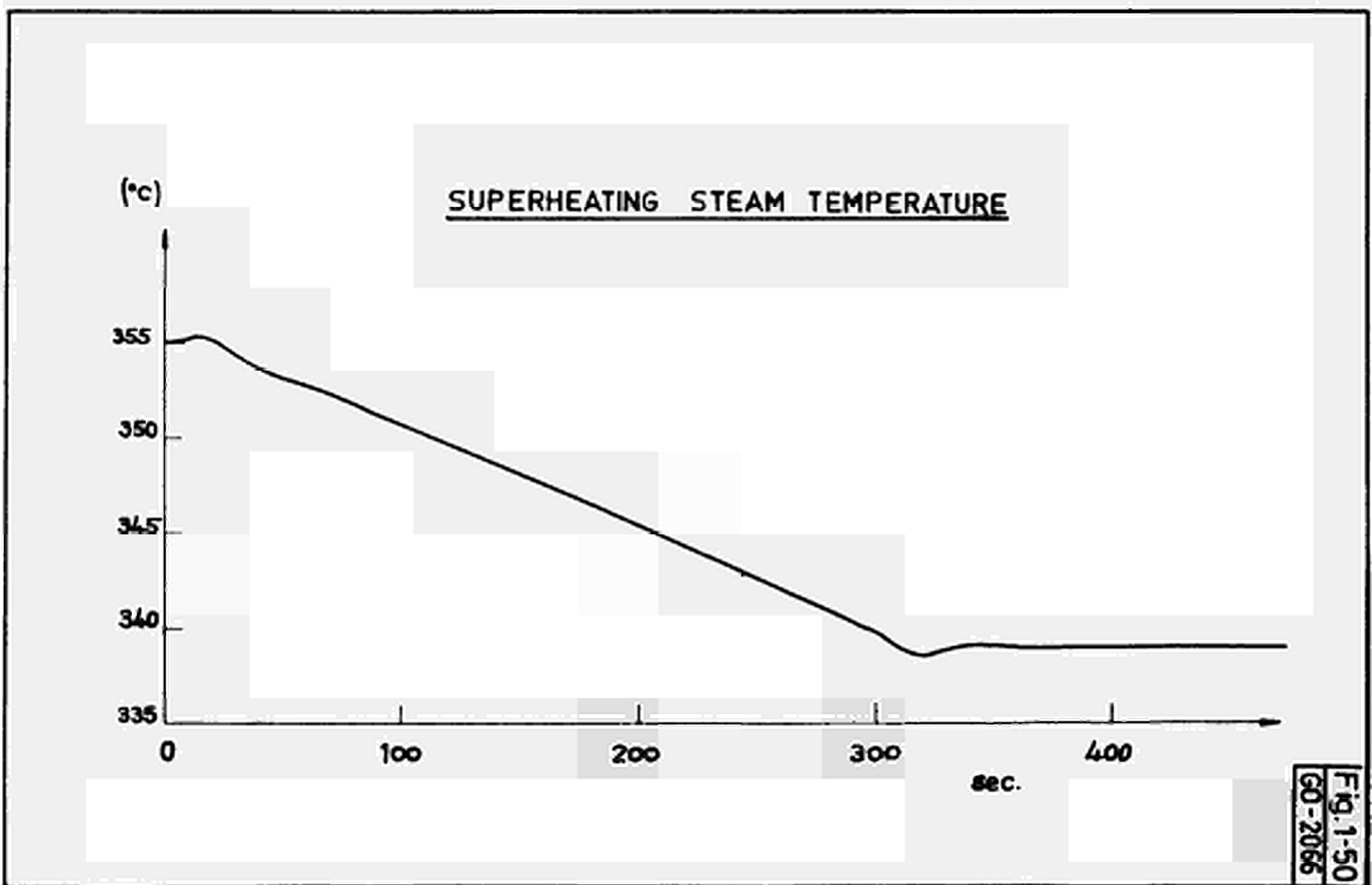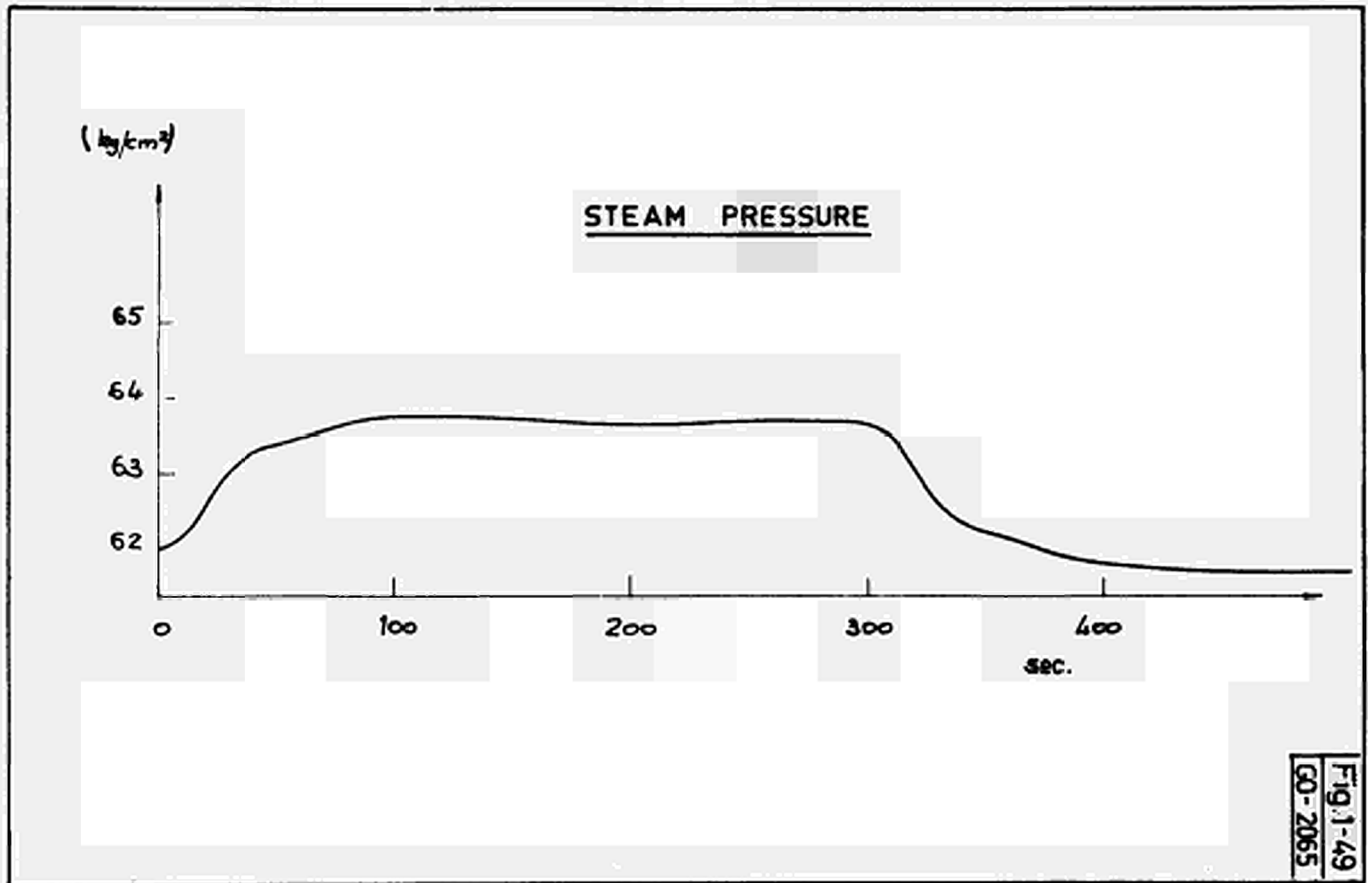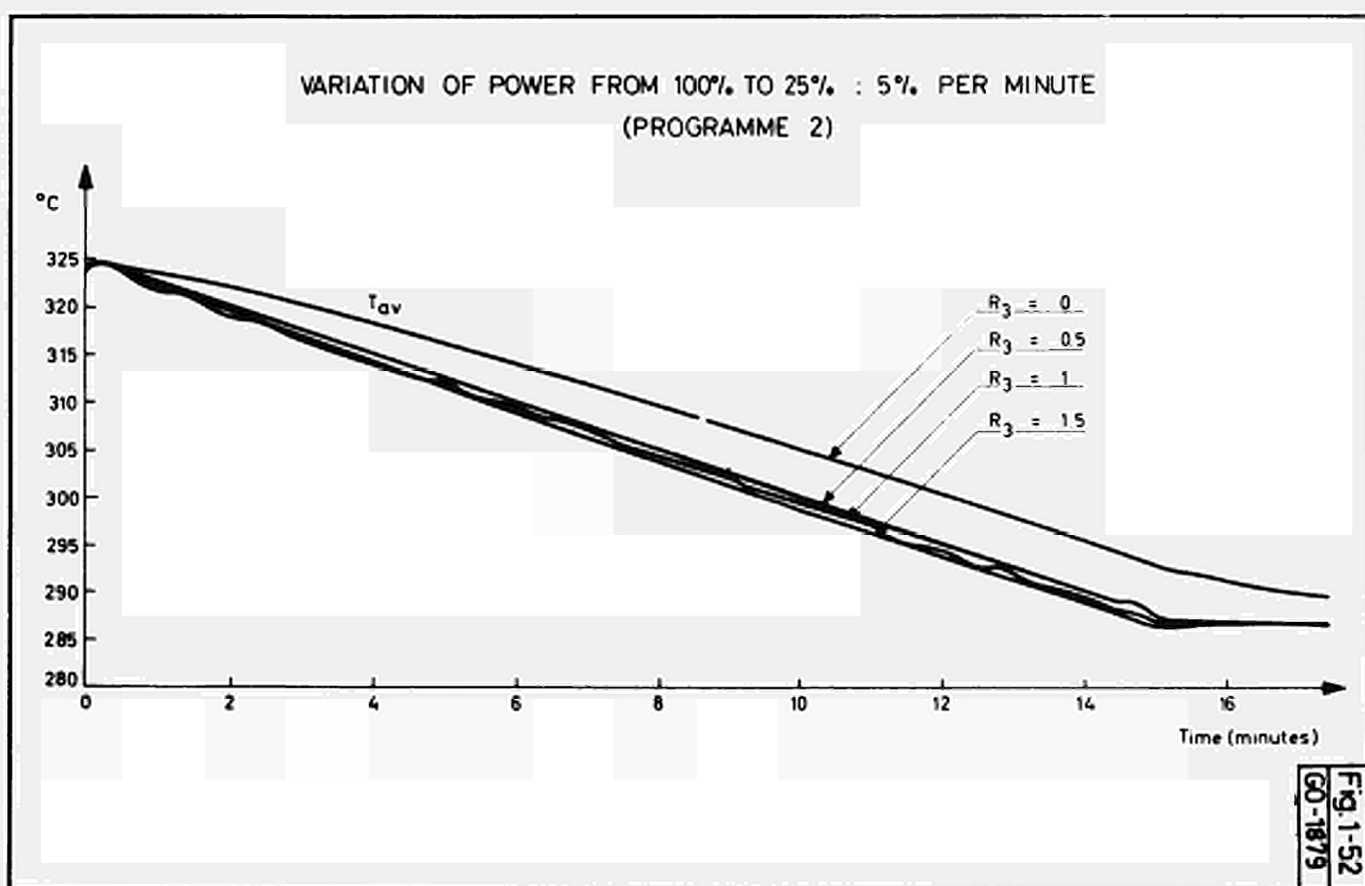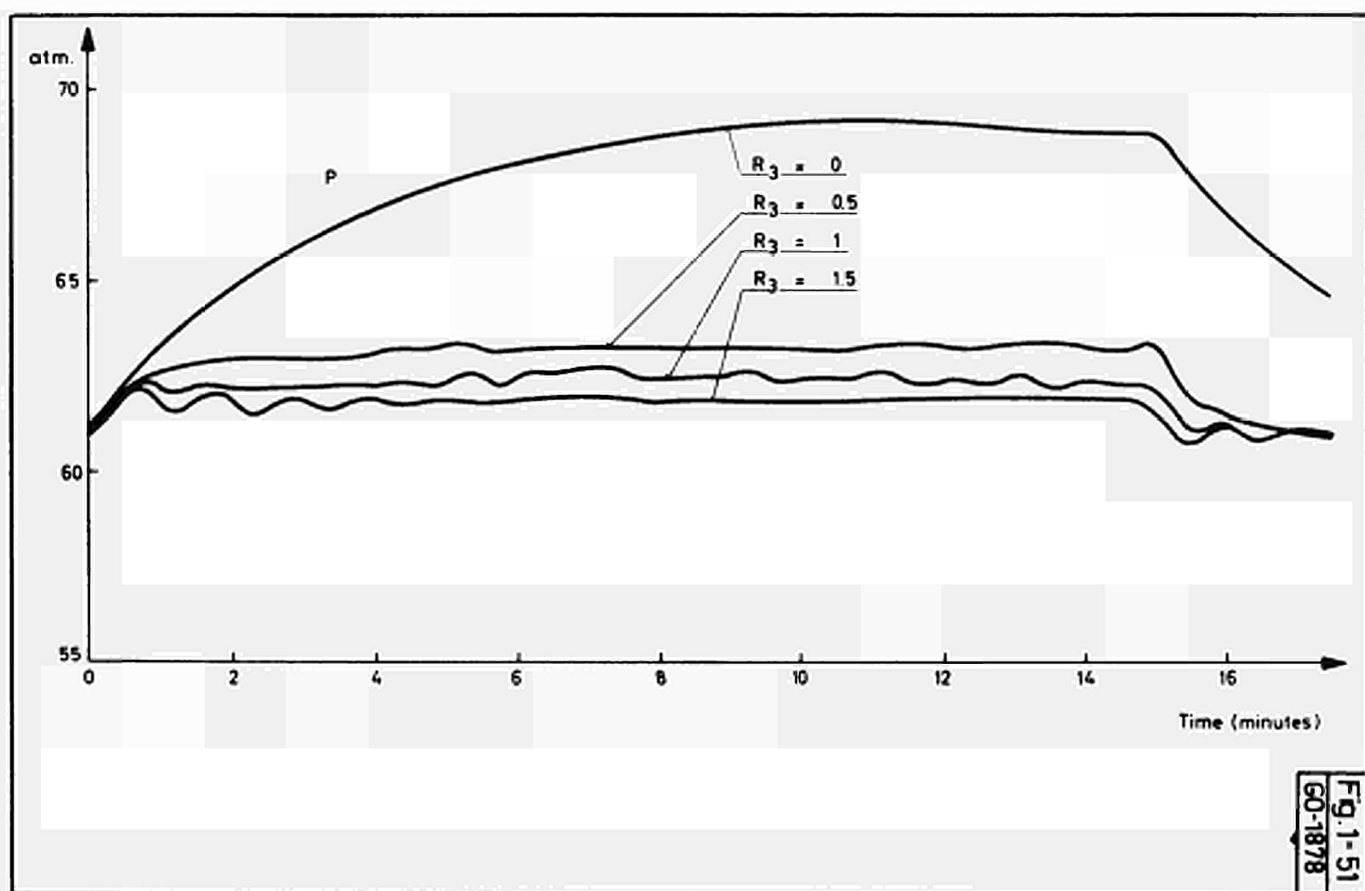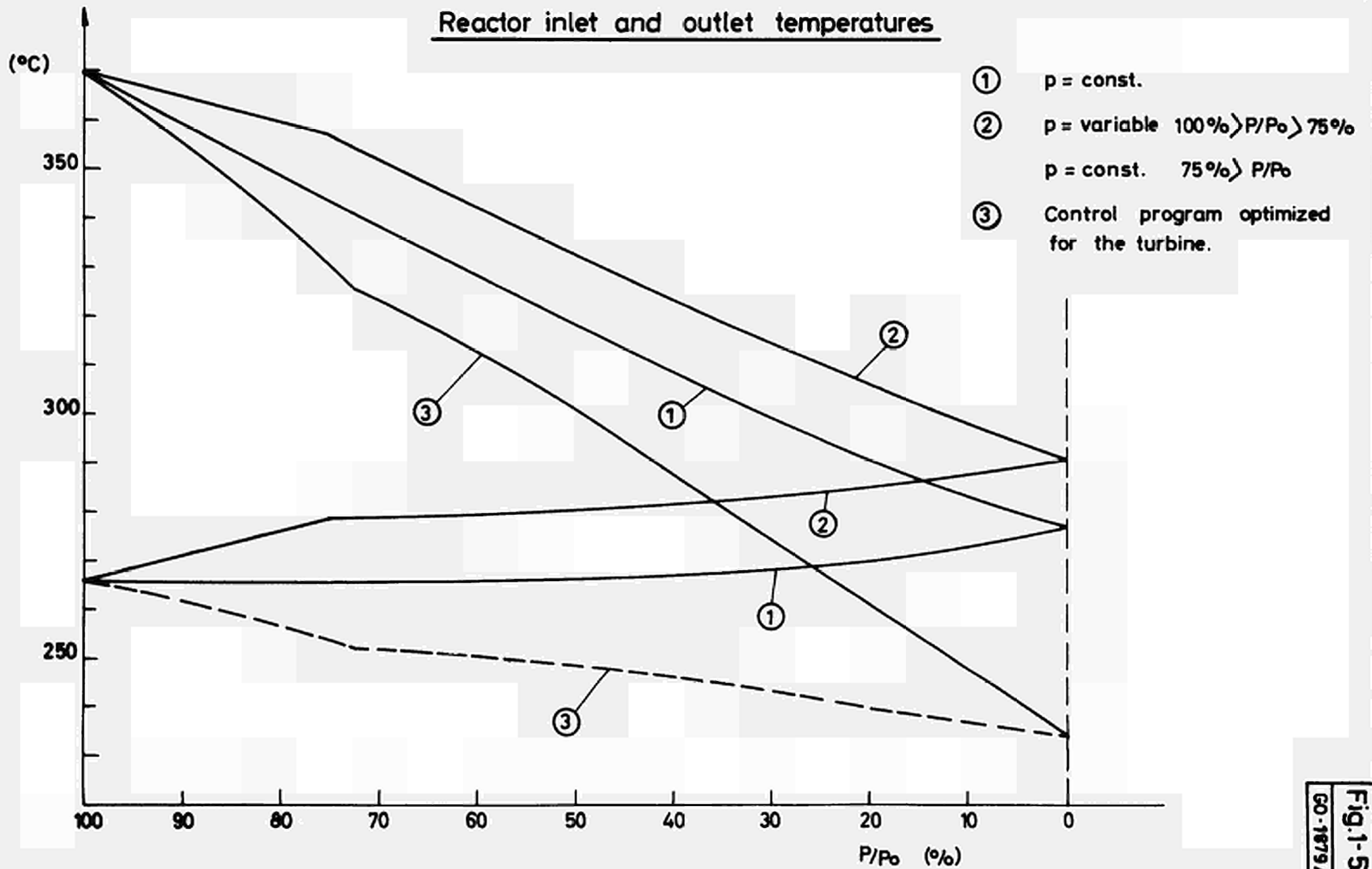
① p = const.

② p = variable 100% > P/Po > 75%
   p = const. 75% > P/Po

③ Control program optimized for the turbine
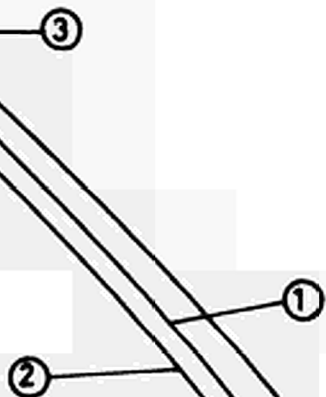
Fig.1-55

GO-1879 C

OPTIMIZED PROGRAM

CHANGE OF POWER FROM 100% TO 75% (5%/MIN.)
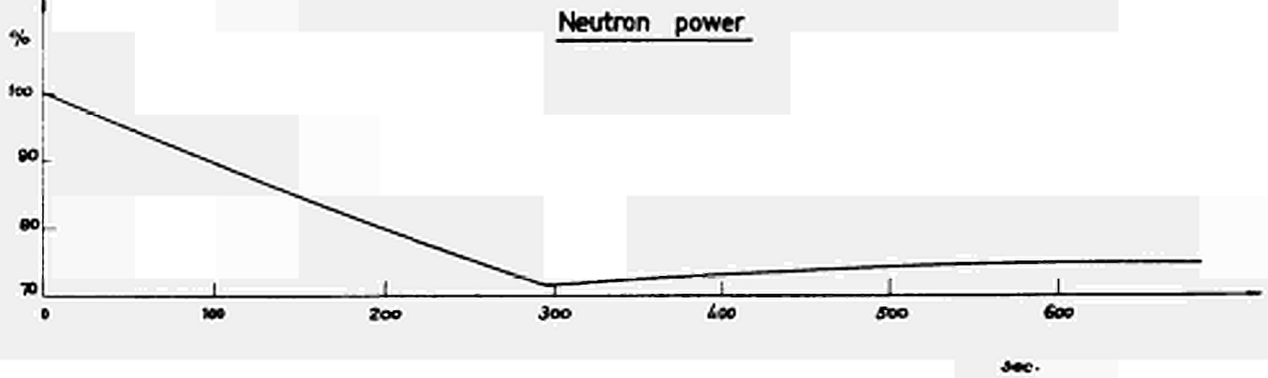
Neutron power

Fig.1-56
GO-2049

OPTIMIZED PROGRAM

CHANGE OF POWER FROM 100% TO 75% (5%/MIN)

Coolant temperatures on the reactor side

Output temperature

Average temperature
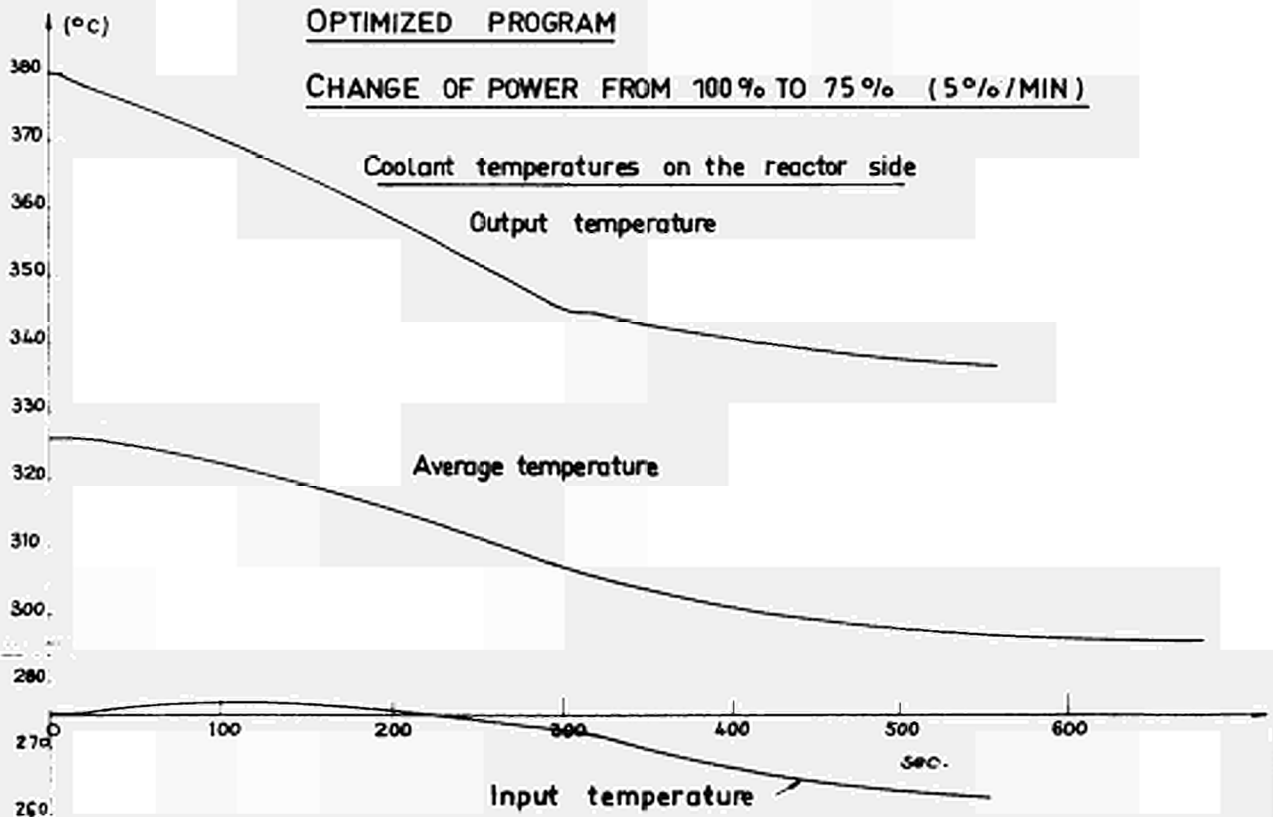
Input temperature

Fig.1-57
GO-2046

CONTROL LOSS AND RECOVERY

NEUTRON POWER
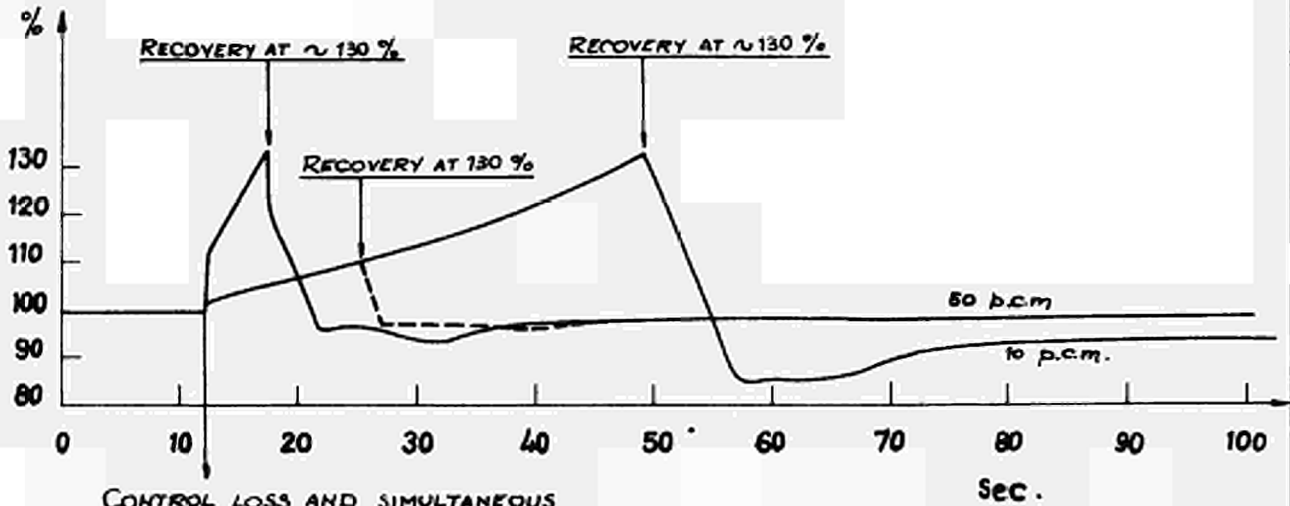
Fig.1-58
GO-2061

CONTROL LOSS AND RECOVERY

AVERAGE COOLANT TEMPERATURE ON THE REACTOR SIDE.
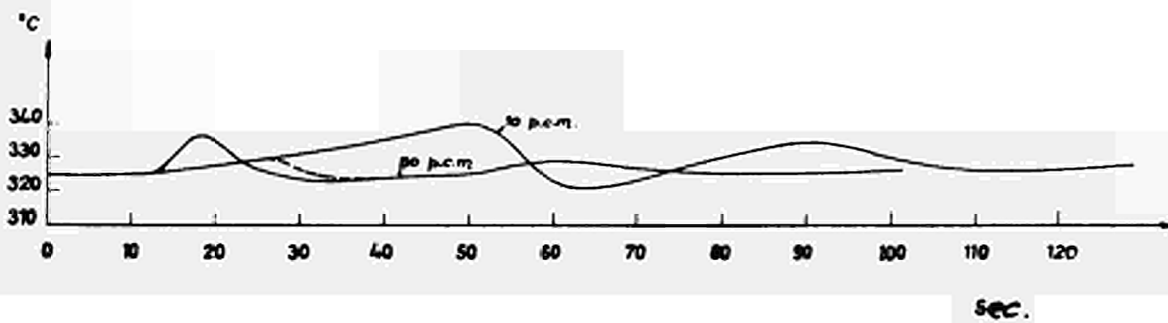
Fig.1-59
GO-2052

CONTROL LOSS AND RECOVERY

AVERAGE CLADDING TEMPERATURE
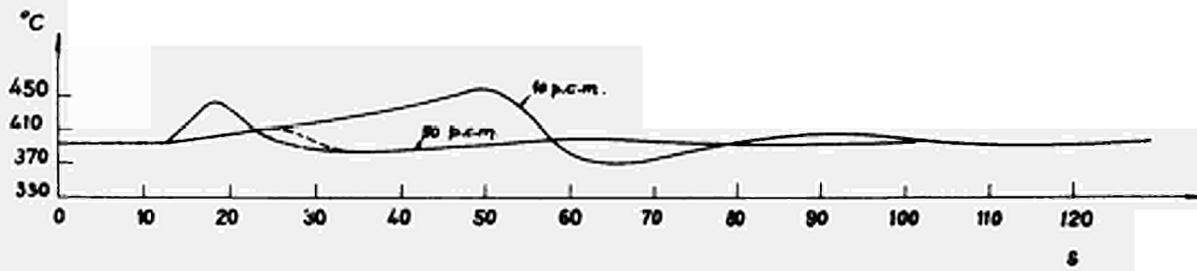
Fig.1-60
GO-2051

CONTROL LOSS AND RECOVERY

AVERAGE FUEL TEMPERATURE
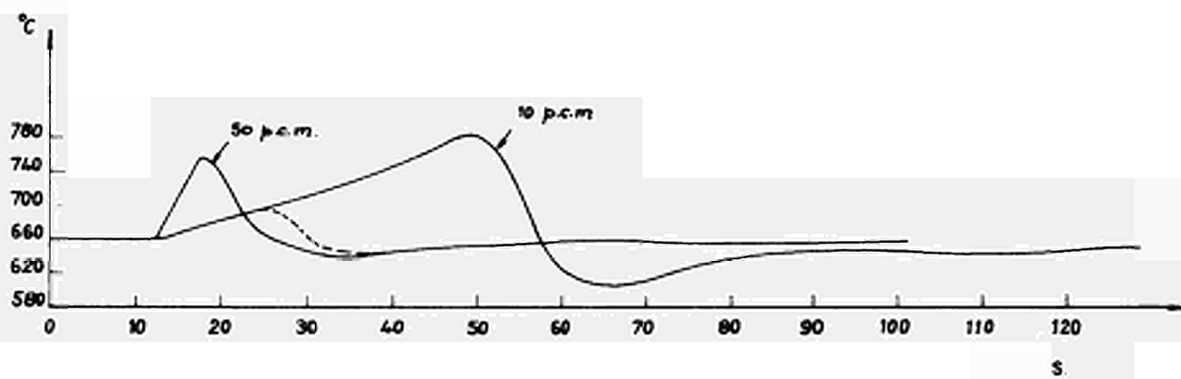
Fig.1-61
GO-2050

Scram

Neutron Power

Fig. 1-62
do. 2064

SCRAM

SCRAM

REACTOR TEMPERATURE

AVERAGE COOLANT TEMPERATURE Tᴄ

AVERAGE CLADDING TEMPERATURE Tɢ

AVERAGE FUEL TEMPERATURE Tᵤ

Fig.1-64
GO·2062

SCRAM

STEAM PRESSURE (kg/cm²)

STEAM FLOW (kg/sec.)

SUPERHEATING STEAM TEMPERATURE (°C)

Fig.·1-65
GO·2063

SCRAM WITH THROTTLE CLOSING

STEAM FLOW (kg/sec)

INERTIA TIME CONSTANT $\tau = 0$ sec
(PREVIOUS CASE)

INERTIA TIME CONSTANT $\tau = 20$ sec.

INERTIA TIME CONSTANT $\tau = 30$ sec.

$\tau = 30$

$\tau = 0$

$\tau = 20$

Fig. 1-66
No.2098

SCRAM WITH THROTTLE CLOSING

COOLANT TEMPERATURES

REACTOR OUTPUT TEMPERATURES

$\tau = 20$ sec.
$\tau = 20$ sec.
$\tau = 30$ sec.
$\tau = 30$ sec.

REACTOR INPUT TEMPERATURES

AVERAGE TEMPERATURES ON THE BOILER SIDE

$\tau = 20$ sec.
$\tau = 30$ sec.

AVERAGE TEMPERATURES ON THE REACTOR SIDE

Fig.1-67
G0.2056

SCRAM WITH THROTTLE CLOSING

Fig. 1-68

Fig.1-70
GO-2069

RESPONSE TO A LIKESTEP CHANGE IN REACTIVITY OF 50 p.c.m.

AVERAGE COOLANT TEMPERATURE ON THE BOILER SIDE

WITHOUT INTEGRATED FEEDBACK

WITH INTEGRATED FEEDBACK
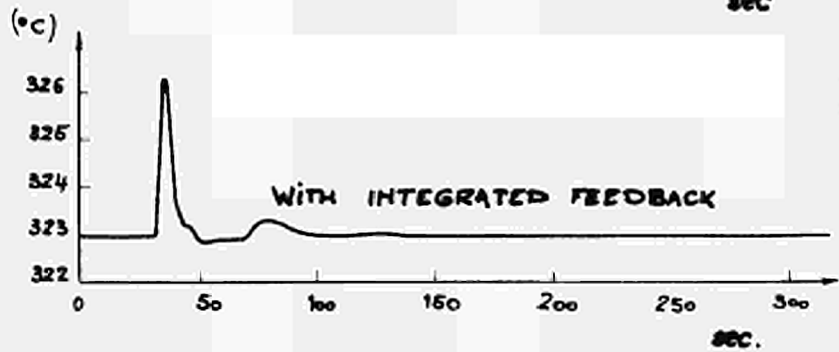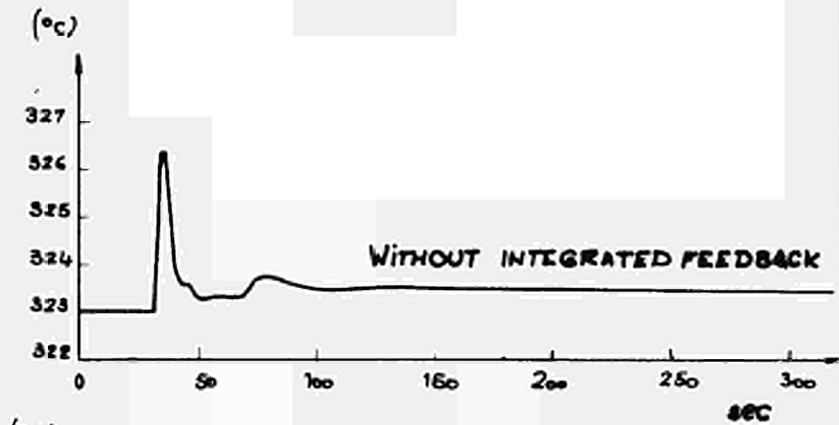
Fig.1-69
GO-2068

RESPONSE TO A LIKESTEP CHANGE IN REACTIVITY OF 50 p.c.m.

NEUTRON POWER

WITHOUT INTEGRATED FEEDBACK

WITH INTEGRATED FEEDBACK

135
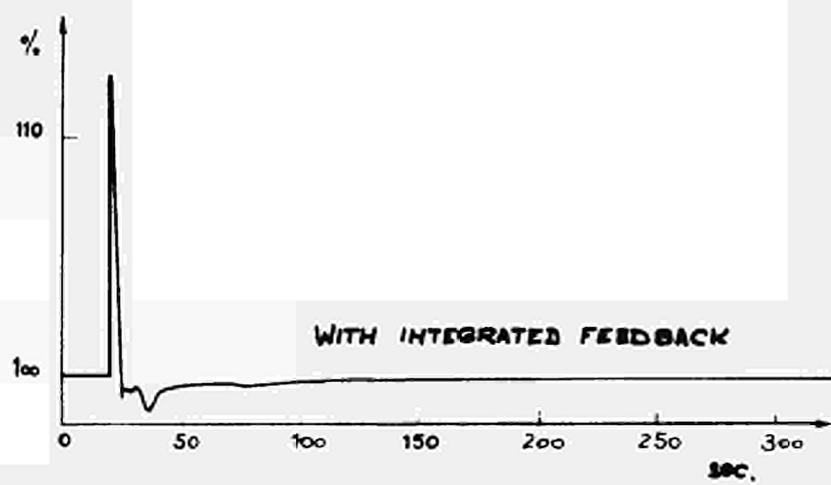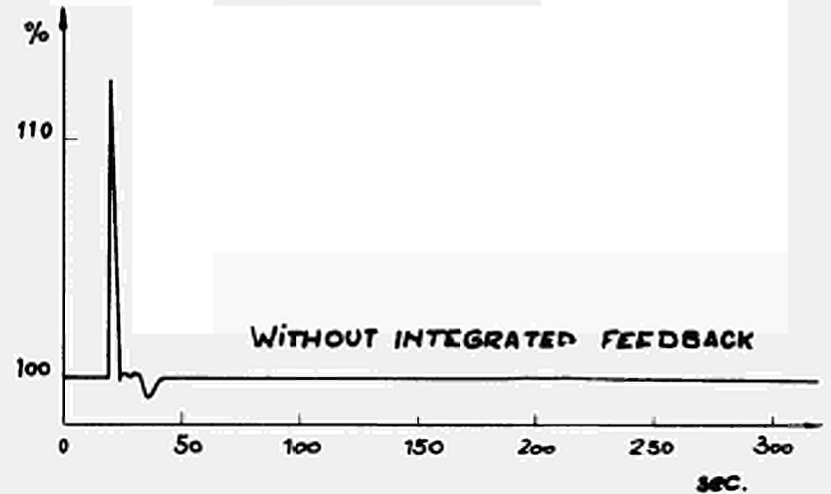
Fig.1-71
GO-2070

RESPONSE TO A LIKESTEP CHANGE IN REACTIVITY OF 50 P.C.M.

STEAM PRESSURE

WITHOUT INTEGRATED FEEDBACK

WITH INTEGRATED FEEDBACK
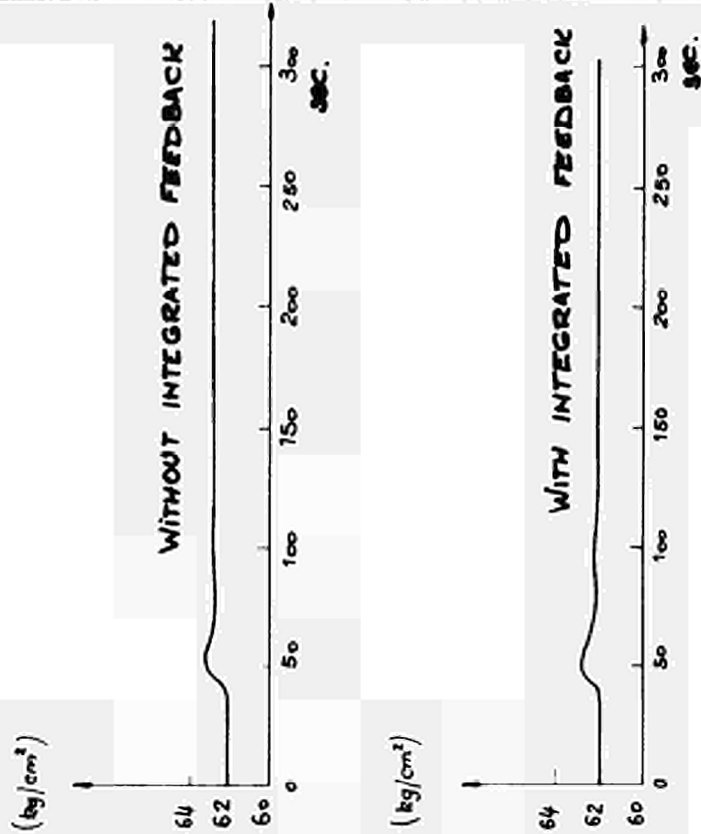
STABLE REACTOR: CASE 1 WITH ON-OFF CONTROL
RESPONSE TO A STEP OF 50 P.C.M.

DEAD ZONE : ± 1%
INERTIE TIME CONSTANT OF THE BAR : 2 SEC.
VARIABLE VELOCITY OF THE BAR

NEUTRON POWER

5 p.c.m./sec   OPTIMUM CASE

10 p.c.m/sec

15 p.c.m/sec

20 p.c.m/sec

Fig.1-72
GO-2041

DEAD ZONE : ± 0.5 %
INERTIA TIME CONSTANT : 2 SEC.
VARIABLE VELOCITY

Fig.1-73
GO-2043

DEAD ZONE : ± 2%
INERTIA TIME CONSTANT : 2 SEC.
VARIABLE VELOCITY

Fig.1-74
GO-2044

DEAD ZONE
BAR VELOCITY 5 p.c.m./sec.
VARIABLE INERTIA TIME CONSTANT

NEUTRON POWER   0.2 sec.

1 sec.

2 sec.

10 sec.

20 sec.

Fig. 1-75
GO-2042

DEAD ZONE : ± 1%
INERTIA TIME CONSTANT : 2 sec.
BAR VELOCITY : 1 p.c.m./sec.

NEUTRON POWER

1 p.c.m / sec

STEAM PRESSURE

Fig. 1-76
GO-2045

STABLE REACTOR: CASE 1 WITH ON-OFF CONTROL
CONSTANT - AVERAGE - TEMPERATURE PROGRAM

DEAD ZONE ± 1%
BAR VELOCITY : 5 p.c.m./sec.

NEUTRON POWER

Fig.1-77
GO - 2033

REACTIVITY OF THE BAR

Fig.1-78
GO - 2032

STEAM PRESSURE

Fig.1-79
GO-2031

AVERAGE COOLANT TEMPERATURE ON
THE BOILER SIDE

Fig.1-80
GO-2030

STABLE REACTOR: CASE 1 WITH ON OFF CONTROL

DEAD ZONE ± 1‰
BAR VELOCITY : 5 p.c.m./sec.
RESPONSE TO A STEP OF 200 μq.m.

NEUTRON POWER

RELAY RUNNING

Fig.1-81
GO-2022

STABLE REACTOR: CASE 1 WITH THERMAL
MEASUREMENT OF THE POWER

BAR VELOCITY : 15 p.c.m./sec.

$R_5 = 5.10^{-2}$

$R_4 = 10^{-2}$

INJECTION OF 50 p.c.m. IN STEP

NEUTRON POWER

Limit cycle

Fig.1-82
GO-2021

RESPONSE TO 50 p.c.m. IN STEP
BAR VELOCITY : 5 p.c.m./sec. (optimum)
DELAY IN THE TEMPERATURE MEASURE : 4 sec.

NEUTRON POWER

INJECTION OF THE STEP

$R_5 = 2,5.10^{-2}$
$R_4 = 0,5.10^{-3}$

$R_5 = 5.10^{-3}$
$R_4 = 0,5.10^{-3}$

$R_5 = 5.10^{-3}$
$R_4 = 0,2.10^{-3}$

$R_5 = 1.10^{-3}$
$R_4 = 0,5.10^{-3}$

$R_5 = 1.10^{-3}$
$R_4 = 0,2.10^{-3}$
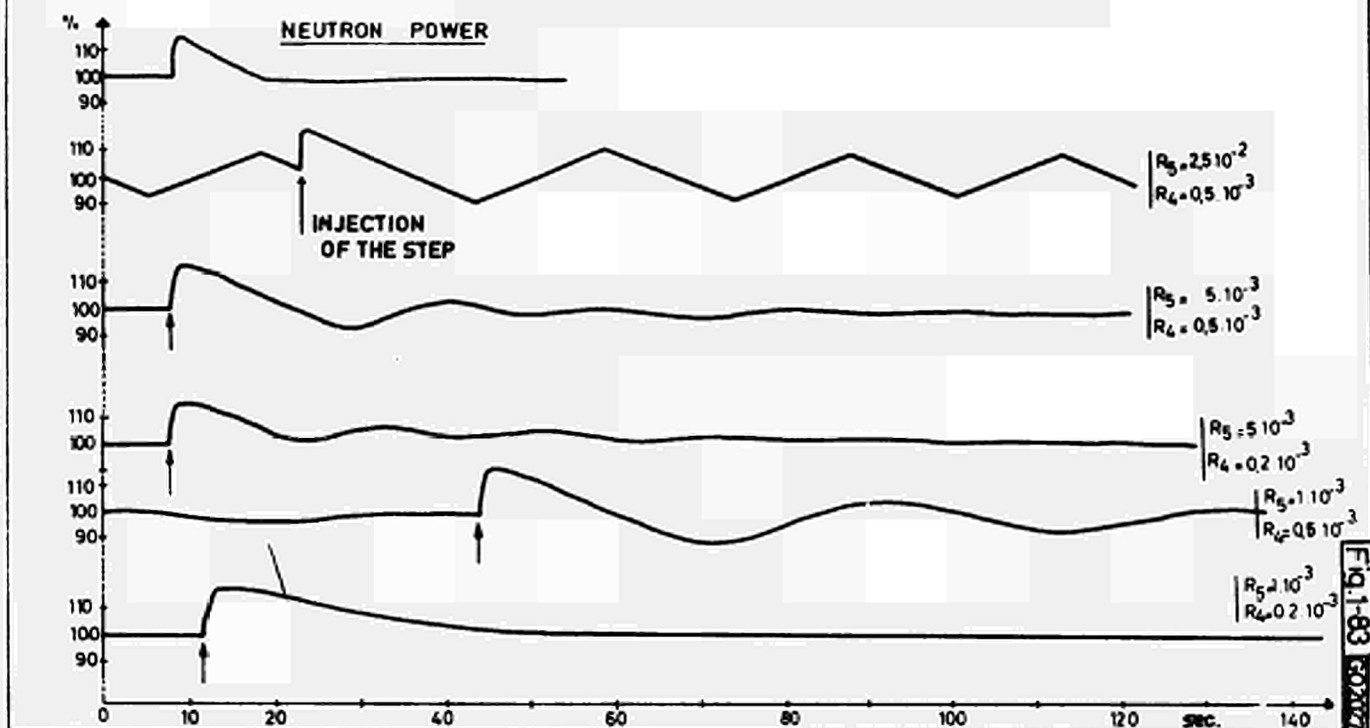
Fig.1-83 GO-2029

STABLE REACTOR : CASE 1. CONTROL LOSS WITH
INJECTION OF 50 p.c.m. IN STEP, WITHOUT RECOVERY
BUT WITH STEAM DISCHARGE AT 80 Kg/cm²
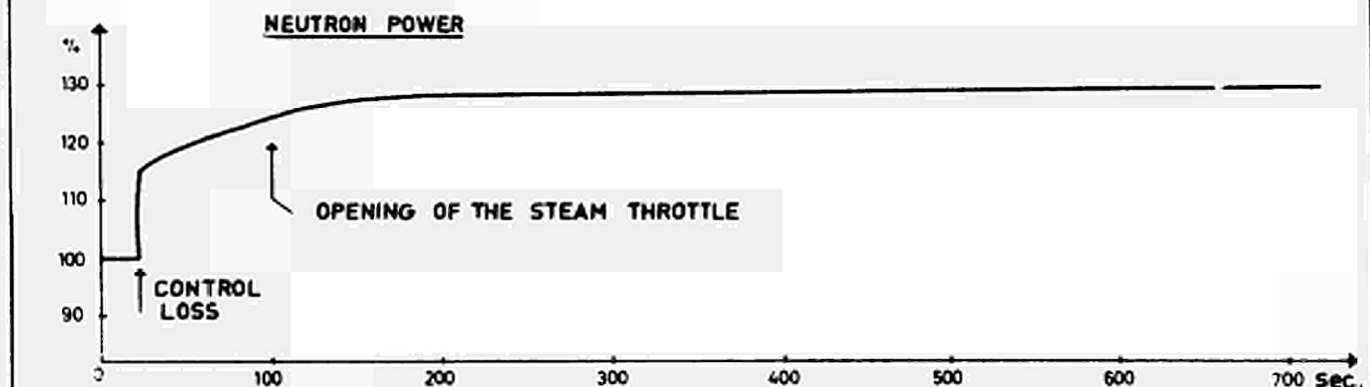
NEUTRON POWER

OPENING OF THE STEAM THROTTLE

CONTROL LOSS

Fig.1-84 GO-2029

AVERAGE COOLANT TEMPERATURE ON THE REACTOR-SIDE

Fig.1-85
GO-2028

STEAM PRESSURE

Fig.1-86
GO-2026

STABLE REACTOR : CASE 1. CONTROL LOSS WITH
INJECTION OF 50 p.c.m. IN 25 sec. WITHOUT
RECOVERY BUT WITH STEAM DISCHARGE
AT 80 Kg/cm².

Fig.1-87
GO-2020

AVERAGE COOLANT TEMPERATURE ON THE REACTOR SIDE

Fig.1-88
GO-2019

STABLE REACTOR: CASE 2.ON OFF CONTROL RESPONSE TO 50 p.c.m. IN STEP

Fig. 1-89 GO-2037

STABLE REACTOR: CASE 2.ON-OFF CONTROL AND THERMAL MEASURE OF THE POWER

Fig. 1-90 GO-2034
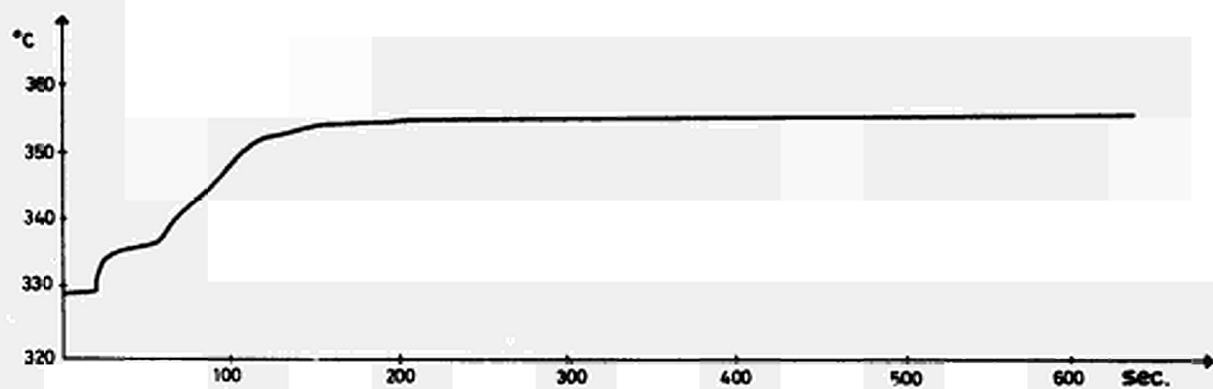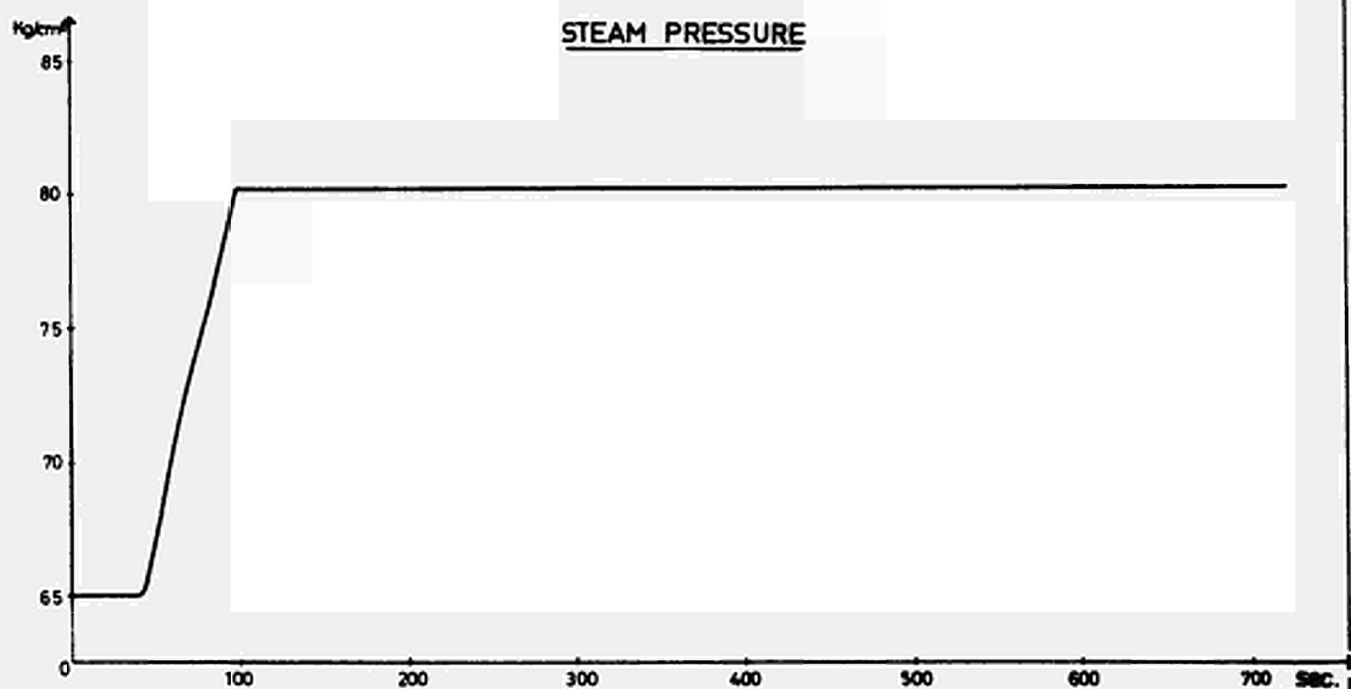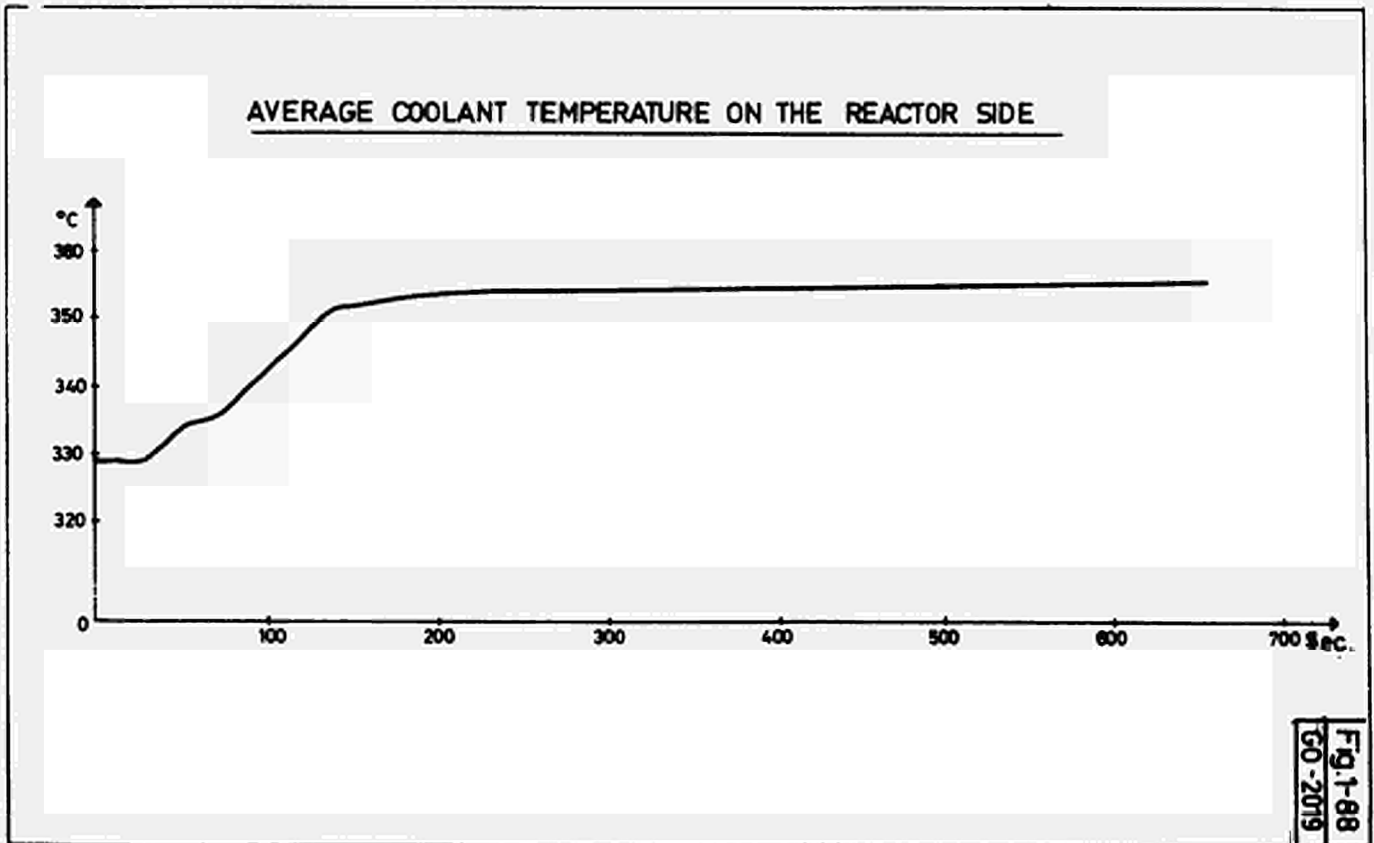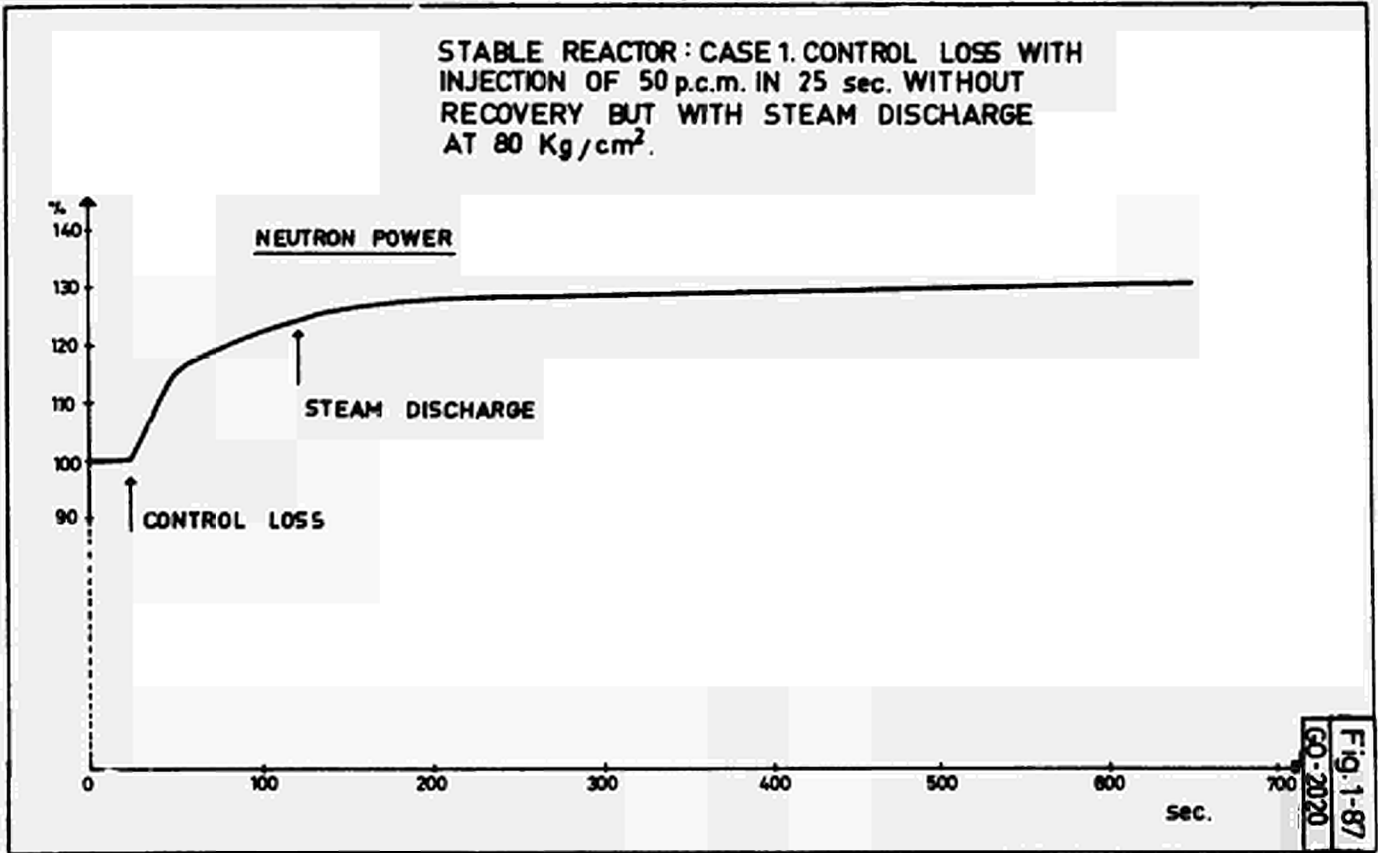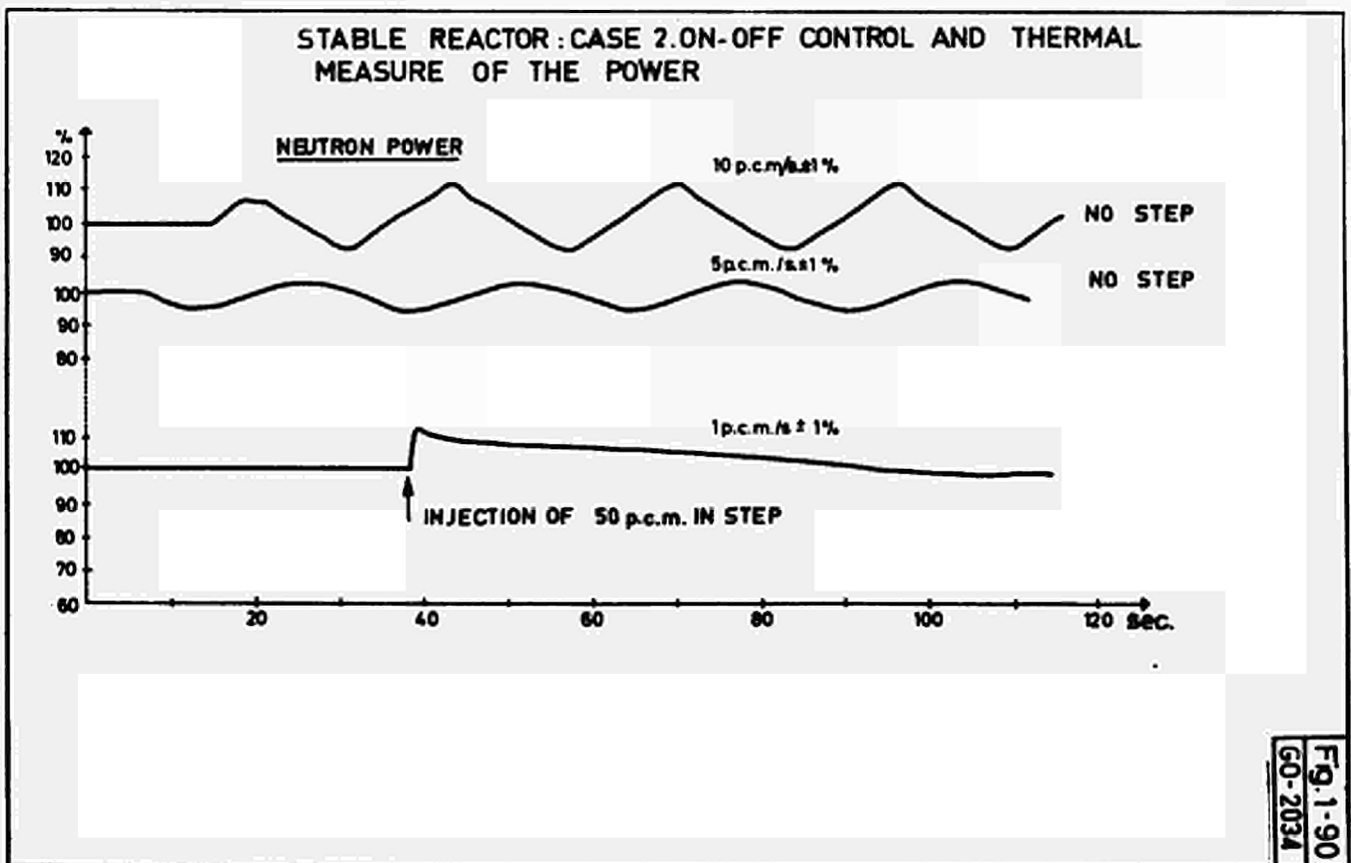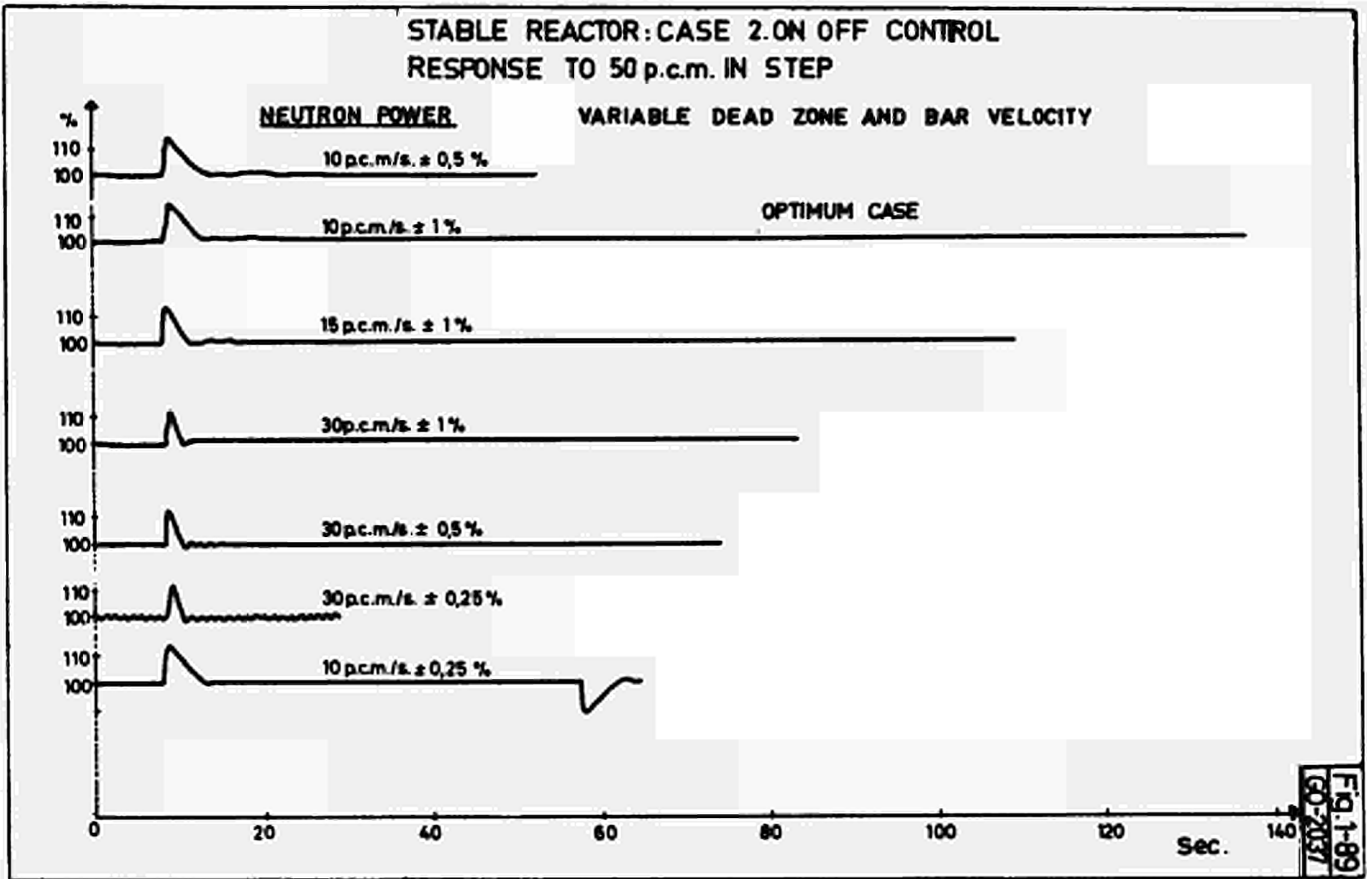
POWER CHANGE FROM 100 TO 75 % (5%/min.)
CONSTANT AVERAGE TEMPERATURE PROGRAM

DEAD ZONE ± 1 %
BAR VELOCITY : 1 p.c.m. / sec.

NEUTRON POWER
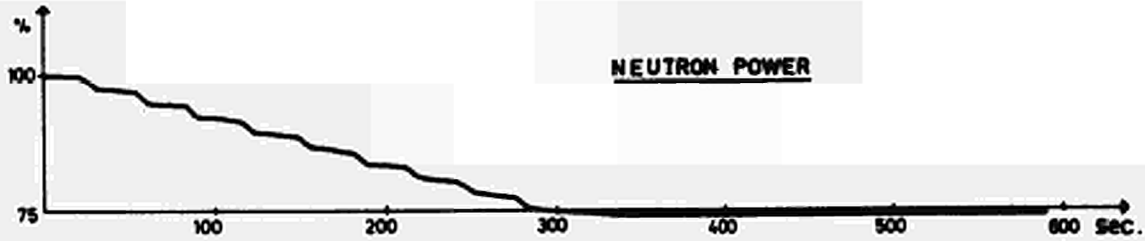
Fig.1-91
GO-2035

AVERAGE COOLANT TEMPERATURE ON THE BOILER SIDE

Fig.1-92
GO-2036

STABLE REACTOR : CASE 2 WITH PROPORTIONAL CONTROL AND THERMAL MEASURE OF THE POWER

Fig.1-93
GO-2038

STABLE REACTOR : CASE 2. CONTROL LOSS WITH INJECTION OF REACTIVITY WITHOUT RECOVERY, AND STEAM DISCHARGE AT 80 kg/cm²

Fig.1-94
GO-2039

STABLE REACTOR: CASE 2-SCHEME WITH PROPORTIONAL REGULATION ON NEUTRON POWER, THERMAL POWER, AVERAGE TEMPERATURE. CUTTING OF THE DIFFERENT CIRCUITS WITH INJECTION OF 50 p.c.m.

MAXIMAL BAR VELOCITY : 15 p.c.m./sec.
$R_1 = R_2 = 1$
$K = 0,5$
$R_t = 0,5 . 10^{-3}$
$R_g = 2,5 . 10^{-3}$

COMPLETE CIRCUIT $R_t = 0,5 . 10^{-3}$
                          $R_g = 2,5 . 10^{-3}$

NEUTRON CIRCUIT CUT

TEMPERATURES CIRCUIT CUT

WITHOUT REGULATION

Fig.1-95
GO-2040

STABLE REACTOR : CASE 2. SCHEME WITH PROPORTIONAL REGULATION ON NEUTRON POWER, THERMAL POWER, AVERAGE TEMPERATURE - CONSTANT AVERAGE TEMPERATURE PROGRAM FROM 100 TO 75 % OF THE POWER (5 %/Min.)

COURBE 1 : COMPLETE CIRCUIT
COURBE 2 : NEUTRON CIRCUIT CUT 40 sec. AFTER THE POWER RAMP
COURBE 3 : TEMPERATURE CIRCUIT CUT 40 sec. AFTER THE POWER RAMP

NEUTRON POWER

Fig.1-96
GO-2023

AVERAGE COOLANT TEMPERATURE
ON THE BOILER SIDE

Fig. 1-97
GO-2024

STEAM PRESSURE

Fig.1-98
GO-2025

FIG. 2-1

FIG 2-2

Characteristics of the primary valves

- • $A(y) = 4.3651 \times 10^{-2} + 2.9649 \times 10^{-1} \times y^2 + 6.5419 \times 10^{-1} \times y^4$
- —— Given function

A(y)

Y % Valve opening
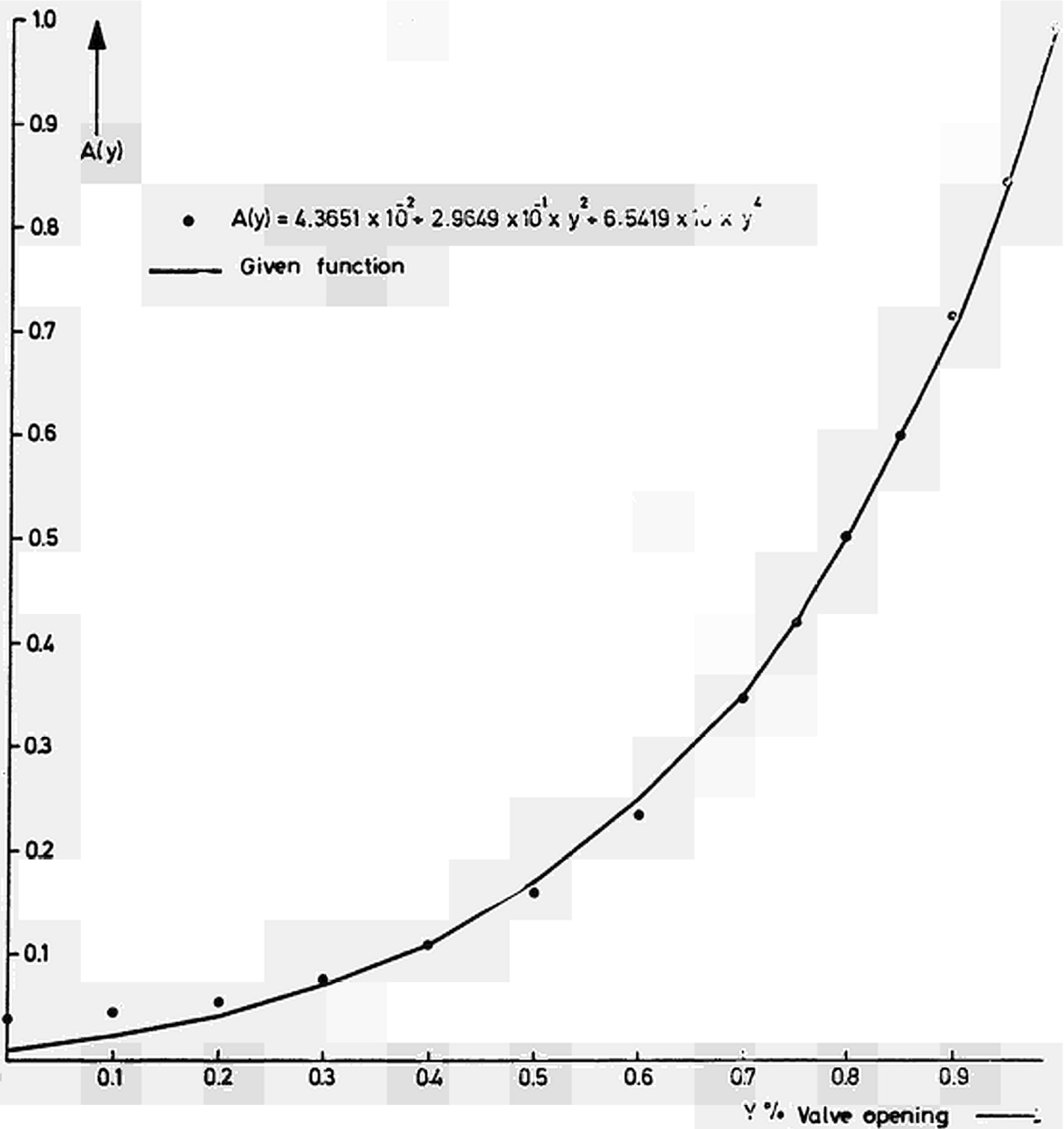
FIG 2-3

Characteristics of the primary pumps

DELPO (bar)

15

10

5

n = 1

n = 0.9

n = 0.8

n = 0.5

0   500   1000   1500

(kg/sec)

FIG. 2-4

Collector   PD002 , TD002, RO002, HD002

FD002
To   the
turbine

FD402   FD302   FD202   FD102
TD402   TD302   TD202   TD102

4   3   2   1

ECO – EVA – SUR   ECO – EVA – SUR   ECO – EVA – SUR   ECO – EVA – SUR

Boilers

TD101 | Regulation
FD401   FD301   FD201   FD101 | valves

PD001
FD001
TD001

$FD_{201} = FD_{101}$

Pump
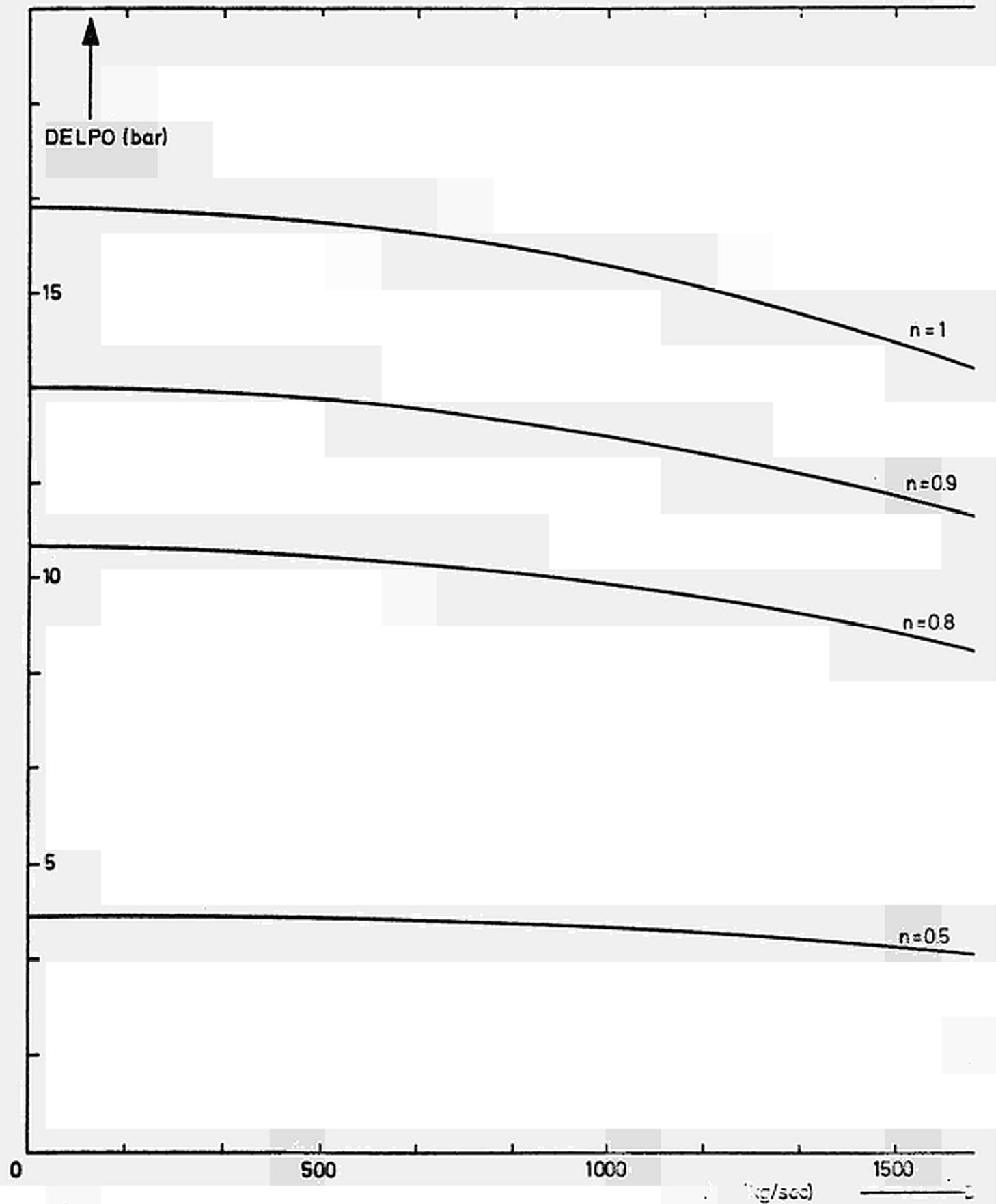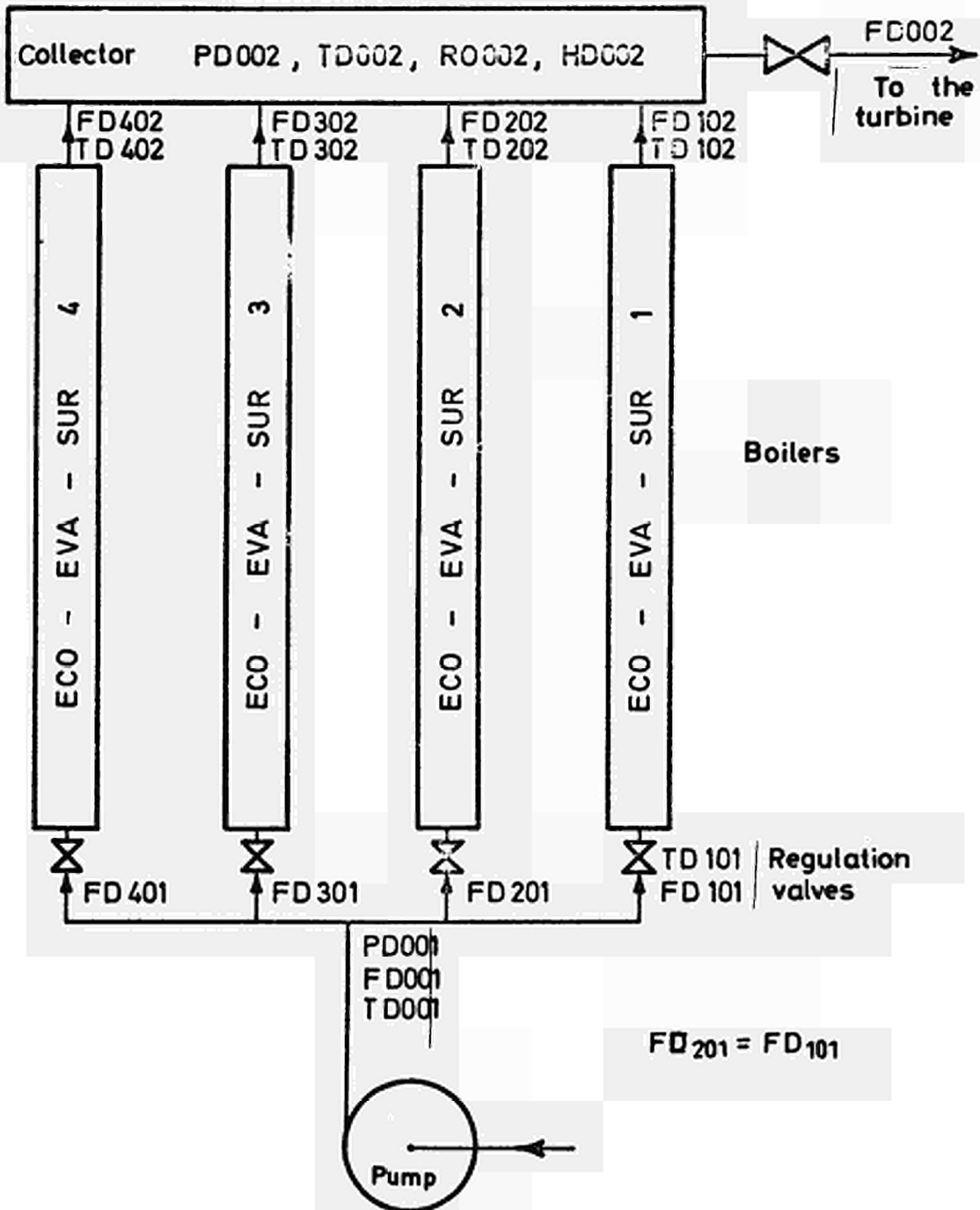
FIG. 2.5
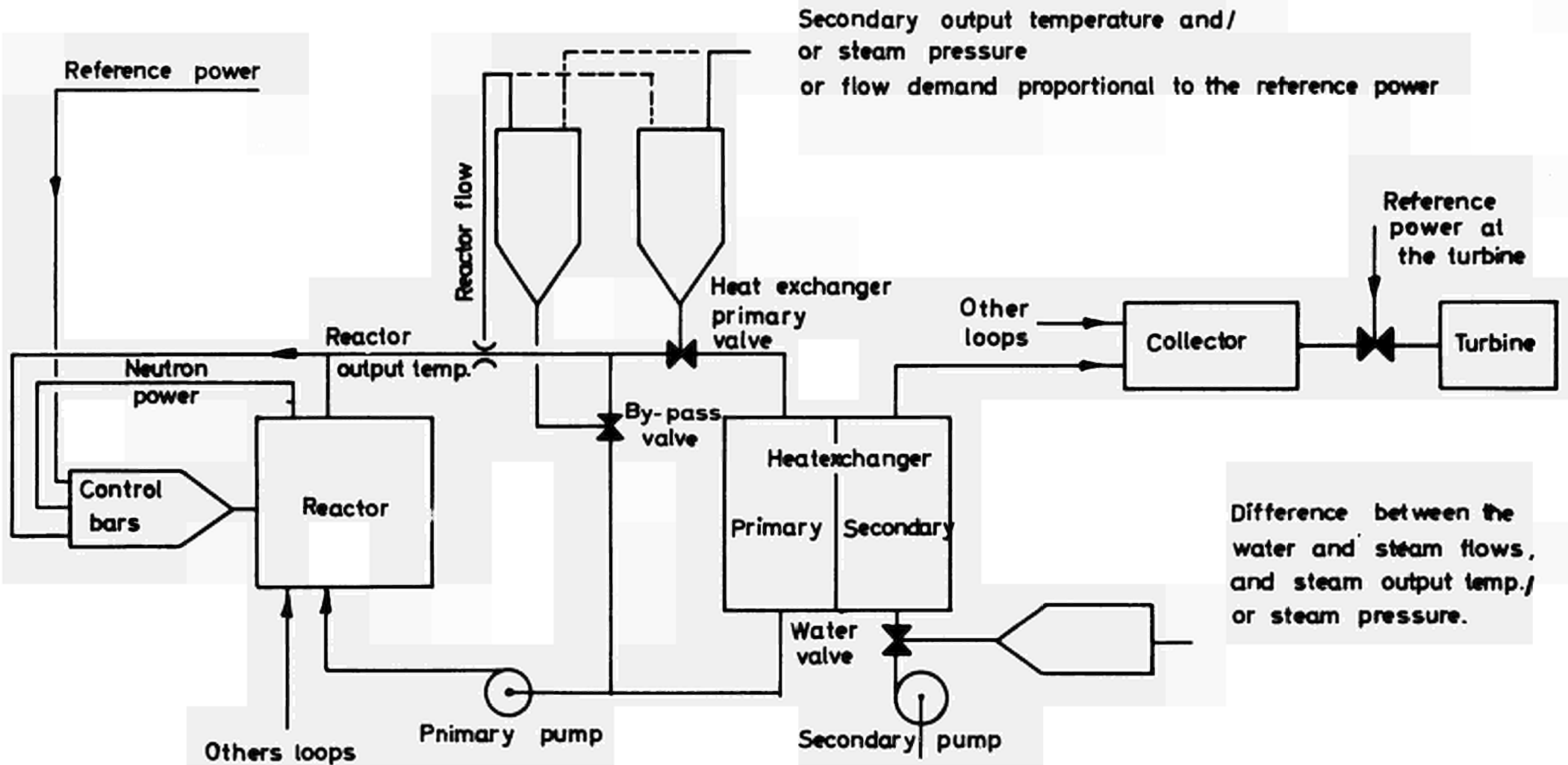
FIG 2·6

F_1 F_2 F_3 as function of Y_2
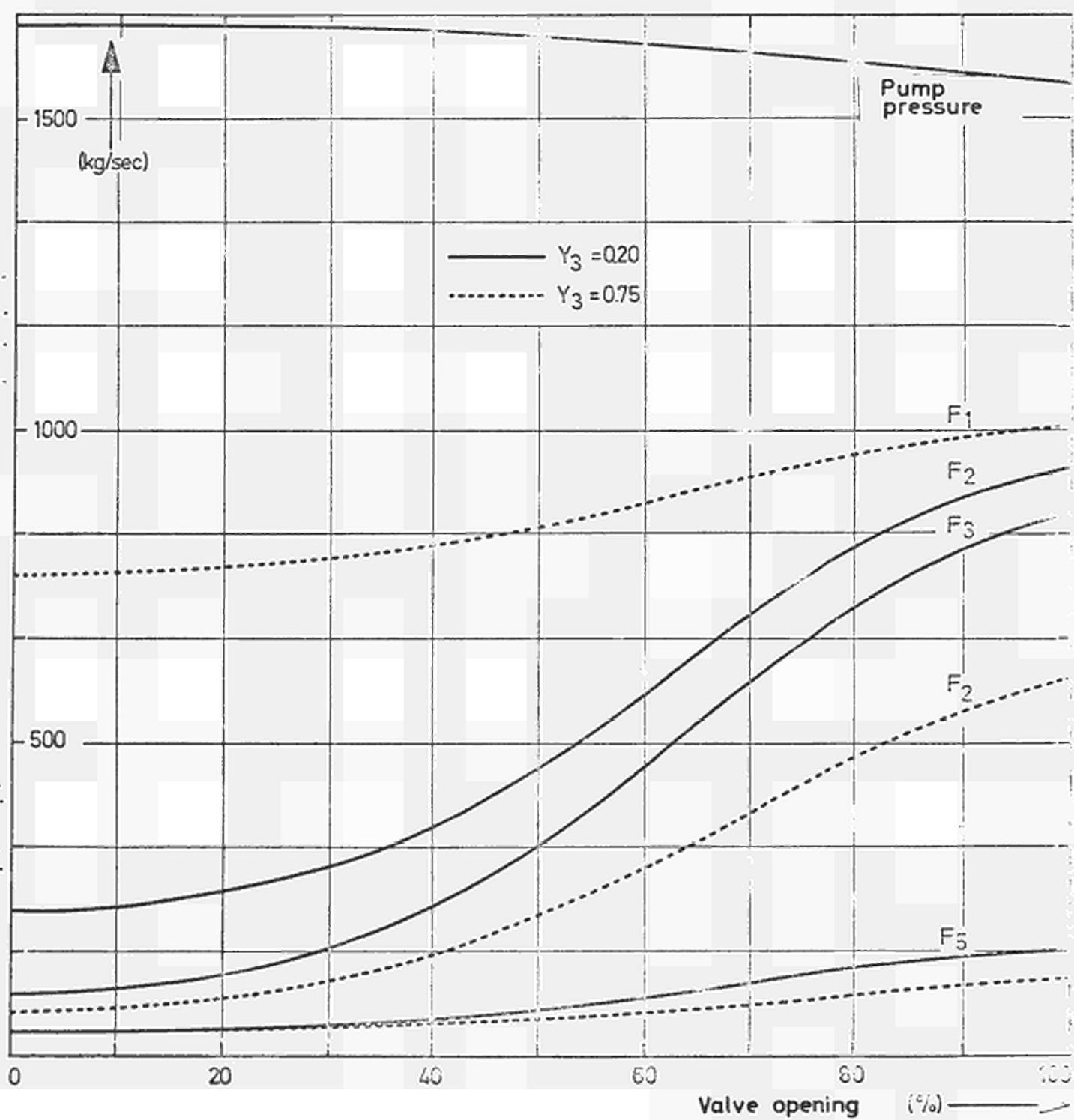
FIG. 2-7

Position of Y_3 vs Y_2 for F_1 constant
F_1 is constant Y_5 completely open
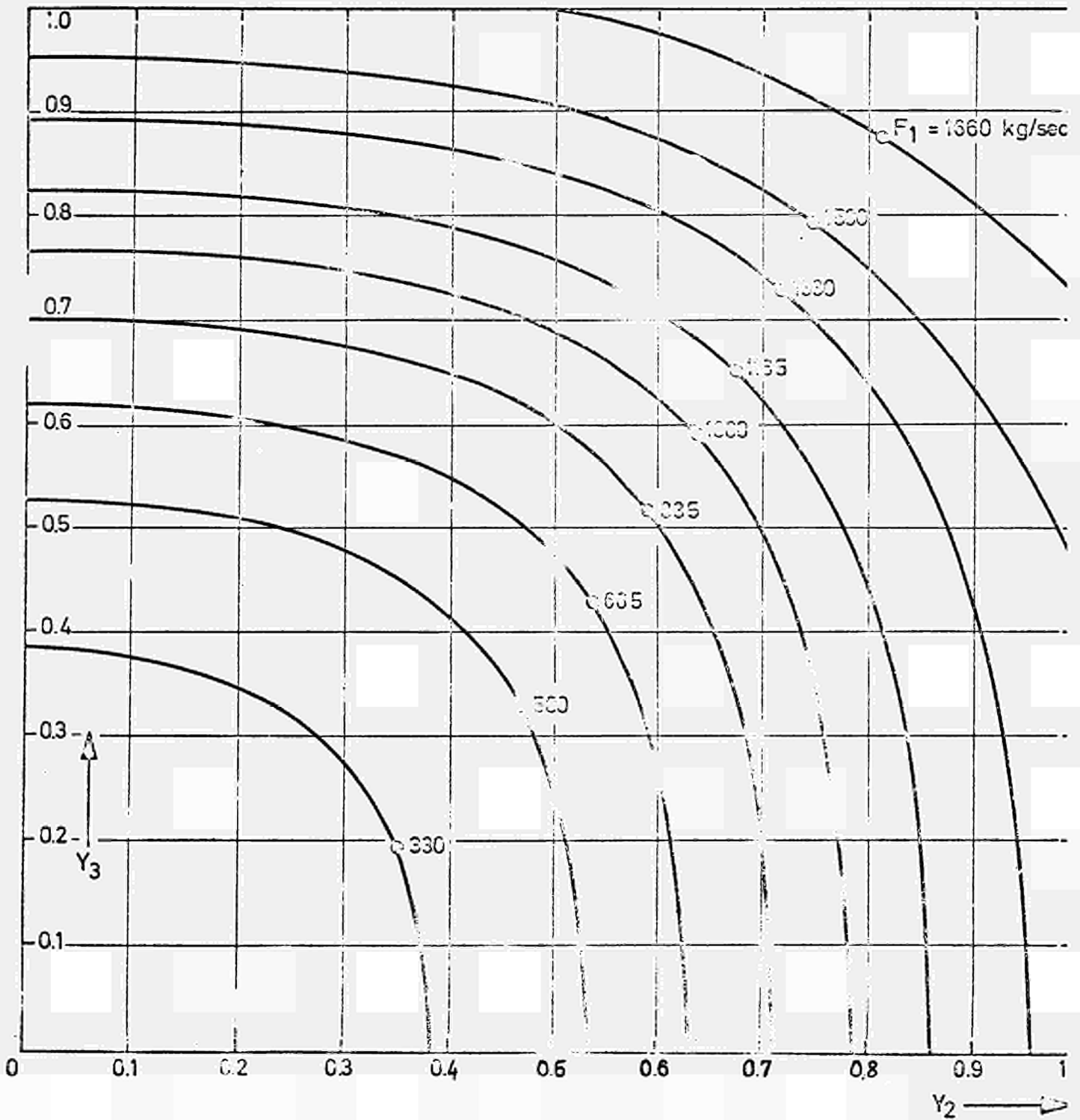
FIG. 2-8

Flow in the heat exchanger and in the reheater (F_2) as function of the total flow F_1
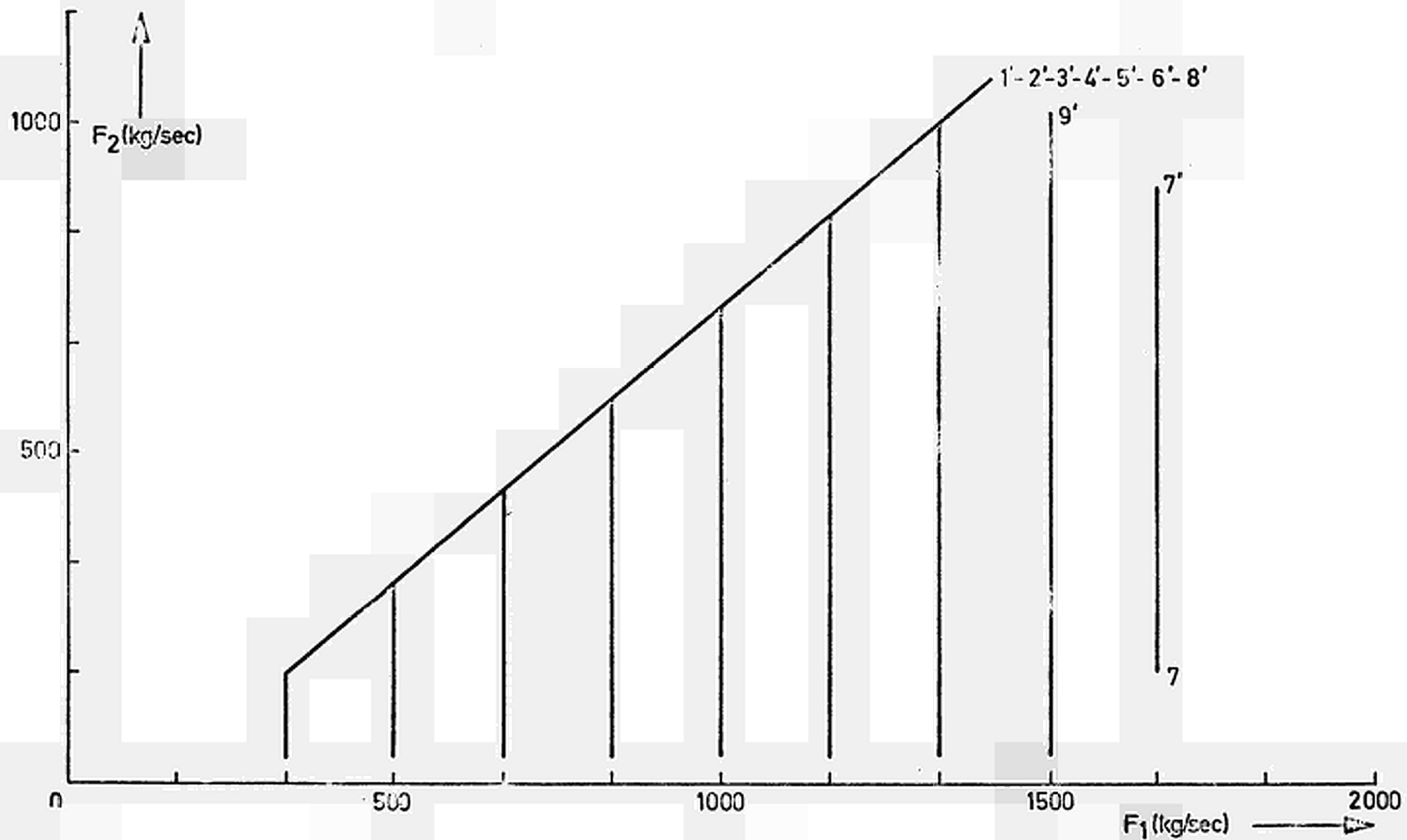
FIG. 2-9

Flow in the reheater (F_5) as function of the total flow F_1

FIG. 2-10

Valve opening

| | 0.50 | 0.54 | 0.56 | 0.57 | 0.575 | 0.58 | 0.58 |

FD 1 kg/sec **Water flow**

FD 2 kg/sec Steam flow

PD 2 kg/cm^2 Pressure at the steam collector

TS (7) °C Steam output temperature
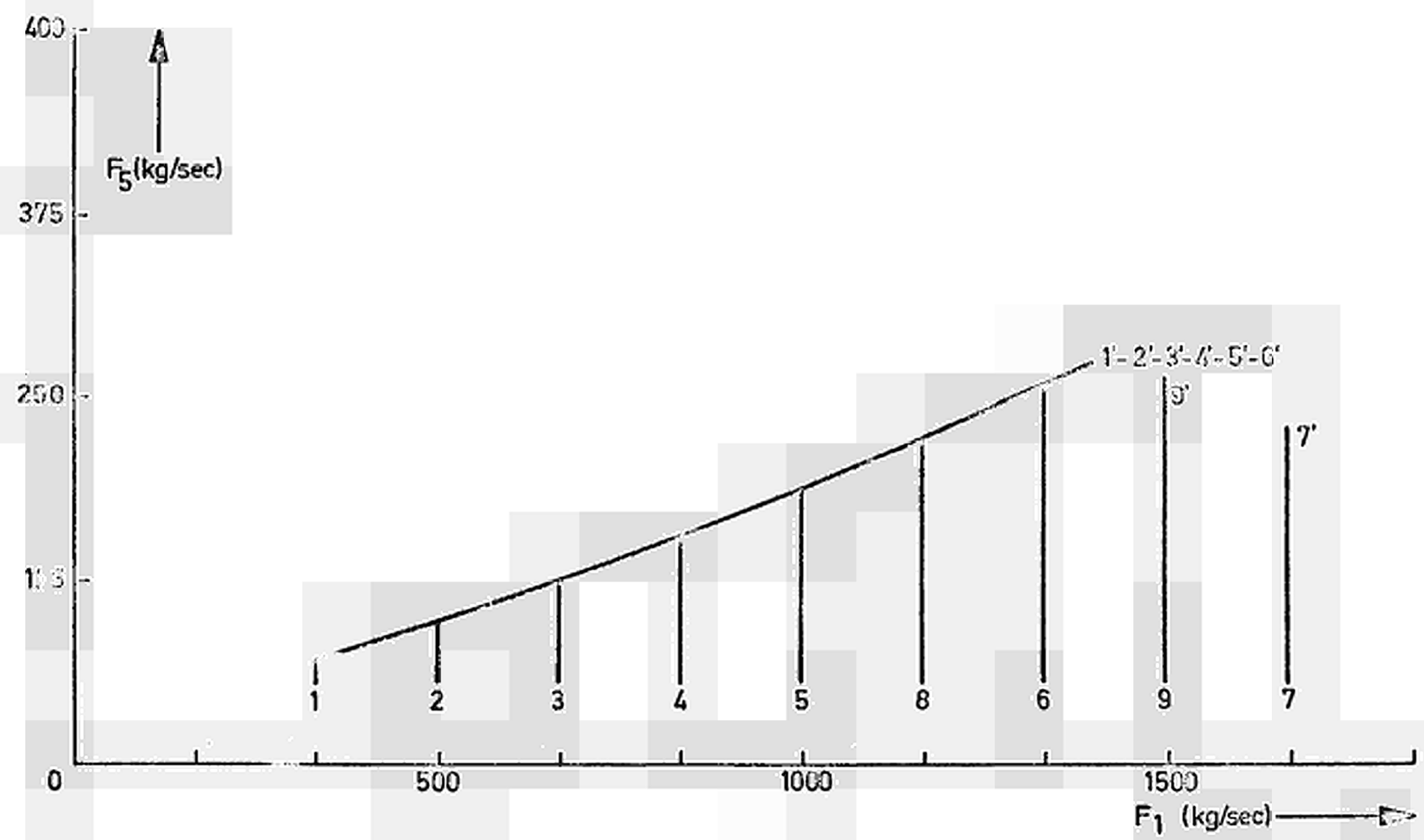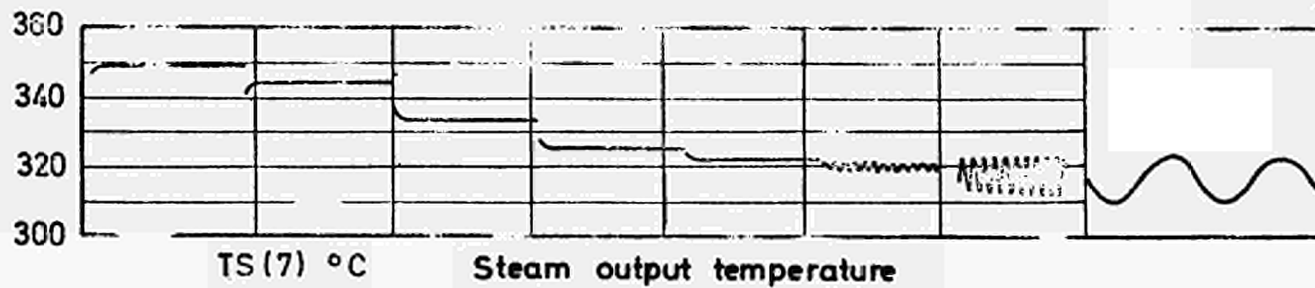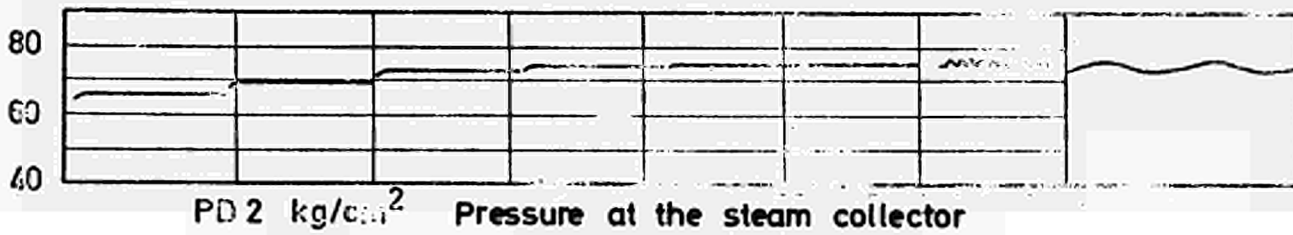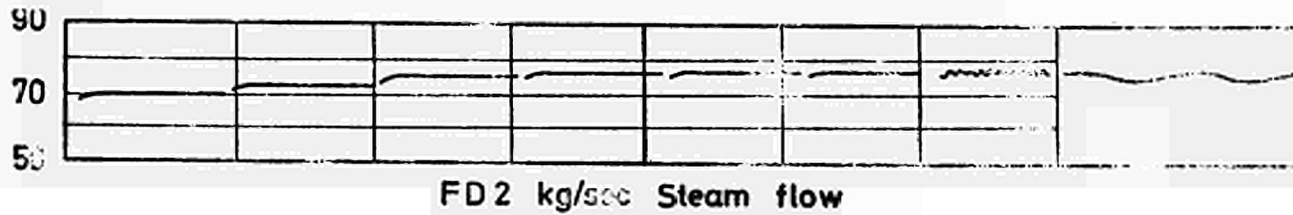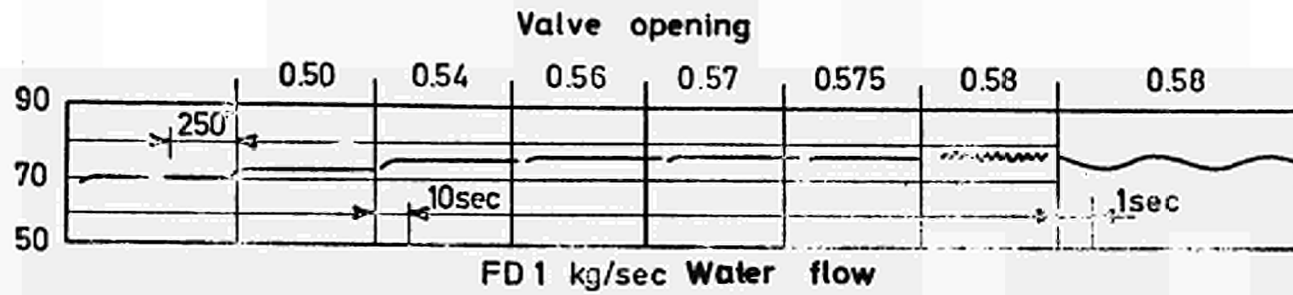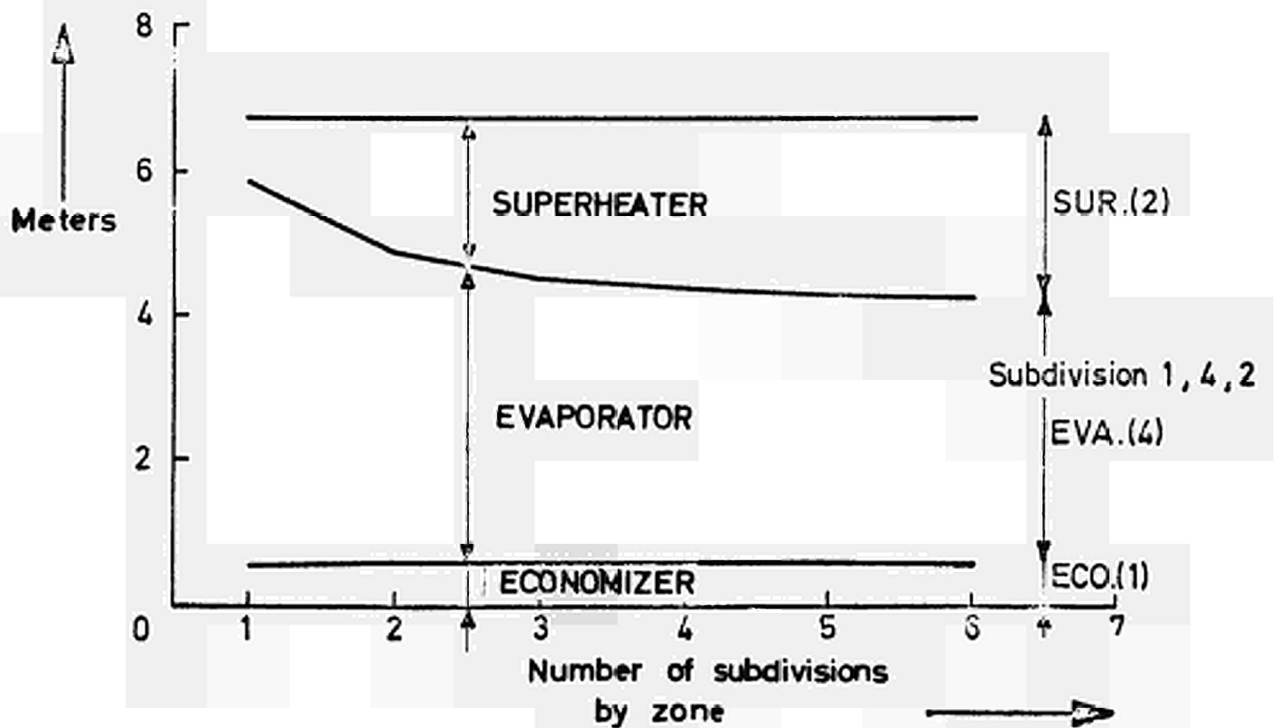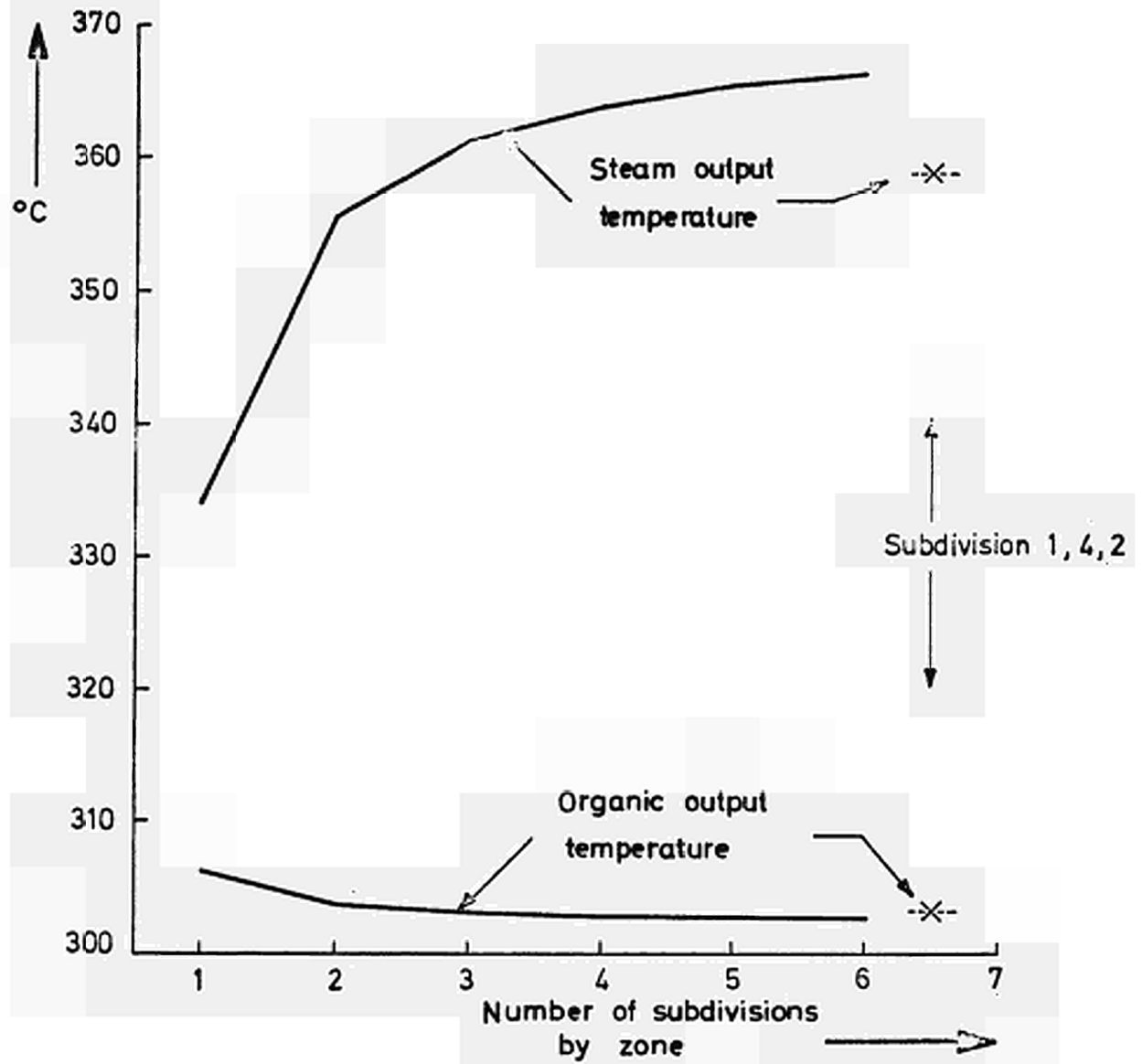
FIG. 2-11

FIG. 2-12

Constant organic input temperature

161

FIG. 2-13

Organic flow

Primary output temperature

162
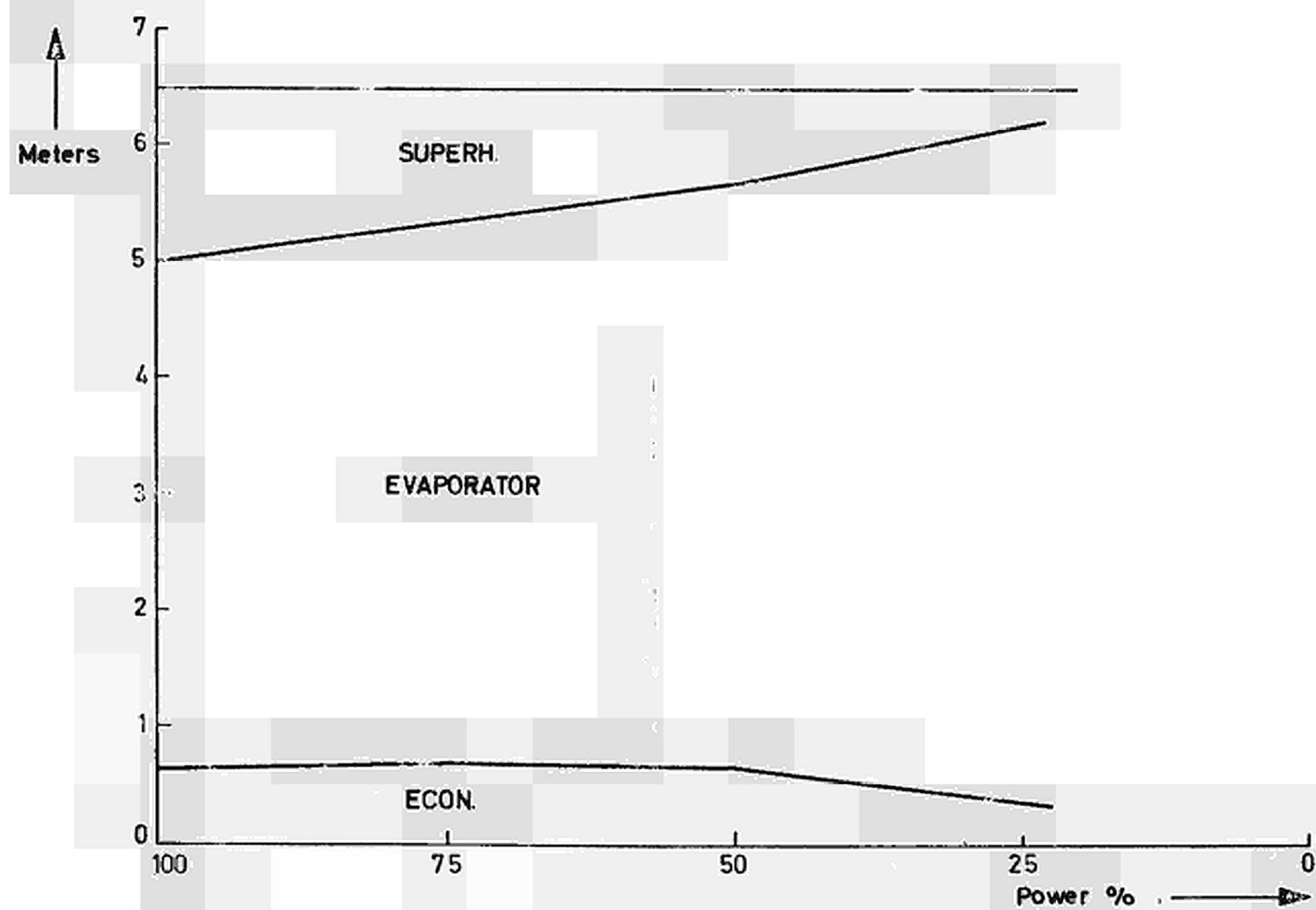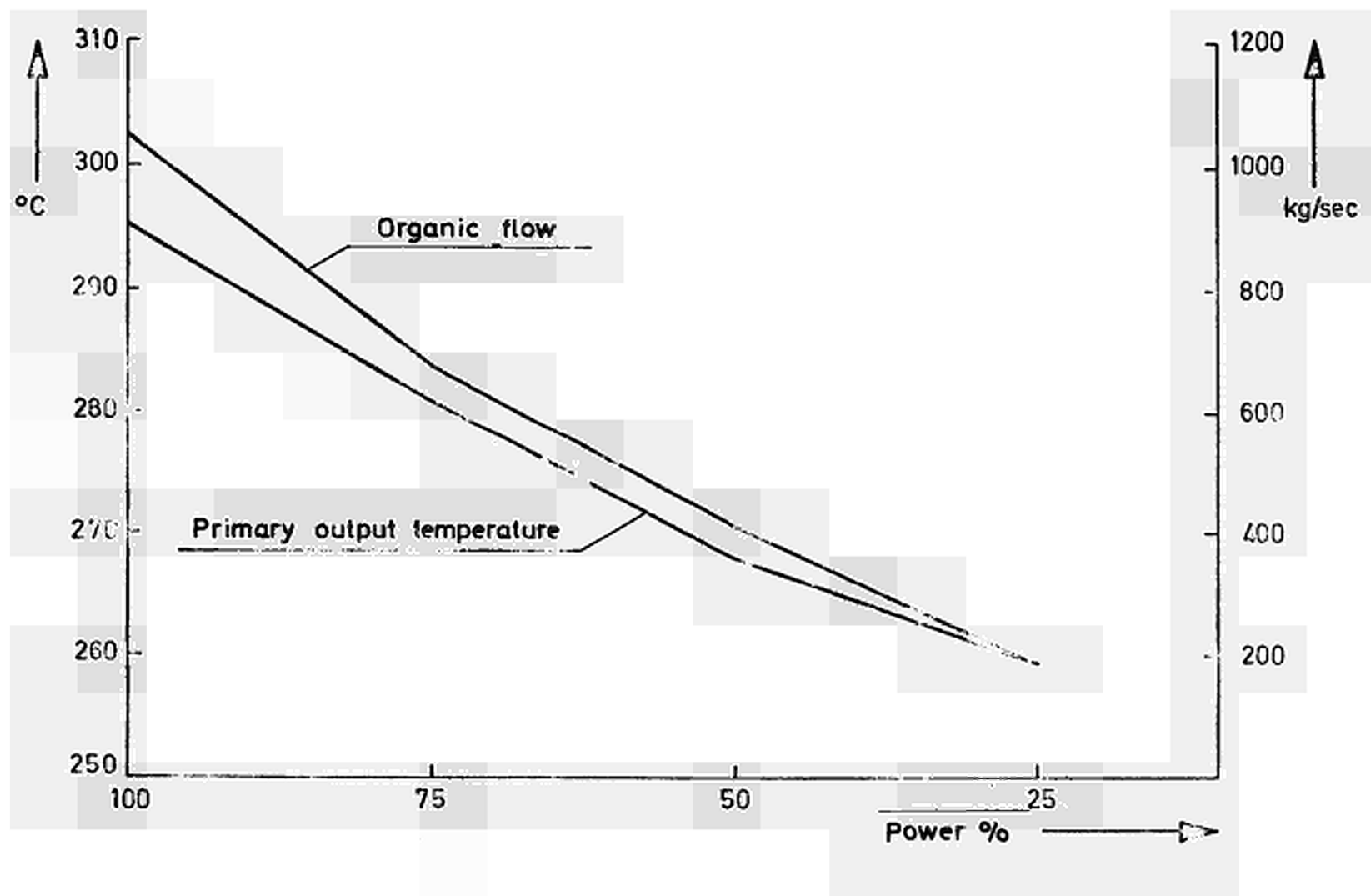
FIG. 2-14

Constant primary flow

SUPERHEATER

EVAPORATOR

ECON.

Meters

Power %

I63
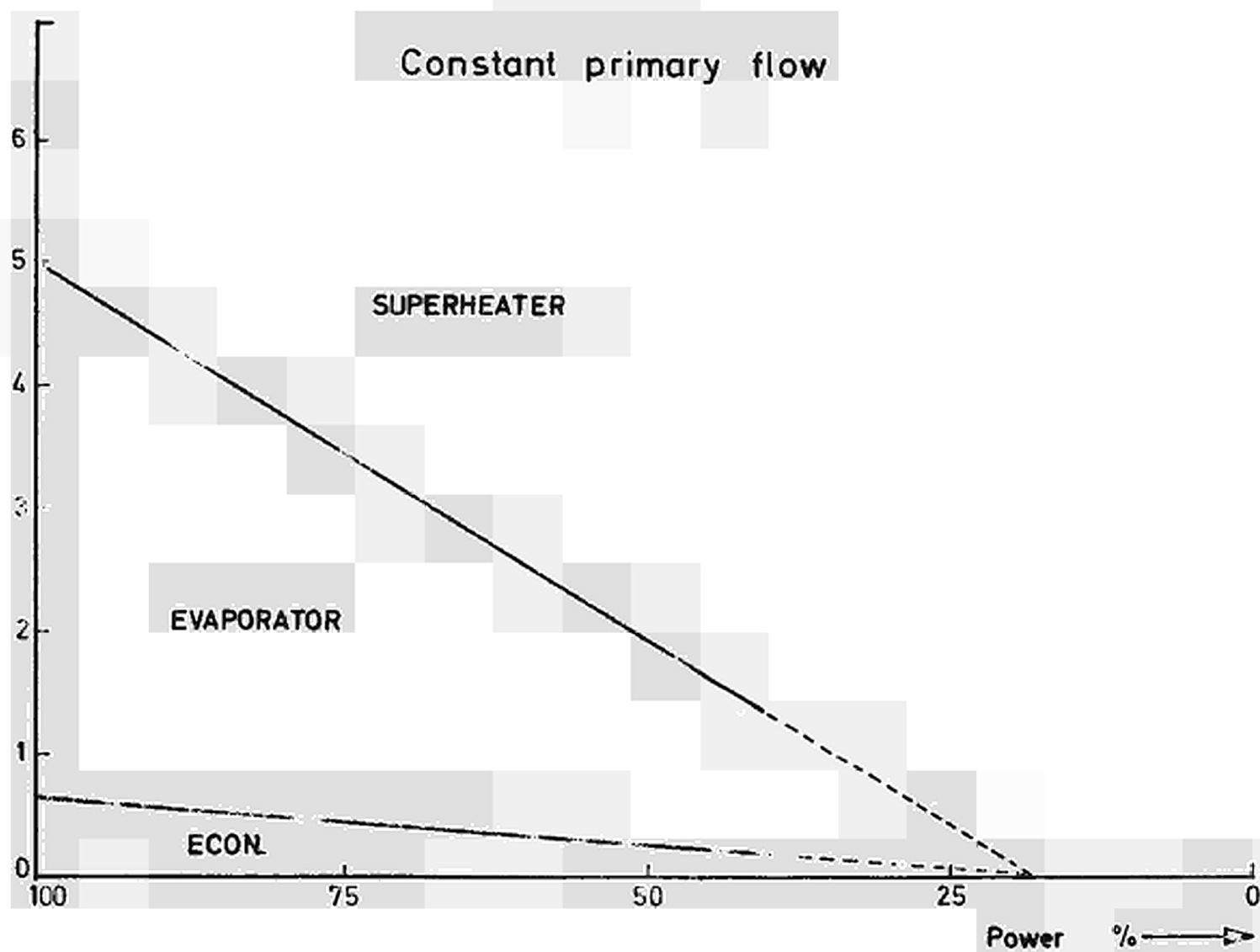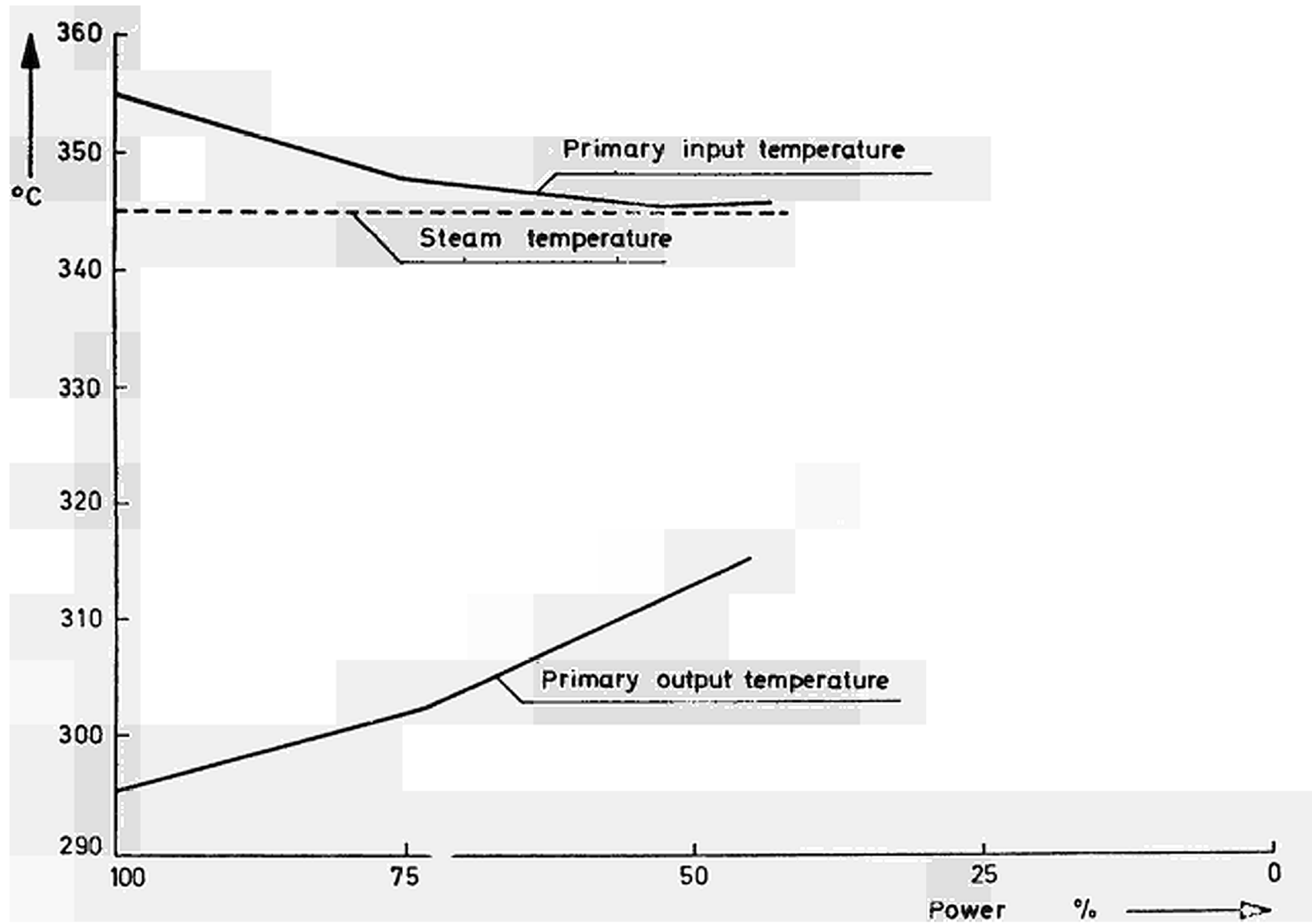
FIG. 2-15

FIG. 2-16

Organic input temperature and variable primary flow

FIG. 2·17

FIG. 2-18

Transfer function response of the Benson
Organic input temp./Output steam temp.
Input step : 5 % of ΔT (2.75°C)

Primary flow   1055 kg/sec
Secondary flow   72 kg/sec
Organic input temp. 355 °C

Response at 100 % of the nominal power

Steam temp.

345°C

Negative step

100 sec

100%

100%

1°C

10 sec

100%

Positive step

345 °C

FIG. 2-19

Scheme with by-pass

Transfer fonction response of the Benson
Input temp./Steam temp.
Response to a step of 5% (ΔT=275°C)

Prim. flow   675 kg/sec ≝75% nom. fl.
Sec. flow   54 kg/sec   "   "
Org. input temp   355 °C

Case 75% a)

FIG. 2-20

Scheme with by pass

Transfer function of the Benson
Input temp./Output temp.
Response to a step of 5%=2.75°C

Primary flow   408   kg/sec
Secondary flow   36   kg/sec
Org. input temp.   355   °C
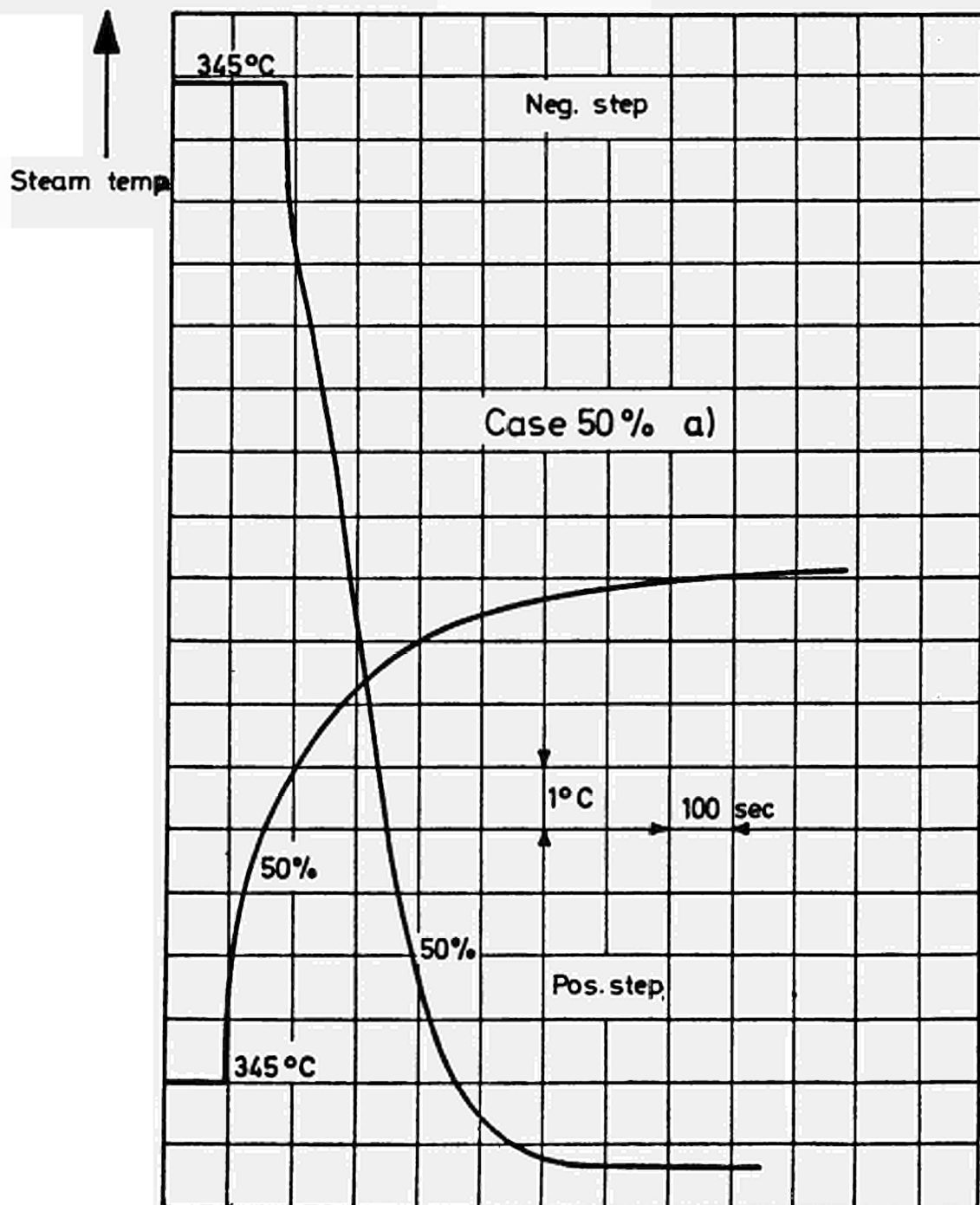
FIG. 2-21

Scheme with by-pass

Tranfer function of the Benson
Input flow / Output temperature
Response to a step of 2%

Primary flow	1055 kg/sec.
Secondary flow	72 "
Org. input temp.	355 °C

345 °C Pos. step

Case 100%

Steam temp.

1°C   100 sec
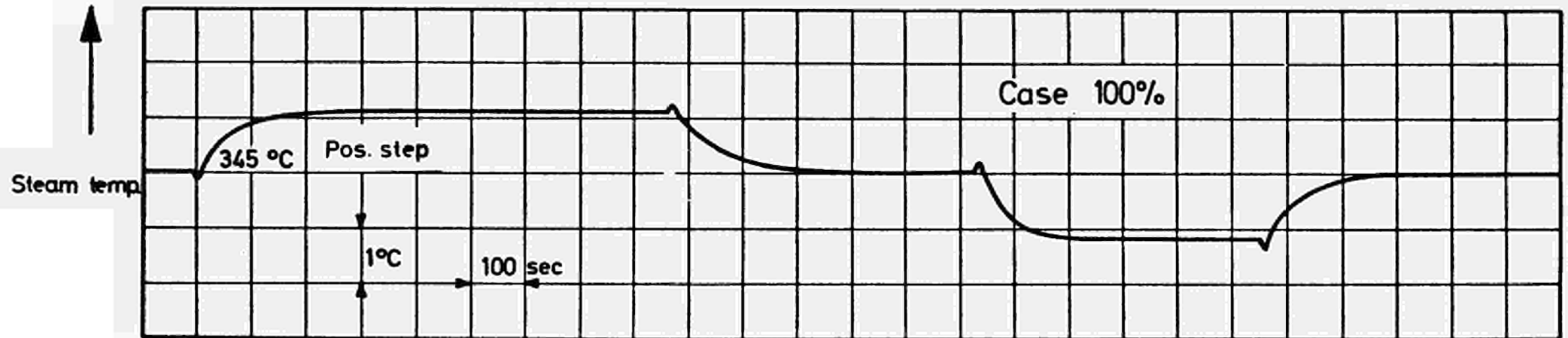
FIG. 2-22

Scheme with by-pass

Transfer function of the Benson
Primary flow/Secondary temperature
Response to a step of 2%

Primary flow   675 kg/sec.
Secondary flow   54   "
Prim. input temp.. 355 °C

Steam temp.

345 °C

Case 75% a)

1°C

100 sec
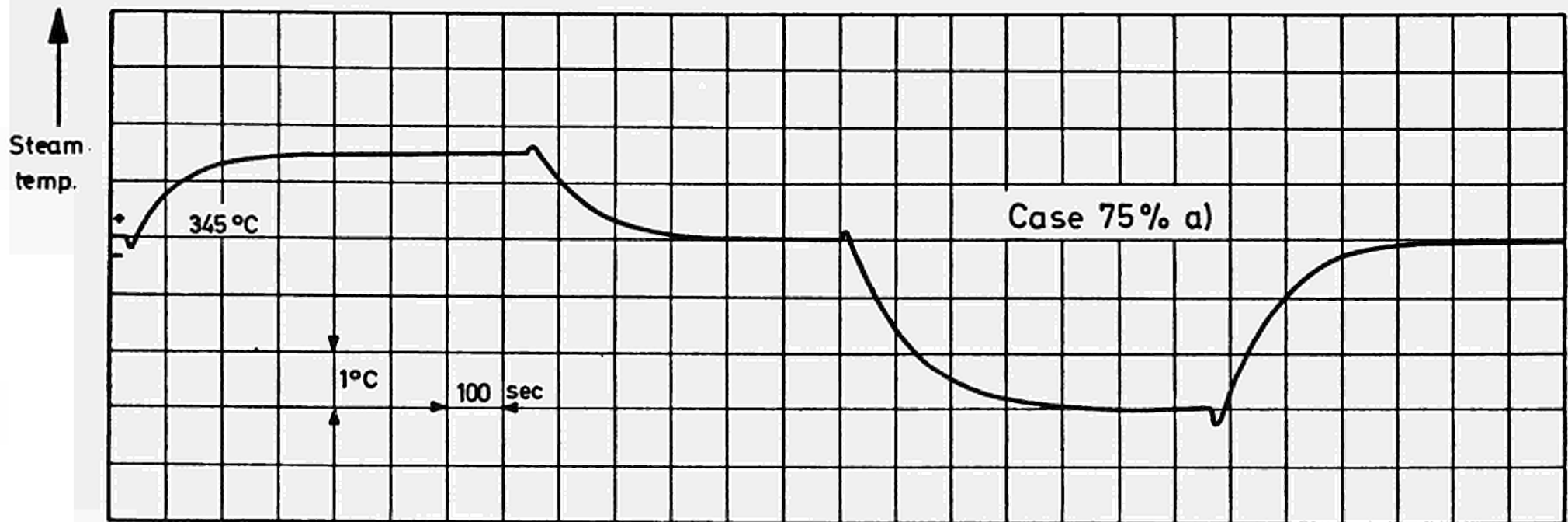
FIG. 2-23

Scheme with by pass

Transfer function of the Benson
Primary flow/Secondary temperature
Response to a step of 2%

Primary flow   408 kg/sec
Secondary flow   36 "
Primary input temp.   355 °C

Steam temp.

345°C

Neg. step

1°C   100 sec

Case 50% a)

Pos. step

345°C
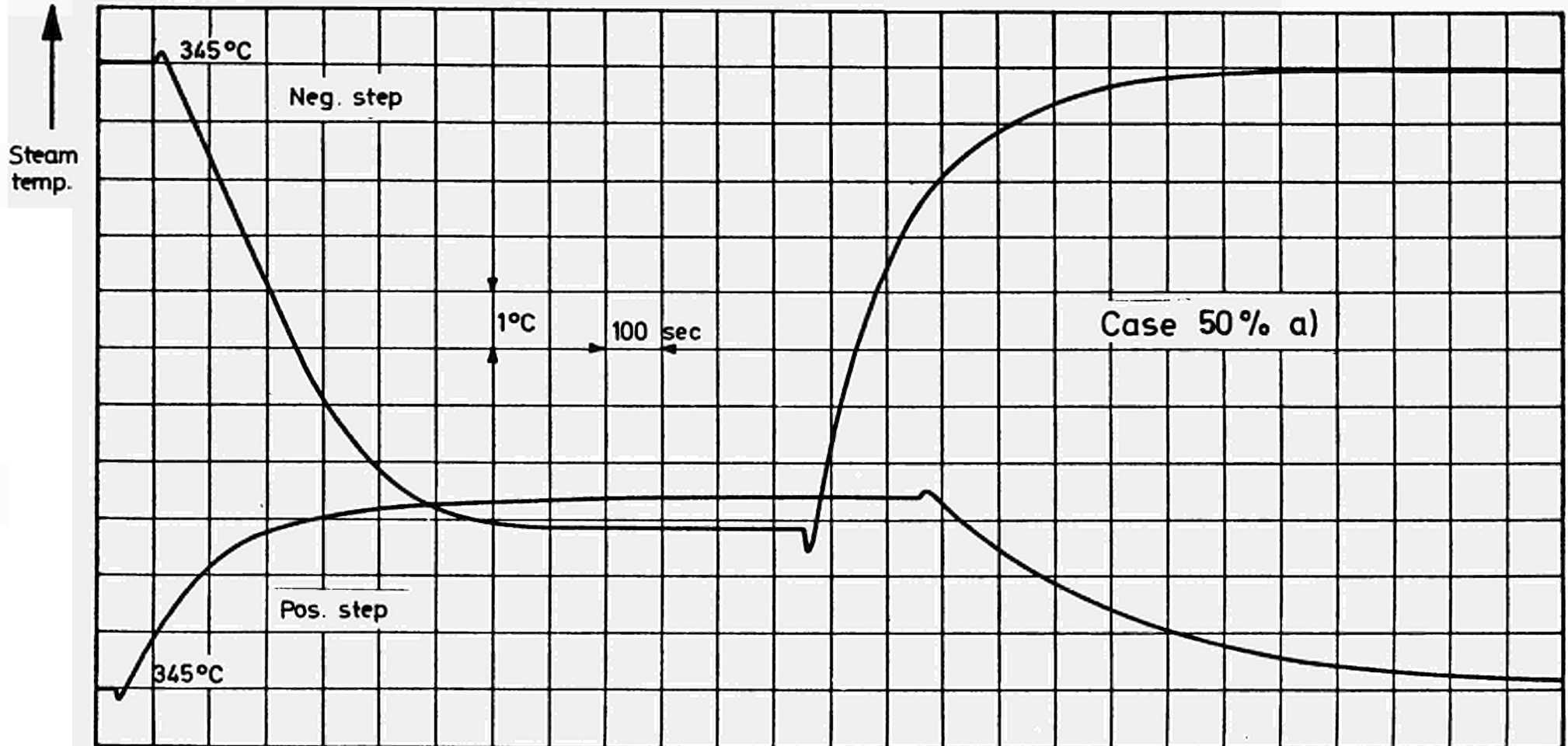
FIG. 2-24

Scheme without by pass

Transfer function of the Benson
Input temp./Output temp.
Response to a step of 5% = 2.4°C

Primary flow   1055 kg/sec
Secondary flow   54 kg/sec
Org. input temp.   = 348°C

345°C

Steam temp.

Neg. step

1°C

10 sec

Case 75% b)

Pos. step

75%

345°C
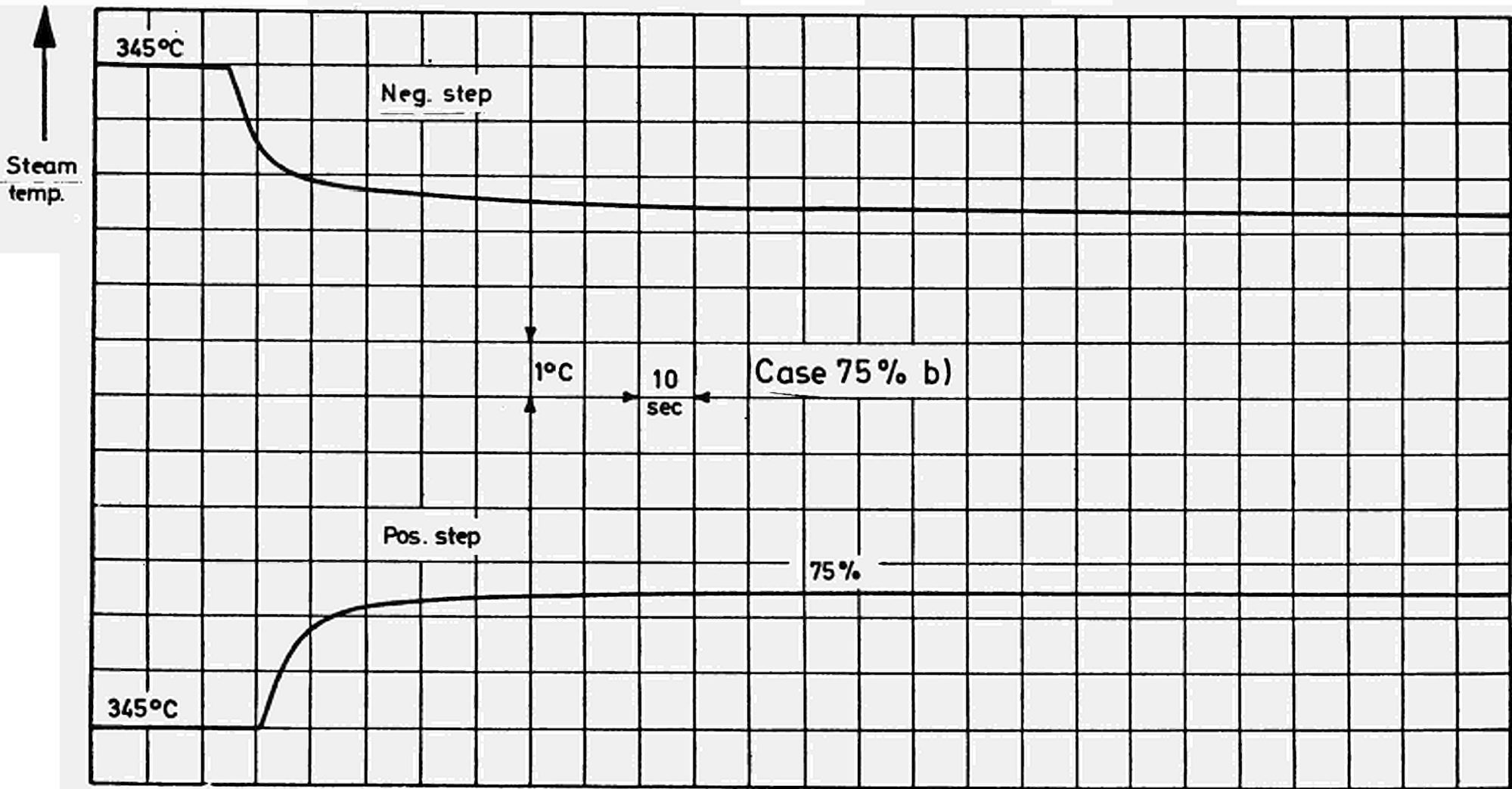
FIG. 2-25

Scheme without by pass

Transfer function of the Benson
Input temp. / Output temp.
Response to a step of 5% ≡ 2.27 °C

Primary flow   1055 ≡ max. flow
Secondary flow   36 kg/sec.
Org. input temp.   = 345,5 °C

Steam temp.

345°C

Pos. step

1°C

10 sec

Case 50% b)

345°C

Neg. step
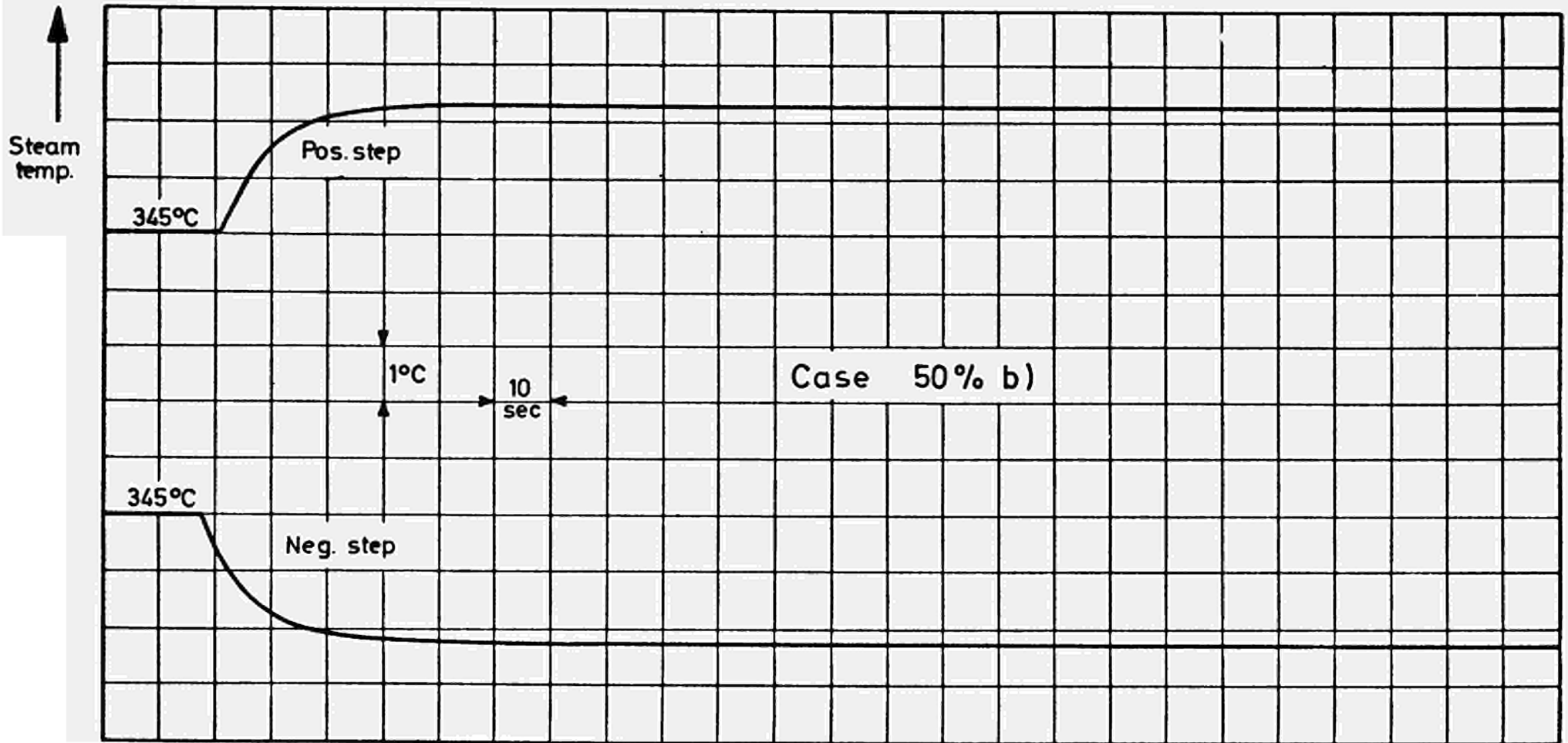
FIG. 2-26

Response to a primary flow step of 2%, for different power levels varied according to the scheme C.

The primary flow and the organic temp. are varied in the same time in order to maintain the reheater height in the Benson and the steam output temperature constant.

Steam temp.

345°C   75%W

1°C   100 sec

Primary flow   729 kg/sec
Secondary flow   54   "
Primary input temp. 352 °C

Steam temp.

345°C   50%W

1° C   100 sec

Primary flow   458 kg/sec
Secondary flow   36   "
Primary input temp. 350 °C

Steam. temp.

Continuation

345°C   25%W

1°C   100 sec

Primary flow   220 kg/sec
Secondary flow   18   "
Primary input temp. 347 °C

FIG. 2-27

STEP + 10%

Secondary input temperature — 50"

Economizer height — 50"

Evaporator height — 50"

Superheater height — 50'

Steam temp. — 50"

Organic output temp. — 50"

FIG. 2-28

FIG. 2-29

STEP + 10%

50"   Secondary water flow

50"   Economizer height

50"   Evaporator height

50"   Superheater height

50"   Steam temp.

50"   Organic output temp.

FIG. 2·30

STEP + 10%

50″   Primary organic flow

Economizer height

Evaporator height

Superheater height

Steam temp.

Organic output temp.

APPENDIX A

SERVO-MECHANISM ANALYSIS

OF THE

ORGEL REACTOR CONTROL SYSTEM

1. INTRODUCTION

The scope of this study is to complete and generalize some results concerning the control loop system, given by the analogue simulation.

The mathematical tool used is the servo theory; this theory assumes that the studied physical systems are described by sets of linear differential equations with constant coefficients; this is not the case for the kinetic equations of a reactor, which is why this study is valid only for small variations around a specified steady state. The method is not so restrictive as it would seem; the stability problems are described by equations of small variations which are actually linear; on the other hand, it presents the great advantage to give the analytic relations which link the different parameters of stability and, even to a certain degree, the transient response, which is not possible when using a numerical method; moreover, one must check the validity of the theory on the particular cases of the 100 and 250 MWe prototypes studied previously by analogue or digital methods. In fact, the real limit of the method is on the transient response when the limitations on the reactivity and velocity of the control rod are reached: obviously, these limitations cannot be examined when only the linear phenomena are taken into account.

Thus, the same sets of reactor equations used already in the analogue simulation are retaken, but they

are linearized in order to obtain the complete description of
the reactor as a control element;   then this element is used
in a control system and the entire system may again be examined
for stability and transient reponse.   The type of transient
apt to be more disturbing for a nuclear power plant is usually
not a change in the power level demand which can be limited
externally to any desired value, but an internal change in
reactivity during which the thermodynamical quantities of the
power plant do not shift perceptibly because of the important
time-delays involved in the circulation of the coolant;   this
justified the fact that, in this study, no plant is attached to
the reactor to remove the power, which is however impossible
without a good transfer function representation of the heat
exchanger.

2. THE REACTOR AS A CONTROL ELEMENT

2.1. Solution of kinetic equations for sinusoïdal reactivity input

The response of the reactor is studied from
a one-point black-box type of approach, i.e. the only significant
reactor constants that are present are δK, 1 and n in a
multiplying medium;   the temperature coefficients will be
presumed to be zero.

The kinetic equations are the familiar ones:

$$\frac{dn}{dt} = \frac{K_{eff}(1 - \beta) - 1}{1} \, n + \sum_{i=1}^{6} \lambda_i \, c_i$$

where $\quad \beta = \sum_{i=1}^{6} \beta_i$

$$\frac{dc_i}{dt} = \frac{K_{eff} \, \beta_i}{1} \, n - \lambda_i \, c_i$$

let us take $\quad \delta K = \dfrac{K_{eff} - 1}{K_{eff}} \quad$ with $K_{eff} \neq 1$

then:

$$\frac{dn}{dt} = \frac{\delta K}{1} n - \sum_{i=1}^{6} \frac{dC_i}{dt}$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{1} n - \lambda_i C_i$$

This set of linear equations has no constant coefficients, but, if we assume sufficiently small sinusoïdal excursions of n around the static value n_o, these equations can be approximated by a set of constant coefficients. This calculation is trivial and developed for instance in /Ref. 1./ The searched transfer function, indicated in Fig.2.1., is the following:

$$\delta K(s) \rightarrow \boxed{\begin{array}{c}\text{Reactor transfer}\\\text{function}\\ n_o\ \emptyset_R\ G_R(s)\end{array}} \rightarrow \delta n(s)$$
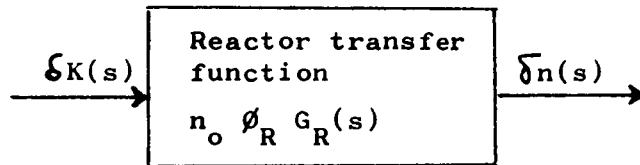
Fig. 2.1.

$$\frac{\delta n(s)}{n_o\ \delta K(s)} = \emptyset_R G_R = \frac{1}{s1\left[1 + \sum\limits_{i=1}^{6} \dfrac{\beta_i}{1(s+\lambda_i)}\right]}$$

where s is the Laplace operator; it becomes, in expanded form:

$$\frac{\delta n}{n_o\ \delta K} = \frac{a_o + a_1 s + \ldots + a_6 s^6}{b_1 s + b_2 s^2 + \ldots + b_7 s^7}$$

For a single group of delayed neutrons:

$$\frac{\delta n}{n_o\ \delta K} = \frac{s + \lambda}{s1(s + + \lambda \beta/1)}$$

where $\lambda = \beta \Big/ \sum\limits_{i=1}^{6} \dfrac{\beta_i}{\lambda_i}$

and in expanded form:

$$\frac{\delta n}{n_o \delta K} = \emptyset_R G_R = \frac{A_o + A_1 s}{B_1 s + B_2 s^2} \qquad (2.1.)$$

where:

$$\left| \begin{array}{l} A_o = \lambda/1 \\ A_1 = 1/1 \end{array} \right. \qquad \left| \begin{array}{l} B_1 = \lambda + \beta/1 \\ B_2 = 1 \end{array} \right.$$

Fig. 1 and 2 show the amplitude and phase frequency response (substituting s by $j\omega$) of the 250 MWe prototype in the two cases of a single group and six groups of delayed neutrons when the power level is 100% and the reactor irradiated.

The calculations have been achieved with the help of a FORTRAN code. As it can be seen, the transfer function (2.1.) is a good approximation, easy to use for later determining analytical expressions; besides, it will not change the general results of the study.

$$\frac{\delta n}{n} \sim \frac{A_o}{B_1 S} \longrightarrow + \infty$$ If δK is a step function, when $t \longrightarrow + \infty$, i.e. when a small amount of positive reactivity is inserted into the reactor, the power level rises infinitely.

2.2. Feedback loop due to temperature coefficients

The physical effects of the temperature coefficients will be translated in servo-loop feedback which modifies the elementary reactor transfer function. Because of the presence of this feedback, the problèm of stability will exist.

Two-path temperature coefficient feedback is considered according to the block diagrams of Fig. 2.2., which are equivalent.
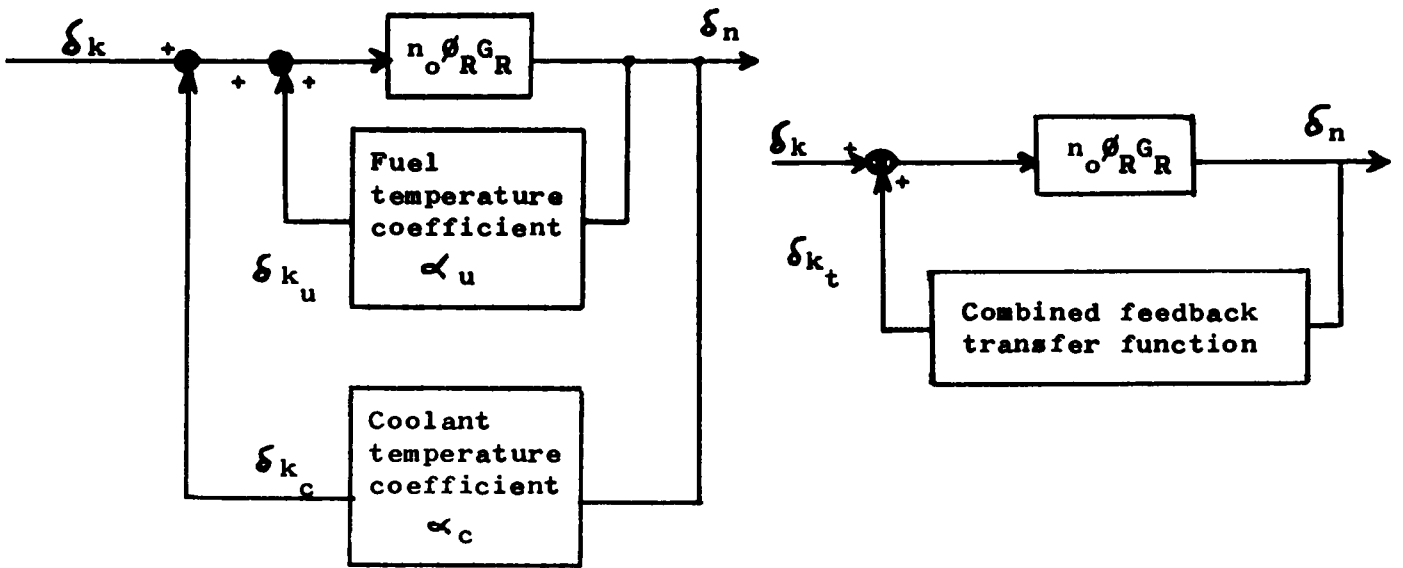
Fig. 2.2.

The total feedback reactivity is:

$$\delta K_t(s) = \delta K_u(s) + \delta K_c(s)$$

Assuming that the steady-state program of the reactor is a constant coolant flow with a constant inlet coolant temperature T_i (which is not restrictive because of the insensibility of the thermodynamical quantities during an internal change of reactivity), and taking again the equations of the heat transmission of the analogue reactor model, we get:

$$\delta K_t(s) = \alpha_u \, \delta T_u^*(s) + \alpha_c \, \delta T_c^*(s) \qquad (2.2.)$$

where

$$\delta T_u^* = \gamma_c \, \delta T_c + \gamma_u \, (\delta T_u - \delta T_c) \qquad (2.3.)$$

$$\delta T_c^* = \gamma_c \, \delta T_c \qquad (2.4.)$$

δT_u and δT_c are small variations about the steady-state values of the average fuel and coolant temperatures of the representative channel, the representative channel being included between the central channel and the channel of medium power and defined by its radius r_o, so that:

$$n(r_o) = \int_o^R n^3 \, (r) \, r dr \Big/ \int_o^R n^2(r) \, r dr$$

where n(r) is the radial thermal flux and R the reactor radius. Combining the Eqs. (2.2.),(2.3.) and(2.4.) gives:

$$\delta K_t(s) = \alpha_u \gamma_u \delta T_u(s) + \left[\alpha_u (\gamma_c - \gamma_u) + \alpha_c \gamma_c \right] \delta T_c(s)$$

and using the notations:

$$\alpha_u^* = \alpha_u \gamma_u \tag{2.5.}$$

$$\alpha_c^* = \alpha_c \gamma_c - \alpha_u (\gamma_u - \gamma_c) \tag{2.6.}$$

$$\delta K_t(s) = \alpha_u^* \delta T_u(s) + \alpha_c^* \delta T_c(s) \tag{2.7.}$$

The variations in the time of δT_u and δT_c are given by the following set of differential equations:

$$\mu_u \frac{d \delta T_u}{dt} = K \delta n - A (\delta T_u - \delta T_g)$$

$$\mu_g \frac{d \delta T_g}{dt} = A (\delta T_u - \delta T_g) - B (\delta T_g - \delta T_c)$$

$$\mu_c \frac{d \delta T_c}{dt} = B (\delta T_g - \delta T_c) - C \delta T_c$$

where A, B and C are heat transfer coefficients obtained from the steady-state with W^o = Kn_o power of the representative channel:

$$A = \frac{W^o}{T_u^o - T_g^o} \tag{2.8.}$$

$$B = \frac{W^o}{T_g^o - T_c^o} \tag{2.9.}$$

$$C = \frac{W^o}{T_c^o - T_i} \tag{2.10.}$$

Taking the Laplace transforms gives:

$$\delta T_u \left(\mu_u s + A \right) = K \delta n + A \delta T_g \tag{2.11.}$$

$$\delta T_g \left(\mu_g s + A + B \right) = A \delta T_u + B \delta T_c \tag{2.12.}$$

$$\delta T_c \left(\mu_c s + B + C \right) = B \delta T_g \tag{2.13.}$$

Combining Eqs. (2.7.), (2.11.), (2.12.) and (2.13.), the transfer function indicated in Fig. 2.3. is:
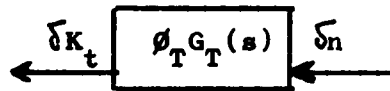
Fig.2.3.

$$\frac{n_o \delta K_t}{\delta n} = \phi_T G_T = \frac{C_o + C_1 s + C_2 s^2}{D_o + D_1 s + D_2 s^2 + D_3 s^3} \tag{2.14.}$$

where:

$$C_o = \frac{\alpha_u^* W^o}{\mu_u} \left[\frac{A(B+C) + BC}{\mu_g \mu_c} + \frac{\alpha_c^*}{\alpha_u^*} \cdot \frac{AB}{\mu_g \mu_c} \right]$$

$$C_1 = \frac{\alpha_u^* W^o}{\mu_u} \left(\frac{A+B}{\mu_g} + \frac{B+C}{\mu_c} \right)$$

$$C_2 = \frac{\alpha_u^* W^o}{\mu_u} \tag{2.15.}$$

$$D_o = \frac{ABC}{\mu_u \mu_g \mu_c}$$

$$D_1 = \frac{AB}{\mu_u \mu_g} + \frac{A(B+C)}{\mu_u \mu_c} + \frac{A(B+C)+BC}{\mu_g \mu_c}$$

$$D_2 = \frac{A}{\mu_u} + \frac{A+B}{\mu_g} + \frac{B+C}{\mu_c}$$

$$D_3 = 1$$

2.3. Reactor stability

Fig. 2.4. represents the block diagram of the reactor and its overall temperature feedback:
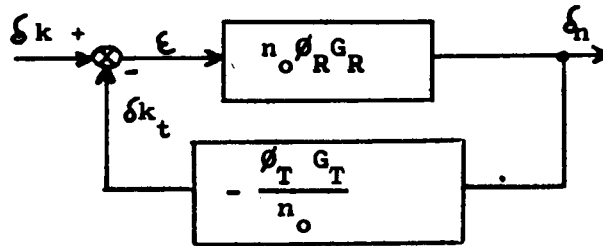
Fig. 2.4.

The sign $\emptyset_T G_T$ has been reversed in order to conserve the usual servo-language convention for the closed-loop feedback transfer equation.

$$\frac{\zeta n}{n_o \delta K} = \emptyset_{RT} G_{RT} = \frac{\emptyset_R G_R}{1 + \emptyset_R \emptyset_T G_R G_T} \qquad (2.16.)$$

To examine the reactor stability, it is necessary to employ the Nyquist plots of the open-loop transfer function: $\emptyset_R \emptyset_T G_R G_T$.

Eqs. (2.1.) and (2.14.) give with a reversed sign for (2.14.)

$$\emptyset_R \emptyset_T G_R G_T = \frac{E_o + E_1 s + E_2 s^2 + E_3 s^3}{F_1 s + F_2 s^2 + F_3 s^3 + F_4 s^4 + F_5 s^5} \qquad (2.17.)$$

where:

$$E_o = -A_o C_o$$

$$E_1 = -(A_o C_1 + A_1 C_o)$$

$$E_2 = -(A_o C_2 + A_1 C_1)$$

$$E_3 = -A_1 C_2$$

$$F_1 = B_1 D_o$$

$$F_2 = B_1 D_1 + D_o$$

$$F_3 = B_1 D_2 + D_1$$

$$F_4 = B_1 + D_2$$

$$F_5 = 1$$

In Figs. 3 and 4 are reported the Bode diagrams of the open-loop transfer functions of the 250-MWe prototype with initial core and equilibrium core.

Fig. 2.5. gives the shapes of the corresponding Nyquist plots:

Initial core

$$|\begin{array}{l} P = o \\ R = 0 \end{array}$$

Stable ($C_o < o$)

Equilibrium core

$$|\begin{array}{l} P = o \\ R = -1 \end{array}$$
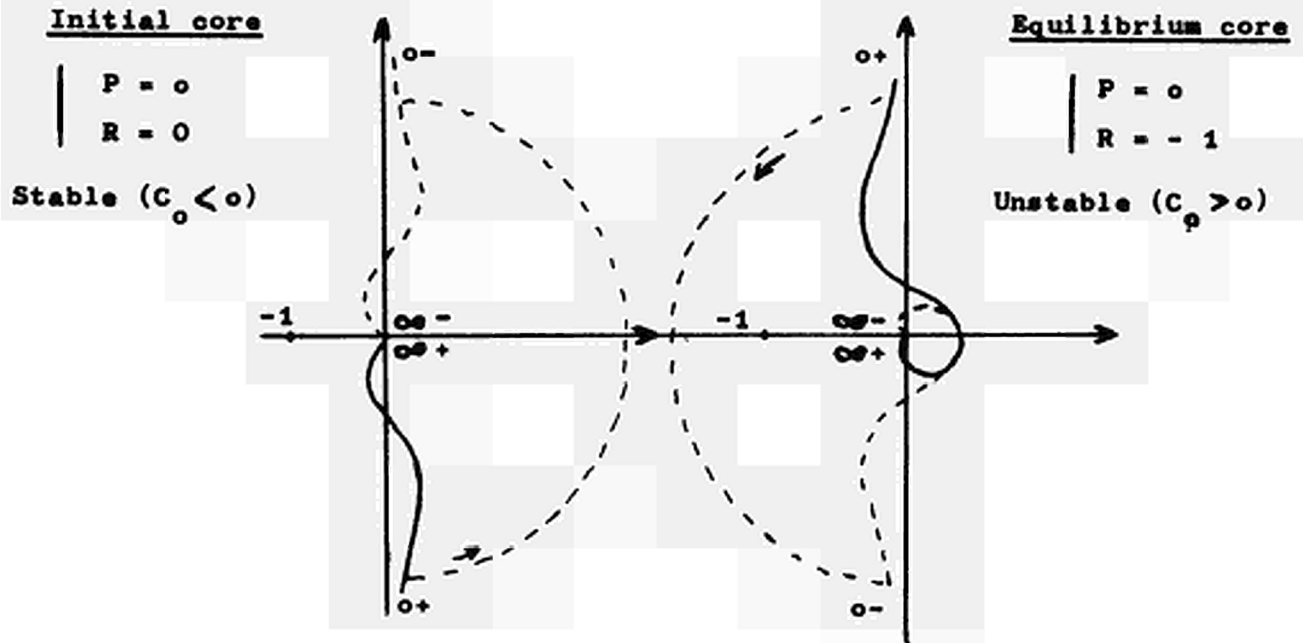
Unstable ($C_\rho > o$)

Fig. 2.5.

It can be seen that the initial core is stable, the equilibrium core unstable, the stability depending only on the sign of C_o.

Indeed, when $s = j\omega \rightarrow + o$

$$\phi_R \phi_T G_R G_T \sim \frac{E_o}{F_1 s} = \frac{A_o C_o j}{B_1 D_o} \longrightarrow \infty$$

A_o, B_1, D_o are positive quantities; thus:

si $C_o > o$ $\qquad \phi_R \phi_T G_R G_T \longrightarrow ^+ \infty$

si $C_o < o$ $\qquad \phi_R \phi_T G_R G_T \longrightarrow - \infty$

The closure of the diagram from $\omega = + o$ and $\omega = - o$ is always achieved in the counterclockwise sense with an angular rotation of π ($F_1 \neq o$).

The stability condition is: $C_o = o$. Taking again the expression of C_o (Eq. 2.15.), this condition becomes:

$$- \frac{\alpha_c^*}{\alpha_u^*} = 1 + C \ (\frac{1}{A} + \frac{1}{B})$$

Substituting the values of A, B and C given by the Eqs. (2.8., 2.9. and 2.10.):

$$- \frac{\alpha_c^*}{\alpha_u^*} = \frac{T_u^o - T_i}{T_c^o - T_i} \qquad\qquad (2.18.)$$

and combining Eqs. (2.5.), (2.6.) and (2.18.),

the stability condition is thus:

$$- \frac{\alpha_c}{\alpha_u} < l_s$$

$$(2.19.)$$

where $l_s = 2 \ \dfrac{\gamma_u}{\gamma_c} \cdot \dfrac{T_u^o - T_c^o}{T_o - T_i} + 1$

The stability is independent of the reactor power level for a constant flow steady-state program. It can be verified that this limit is unchanged for six groups of delayed neutrons. For a negative fuel temperature coefficient and a positive coolant temperature coefficient, the greater is the fuel temperature and the smaller is the coolant span ($\Delta T = T_o - T_i$), the more the reactor is stable.

The γ_u and γ_c coefficients take the axial statistical weight of the temperatures into account and the "representative" channel take the radial statistical weight of the temperatures into account; the coolant temperatures are independent of the radial statistical weight because of the constant coolant temperature span in every channel.

For a cosine axial flux:

$$\gamma_u = \frac{4}{3}$$

$$\gamma_c = 1$$

$$\text{and } l_s = \frac{8}{3} \cdot \frac{T_u^o - T_c^o}{\Delta T} + 1 \qquad (2.20.)$$

In thi case, the coolant temperatures are thus independent from the radial and axial statistical weight; as the fuel temperature coefficient is negative, the statistical weight of the fuel temperatures has a stabilizing effect.

In Fig. 5 are reported the stability limits in the following cases:

Representative channel: $\gamma_u = \frac{4}{3}$, $\gamma_c = 1$
(with axial statis. weight)

Averaged channel (with
axial statistical weight): $\gamma_u = \frac{4}{3}$, $\gamma_c = 1$

Averaged channel (without
axial statistical weight): $\gamma_u = \gamma_c = 1$

In a logarithm plot, the difference between these cases is small, and a good pessimistic and easy approximation is to take the second case. The numerical results are given in the following table:

250-MWE prototype

$T_i = 266°C$

$T_c^o = 318°C$

$T_u^o = 672,5°C$ for the "representative" channel
$= 658\ °C$ for the averaged cha nnel

	case 1	case 2	case 3
l_s	10.1	9.7	7.5

In Fig. 6 are reported the stability limits of the 100- and 250 MWe prototypes comparatively with the numerical previous results. The agreement is good.

100 MWe-prototype

$$T_i = 292°C$$

$$T_c^o = 328°C$$

$$T_u^o = 762°C$$

$$1_s = 15.8$$

2.4. Reactor power coefficient

Taking again the reactor closed-loop transfer function (2.16.), and developing it with (2.1.) and (2.17) gives:

Reactor

$$\delta K \rightarrow \boxed{n_o \emptyset_{RT} G_{RT}} \xrightarrow{\delta n}$$
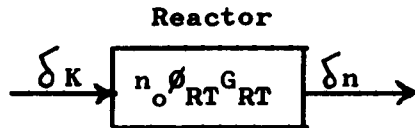
Fig. 2.6.

$$\frac{\delta n}{n_o \, \delta K} = \emptyset_{RT} G_{RT} = \frac{G_o + G_1 s + \ldots + G_5 s^5}{H_o + H_1 s + \ldots + H_6 s^6} \qquad (2.21.)$$

where:

$$G_o = A_o F_1 \qquad\qquad H_o = E_o B_1$$

$$G_1 = A_o F_2 + A_1 F_1 \qquad H_1 = E_o + (E_1 + F_1)B_1$$

$$G_2 = A_o F_3 + A_1 F_2 \qquad H_2 = (E_1 + F_1) + (E_2 + F_2)B_1$$

$$G_3 = A_o F_4 + A_1 F_3 \qquad H_3 = (E_2 + F_2) + (E_3 + F_3)B_1$$

$$G_4 = A_o + A_1 F_4 \qquad\quad H_4 = (E_3 + F_3) + F_4 B_1$$

$$G_5 = A_1 \qquad\qquad\qquad H_5 = F_4 + B_1$$

$$H_6 = 1$$

When C_o is negative, the reactor is stable and all the coefficients H_o, H_1, H_2, H_3 and H_4 are positive (H_5 and H_6 are always positive) or all the roots of $\left(H_o + H_1 s + \ldots + H_6 s^6 = 0\right)$ are negative.

When C is positive, the reactor is unstable, H_o at least is negative and the equation ($H_o + \ldots + H_6 s^6 = 0$) has at least one positive root.

$$(H_o + H_1 s + \ldots + H_6 s^6) = (B_1 + B_2 s)(h_o + h_1 s + \ldots + h_5 s^5)$$

where

$$
\begin{aligned}
h_o &= E_o \\
H_1 &= E_1 + F_1 \\
h_2 &= E_2 + F_2 \\
h_3 &= E_3 + F_3 \\
h_4 &= F_4 \\
h_5 &= 1
\end{aligned}
$$

The problem comes to study the sign of the roots of the equation $(h_o + h_1 s + \ldots + h_5 s^5) = 0$.

For a reactivity input in step function:

when $t \longrightarrow \infty$

where:
$$\frac{\delta n}{n_o \, \delta K} \longrightarrow \frac{G_o}{H_o} = -\frac{D_o}{C_o}$$

$$\frac{\delta K}{\delta n / n_o} = -\frac{C_o}{D_o}$$

Substituting the expressions of C_o and D_o gives (Eq. 2.15.):

$$- \frac{C_o}{D_o} = \alpha_u^* \left[\frac{1}{A} + \frac{1}{B} + \frac{1}{C} \cdot \frac{\alpha_c^*}{\alpha_u^*} \right]$$

$$\left[(\frac{1}{A} + \frac{1}{B} + \frac{1}{C}) + \frac{1}{C} \cdot \frac{\alpha_c^*}{\alpha_u^*} \right]$$

$$= - \alpha_u^* (T_u^o - T_i) - \alpha_c^* (T_c^o - T_i)$$

then:

$$\frac{\delta K}{\delta n/n_o} = - \frac{\gamma_c (T_o - T_i)}{2} \cdot (\alpha_c + \alpha_u l_s) \qquad (2.22.)$$

Doing $\delta n/n_o = 1\%$, δK is the **reactor power coefficient** α_w:

$$\alpha_w (\text{p.c.m/\%}) = 10^{-2} \cdot \frac{\Delta T}{2} (\alpha_c + \alpha_u l_s) \qquad (2.23.)$$

with α_c and α_u in p.c.m./°C.

α_w is constant in the temperature coefficients plan on any parallel to the stability limit straight.

α_w is a measure of the reactor stability degree; it is negative for a stable reactor, positive for an unstable reactor.

Prototype	100 MWe		250 MWe	
Core	Initial	Equilibrium	Initial	Equilibrium
α_c pcm/°C	+ 1	+ 6	- 0.25	+ 5.0
α_u pcm/°C	- 1	- 0.26	- 1.5	- 0.45
α_w pcm/%	- 6	+ 1.45	- 8	+ 0.24

For a stable reactor, the power coefficient has an immediate signification: if a small and given amount of

positive reactivity δk is inserted into a stable reactor, the power, if allowed to be free, will stabilize itself at a superior level, the variation power being given by:

$$\delta n/n_o = - \delta k/\alpha_w.$$

Example: in the case of the initial core of the 250-MWe prototype, when δk = 50 pcm, $\delta n/n_o$ = 6,25%; Fig. 5 gives the lines corresponding to $\alpha_w = \pm 1$, - 10, - 100 pcm/%; Figs. 7 and 8 give the amplitude and phase of the closed-loop transfer functions of the initial and equilibrium core; Fig. 9 gives some analogue cases of verification of the power coefficient.

It should be recalled (Ref. 1, p.206-7) that the maximum **initial** value for $\delta n/n_o$ is given by:

$$\delta n_{max}/n_o = \frac{\delta k}{\beta - \delta k} \qquad (2.24.)$$

when δk is small with respect to β, and neglecting, during this small initial time, the influence of the temperature coefficients.

In the present case,

with β = 395.5 pcm

$$1 = 5.4,10^{-4} \text{ s}$$

and when δk = 10 pcm:

$\delta n_{max}/n_o \neq 2.6\%$, the time constant of the initial peak being $1/(\beta - \delta k)$ = 0.14s.; therefore, very small with respect to the fuel rod thermal time constant, that is 2 sec.

3. THE REACTOR CONTROL LOOP

An external control loop is needed, when the reactor is unstable. It can be operated as a proportional regulating system or an on-off type of regulating system. In a

proportional regulating system, the position of the control rod is changed proportionally to any error created, either by a power demand change, or by an internal system transient; in a discontinuous regulating system, no control is attained unless an error, which is greater than some fixed percentage, is set up in the control rod. It is known, and this has been verified on occasion of the analogue computation, that the on-off type control system is inadequate when the reactor by itself is inherently unstable, the presence of a dead zone involving the control system to be in continuous oscillation. Fig. 3.1. shows the servo-block diagram of reactor control loop used for stability analysis:
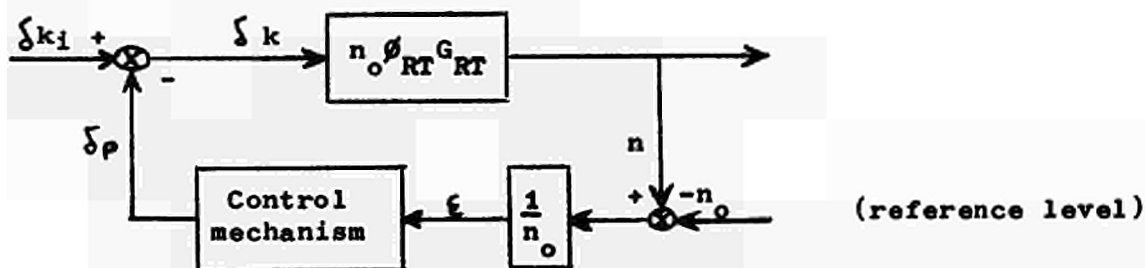
Fig. 3.1.

The reactor output is measured by a neutron detector; this power n is then compared with the reference power level, the activating error $\mathcal{E} = \dfrac{n - n_o}{n_o}$ is amplified and finally controls an activator which moves the rod in order to obtain the necessary antireactivity to eliminate $\mathcal{E}$. During the reactivity change δk_1, it can be assumed that the power level demand n_o does not change. The rod is affected by a time constant τ.

We can assume that the reactivity to be inserted is generated according to the general equation:

$$\delta\rho = \frac{R_1 + \dfrac{R_2}{s} + R_3 s}{1 + \tau s} \; \mathcal{E} \qquad (R_1, R_2, R_3 > 0)$$

where:

R_1 is a <u>proportional</u> term

R_2 is an <u>integral</u> term

R_3 is a <u>differential</u> term

The problem consists in determining the terms or a combination of these necessary terms to stabilize the reactor.

3.1. Effect of a proportional term

We only have:

$$\phi_c G_c = \frac{\delta \rho}{\xi} = \frac{R_1}{1 + \tau s} \qquad (3.1.)$$

Considering the block diagram of Fig. 2.1. where

$$
\begin{aligned}
\delta k &= \delta k_i - \delta \rho \\
\delta \rho &= \xi \phi_c G_c \\
\xi &= \delta n / n o \\
\delta n &= n_o \phi_{RT} G_{RT} \; \delta k
\end{aligned}
$$

the closed-loop transfer function of the reactor control system is:

$$\frac{\delta n}{n_o \, \delta k_i} = \frac{\phi_{RT} G_{RT}}{1 + \phi_c \, \phi_{RT} G_c G_{RT}} \qquad (3.2.)$$

For stability problems, it is necessary to study the Nyquist plots of the open-loop transfer function:

$$\frac{\delta n}{n_o \xi} = \phi_c \phi_{RT} \; G_c G_{RT}$$

Eqs. (2.21.) and (3.1.) give:

$$\frac{\delta n}{n_o \xi} = \frac{R_1 (G_o + G_1 s + \ldots + G_5 s^5)}{(1 + \tau s)(H_o + H_1 s + \ldots + H_6 s^6)}$$

or using the following notation:

$$\frac{\delta n}{n_o \epsilon} = \frac{R_1 (G_o + \ldots + G_5 s^5)}{J_o + \ldots + J_7 s^7} \qquad (3.3.)$$

where:

$$J_o = H_o$$

$$J_1 = \tau H_o + H_1$$

$$J_2 = \tau H_1 + H_2$$

$$J_3 = \tau H_2 + H_3$$

$$J_4 = \tau H_3 + H_4$$

$$J_5 = \tau H_4 + H_5$$

$$J_6 = \tau H_5 + H_6$$

$$J_7 = \tau H_6$$

The study of the limits of $G_c G_{RT}$ and of tg $(\phi_c \phi_{RT})$ when $s \longrightarrow + o$ or $+ \infty$ gives in all cases the following elements of the Nyquist diagram:
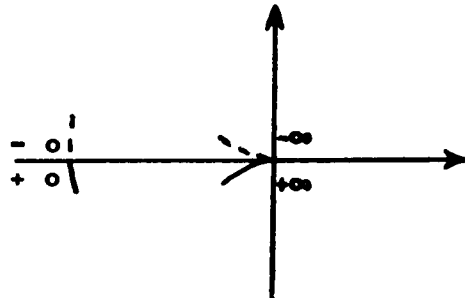
Fig. 3.2.

Fig. 3.3. gives the complete shape of the Nyquist diagrams in the case of the 250-MWe prototype for two values of τ : 1 and 10 sec.

α = 1 sec.
$R_1 = 10^{-2}$

| P = 1
| R = 1

stable

τ = 10 sec.
$R_1 = 10^{-2}$
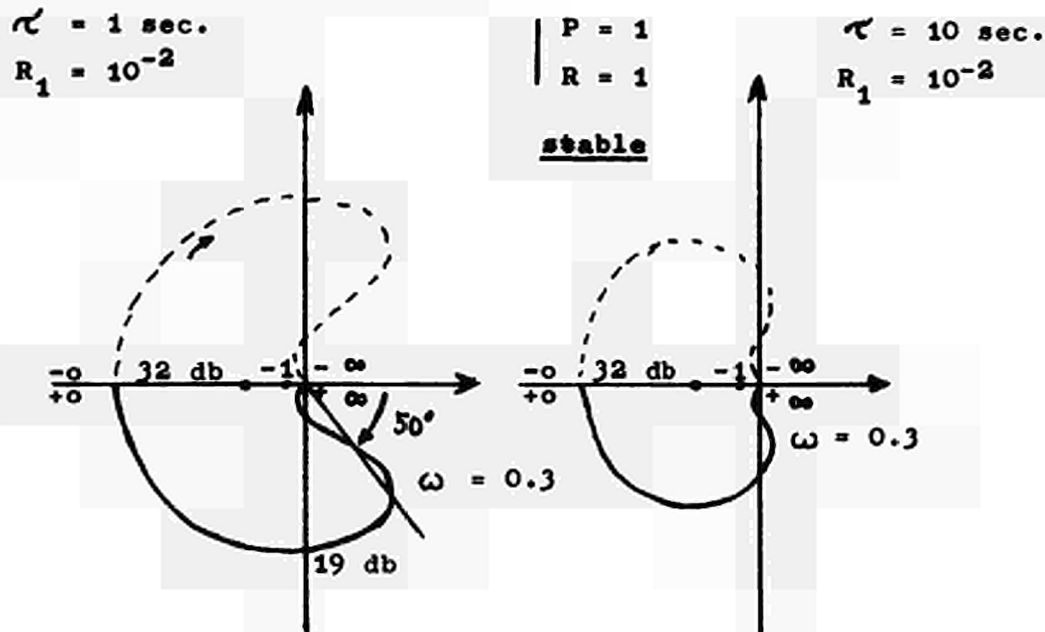
Fig. 3.3.

There is stability if the point (-1) is enclosed or when $s \longrightarrow +0$

$$\frac{\delta n}{n_o \xi} \longrightarrow \frac{R_1 G_o}{H_o} = - R_1 \frac{D_o}{C_o} \quad \text{(with } C_o > o)$$

The stability condition is then:

$$R_1 \frac{D_o}{C_o} > 1 \quad \text{where} \quad R_1 > \frac{C_o}{D_o}$$

In Figs. 10 and 11 are reported the corresponding Bode diagrams. The stability is better for small values of τ because of the greater enclosure of the point (-1); however, the inertia time constant is not a sensitive parameter from a stability point of view. For illustration are reported in Figs. 10 and 11 the Bode diagrams of the 100-MWe prototype: the results are about the same; this allows to conclude that the thermal time constant of the fuel rod (2 sec. in the case of

the 250 MWe, 5 sec. in the case of the 100 MWe) has no significant influence on the inertia time constant of the control rod.

$$\frac{\delta n}{n_o \xi} = \frac{R_1}{1 + \tau s} \quad \phi_{RT} \, G_{RT}$$

$$= \frac{R_1}{1 - j\omega\tau} \quad \phi_{RT} \, G_{RT}$$

Fig. 11 and the previous expression show that the phase loss is equal to $45°$ when τ is varied from 0 to 1 sec. (for $\omega = 1$); it is equal to (arctg 10 - arctg 1) $\neq 40°$ when τ is varied from 1 to 10 sec.

Fig. 3.4. gives an idea of the stability system in function of the inertia time constant of the bar; a reasonable value is τ equal to 1 sec.
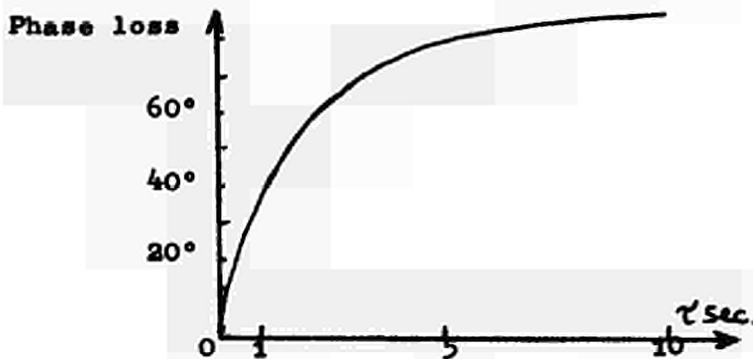
Fig. 3.4.

Taking the reactor control system closed-loop transfer function (3.2.) and developing it, gives:

$$\frac{\delta n}{n_o \, \delta k_i} = \phi_{RTC} G_{RTC} = \frac{L_o + \dots + L_{12} s^{12}}{K_o + \dots + K_{13} s^{13}} \qquad (3.4.)$$

For an input δk_i in step function, when

$$t \longrightarrow \infty$$

$$\frac{\delta n}{n_o \, \delta k_i} \longrightarrow \frac{L_o}{K_o} = \frac{G_o J_o}{H_o(R_1 G_o + J_o)}$$

where $\dfrac{\delta ki}{\delta n/n_o} \longrightarrow (R_1 - \dfrac{C_o}{D_o})$ with R_1 greater than $\dfrac{C_o}{D_o}$

Substituting the expression of C_o and D_o, as it has already been done:

$$10^{-2} \dfrac{\delta ki}{\delta n/no} = R_1 - \alpha_w$$

This relation might be:

$$\alpha'_w = \alpha_w - R_1 \qquad\qquad (3.5.)$$

where α_w is the power coefficient for the unstable reactor

α'_w is the power coefficient for the unstable reactor made stable by the proportional term.

For instance, for the equilibrium core of the 250-MWe prototype

$$\alpha_w = + 0.24 \text{ pcm/\%}.$$

If we want to stabilize it in the conditions of the initial core, it must be taken $\alpha'_w = - 8$ pcm/% and, for this, take $R_1 = 8.24$ pcm/% $= 0.824,10^{-2}$

These relations have been verified by the DYNOR code, as shown in Fig. 12.

3.2. Effect of an integral term

In this case:

$$\phi_c \, G_c = \dfrac{R_2}{s(1 + \tau s)}$$

$$\dfrac{\delta n}{n_o \mathcal{E}} = \dfrac{R_2(G_o + \dots + G_5 s^5)}{s(J_o + \dots + J_7 s^7)}$$

The study of the amptude andse limits when s⟶o or ∞ gives the following eles of tyquist diagram:
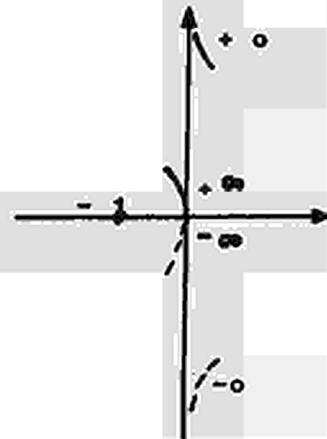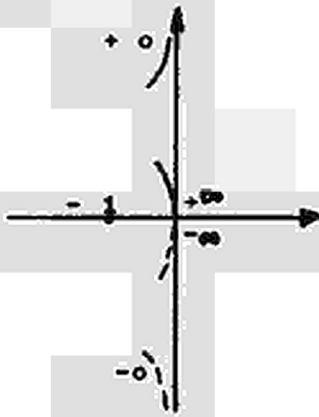
$J_1 > o$ where
$J_1 < o$ with $J_o/J_1 < Go/G_1$ $J_1 < o$ with $J_o/J_1 > Go/G_1$

Fig. 3.5.

The following figure gives the shapes of the Nyquist diagram for the 250-MWe prototype:

Fig. 3.6.

$R_2 = 10^{-1}$

$R_2 = 10^{-2}$

$R_2 = 10^{-5}$

$P = 1$			$P = 1$			$P = 1$	
$R = -1$	unstable		$R = 1$	stable		$R = -1$	unstable
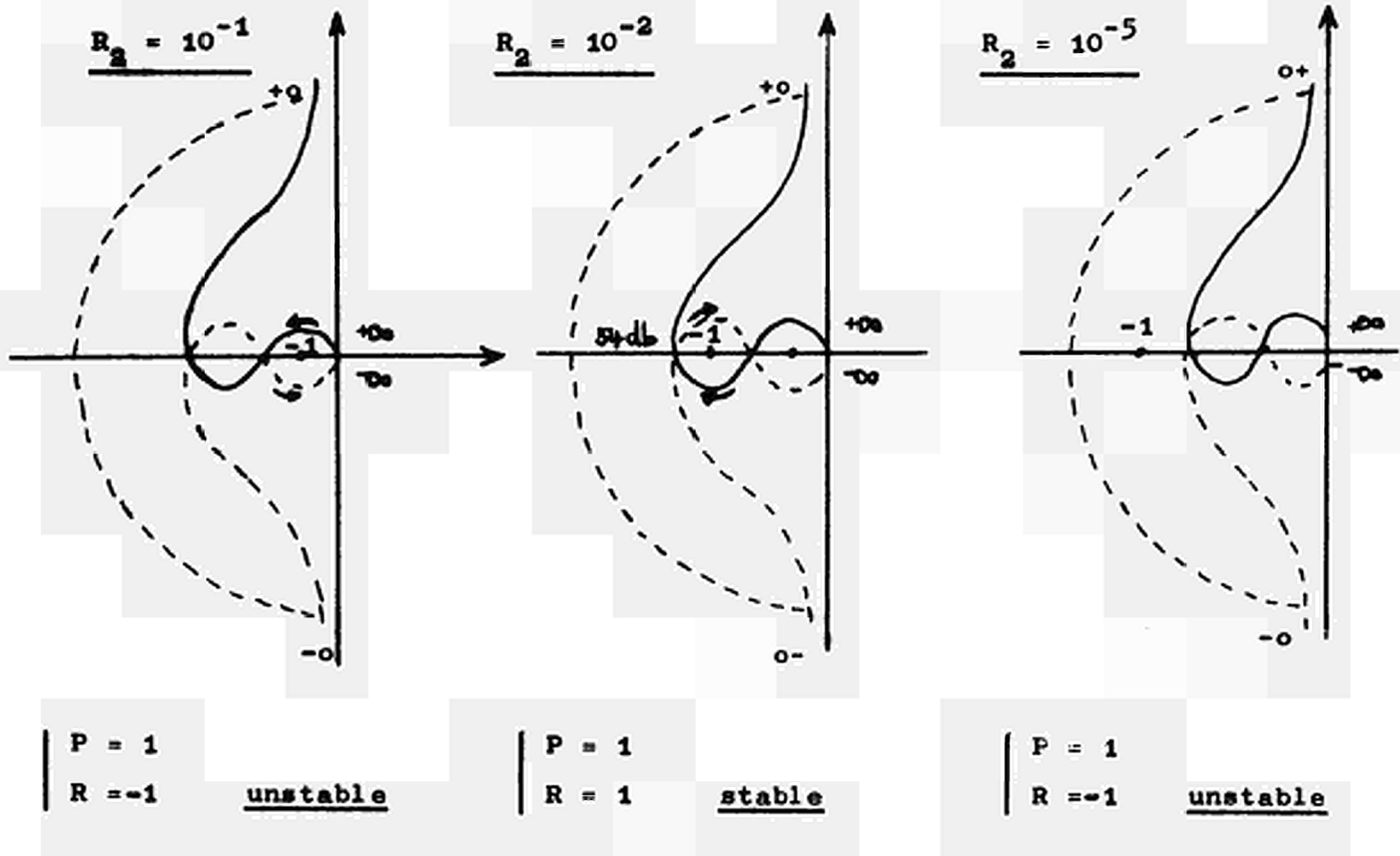
The system is stable only for a certain range of amplitude values.

3.3. Effect of a proportional term and an integral term

In this case:

$$\phi_c G_c = \frac{R_1 s + R_2}{s(1 + \tau s)}$$

$$\frac{\delta n}{n_o \varepsilon} = \frac{(R_2 + R_1 s)(G_o + \dots + G_5 s^5)}{s(J_o + \dots + J_7 s^7)}$$

$$= \frac{I_o + \dots + I_6 s^6}{J_o s + \dots + J_7 s^8}$$

where

$$I_0 = R_2 G_0$$

$$I_1 = R_1 G_0 + R_2 G_1$$

$$I_2 = R_1 G_1 + R_2 G_2$$

$$I_3 = R_1 G_2 + R_2 G_3$$

$$I_4 = R_1 G_3 + R_2 G_4$$

$$I_5 = R_1 G_4 + R_2 G_5$$

$$I_6 = R_1 G_5$$

It can be seen that the amplitude does not change when R_1 is fixed and the ratio R_2/R_1 constant.

The study of the limits when $s \longrightarrow o$ or ∞ gives the following elements:

$R_2/R_1 < \dfrac{1}{\tau} + \beta/1$ $R_2/R_1 > \dfrac{1}{\tau} + \beta/1$
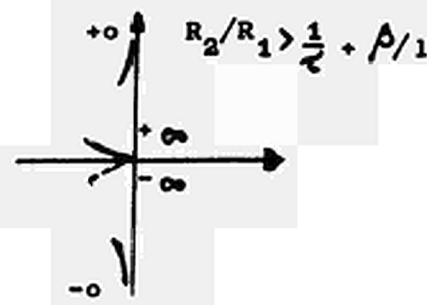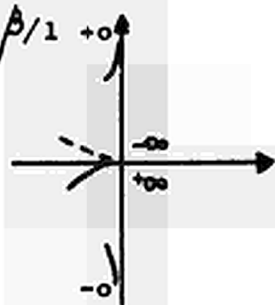
Fig. 3.7.

In Figs. 13 and 14 are reported the Bode diagrams of the 250-MWe prototype for τ equal to 1 and 10 sec. and R_1 equal to 10^{-2} for R_2/R_1 equal to 1/10.

The following figure gives the shape of the corresponding Nyquist diagrams:
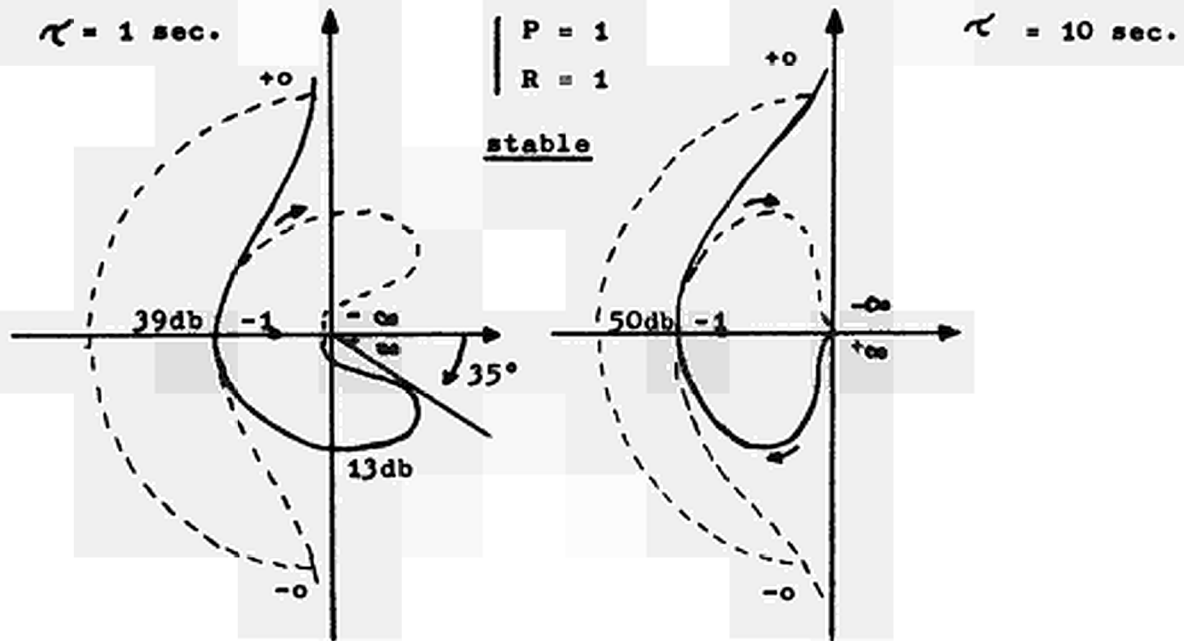
A stability limit is at least:

$$\frac{R_2}{R_1} < \frac{1}{\tau} + \beta/1 \qquad \text{(see Fig. 3.7.)}$$

ORGEL prototype $\tau = 1$ sec.	100 MWe	250 MWe
$\frac{1}{\tau} + \beta/1)$ in sec.$^{-1}$	6	8

$$\emptyset_C \emptyset_{RT} G_C G_{RT} = \left(R_1 + \frac{R_2}{s}\right) \emptyset_{RT} G_{RT}$$

$$= R_1 \left(1 - \frac{R_2}{R_1 \, \omega}\right) \emptyset_{RT} G_{RT}$$

When R_1 and τ are fixed:

- R_1 determined in order to obtain a reasonable value for α'_w (about - 10 pcm/%);

- τ chosen as minimum possible mechanical value (about 1 sec.);

the amplitude rises and the phase is reduced when the ratio R_2/R_1 increases as it is shown by the previous expression (see also Figs. 13 and 14);   a compromise value is then necessary for the R_2/R_1 ratio.

It is interesting to compare Figs. 3.3. and 3.8. (for τ = 1 sec.), where the R_1 value is equal in the two cases: it can be seen that the stability is about the same (similar values are obtained for the amplitude and the phase around the point -1) taking R_2/R_1 = 1/10 in the second case; if R_2/R_1 is greater than 1/10, the amplitude rises, but the phase loss is increased;   it seems that R_2/R_1 equal to about 1/10 constitutes an optimum value (for R_2/R_1 = 1/10 and ω = 0,5, the phase loss is arctg $\frac{1}{5}$ $\approx$ 10°).

Fig. 15 illustrates these results in good agreement with the optimization point of the control loop chosen after analogue computation. Taking again the close-loop transfer function of the reactor (3.2.) where: $\phi_C G_C = \frac{R_1 s + R_2}{s(1 + \tau s)}$ for an input δk_i in step function:

$$\frac{\delta n/n_o}{\delta k_i} \sim \frac{s}{R_2} \to o \quad \text{when} \quad t \to \infty$$

The integral term leads back the power level to its initial value.

3.4. Effect of a differential term

3.4.1. Differential term alone:

$$\phi_C G_C = \frac{R_3 s}{1 + \tau s}$$

$$\frac{\delta n}{n_o \xi} = \frac{R_3 s \, (G_o + \ldots + G_5 s^5)}{J_o + \ldots + J_7 s^7}$$

The study of the amplitude and phase limits give the following elements of diagram:

$$\left| \begin{array}{l} J_1 > o \text{ where} \\ J_1 < o \text{ with } J_1/J_o < G_1/H_o \end{array} \right. \qquad \left| \; J_1 < o \text{ with } J_1/J_o > G_1/G_o \right.$$
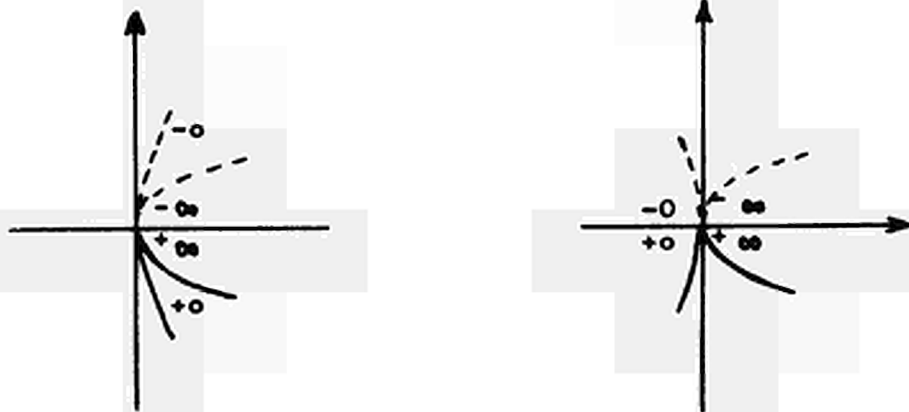
Fig. 3.9.

The corresponding Nyquist plot of the 250-MWe prototype is the following:
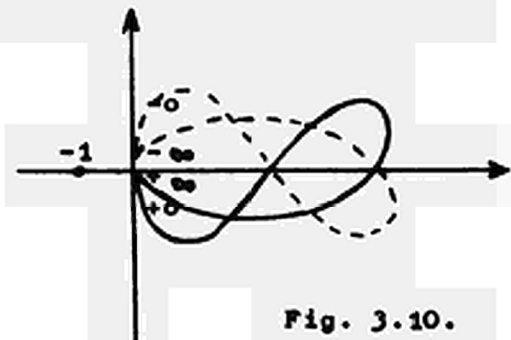
The system is always unstable.

Fig. 3.10.

3.4.2. Combination of a proportional and differential term

$$\emptyset_C G_C = \frac{R_1 + R_3 s}{1 + \tau s}$$

$$\frac{\delta n}{n_o \xi} = \frac{(R_1 + R_3 s)(G_o + \ldots + G_5 s^5)}{J_o + \ldots + J_7 s^7}$$

when $\omega \longrightarrow + o$

$$\frac{\delta n}{n_o \xi} \longrightarrow \frac{R_1 G_o}{H} = - R_1 \frac{D_o}{C_o} \quad \text{(identical limit for the proportional term alone).}$$

When $\omega \longrightarrow + \infty$

$$\frac{\delta n}{n_o \xi} \sim - \frac{R_3 G_5}{J_7} \cdot j \longrightarrow - o$$

$$tg (\emptyset_C \emptyset_{RT}) \sim \frac{-\omega}{(H_5 + 1/\tau) - (R_1/R_3 + G_4/G_5)} \longrightarrow - \infty$$

when $(H_5 + 1/\tau) > (R_1/R_3 + G_4/G_5)$

The following Nyquist plot can be obtained:

$$R_1 = R_3$$

$$\left| \begin{array}{l} P = 1 \\ R = 1 \end{array} \right.$$
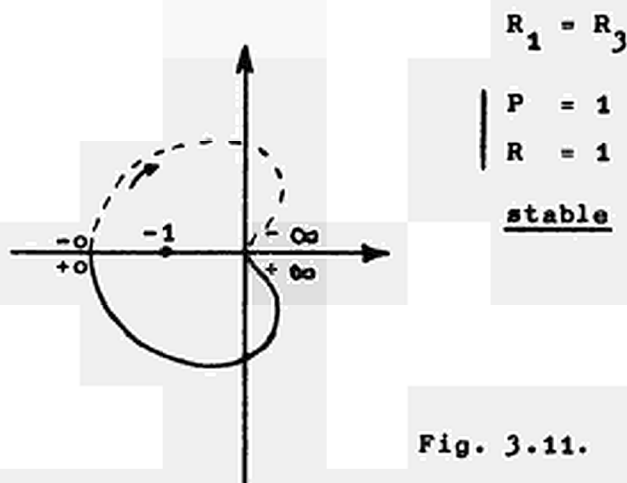
__stable__

Fig. 3.11.

The system is stable if the condition $R_1 > \dfrac{C_o}{D_o}$ is satisfied (closure condition of the point -1).

3.4.3. Combination of proportional, integral and differential terms

$$\phi_C G_C = \frac{R_1 + R_2/s + R_3 s}{1 + \tau s}$$

$$\frac{\delta n}{n_o \xi} = \frac{(R_2 + R_1 s + R_3 s^2)(G_o + \ldots + G_5 s^5)}{s(J_o + \ldots + J_7 s^7)}$$

$R_2/R_1 < \frac{1}{\tau} + \frac{\rho}{I}$

A first necessary stability condition is because of the instability of the differential term.

When $\omega \longrightarrow + o$

$$\frac{\delta n}{n_o \xi} \longrightarrow +\infty \quad (J_o < o)$$

$$tg(\phi_C \phi_{RT}) \longrightarrow - \infty$$

When $\omega \longrightarrow + \infty$

$$\frac{\delta n}{n_o \xi} \longrightarrow - o$$

$$tg(\phi_C \phi_{RT}) \sim \frac{\omega}{R_1/R_2 - (\frac{1}{\tau} + \frac{\rho}{I})} \qquad \text{when}$$

$$\frac{R_1}{R_2} < \frac{1}{\tau} + \frac{\rho}{I}$$

For R₁ = R₂ = R we have obtained the following
Nyquist plot, always in the ▓▓▓▓▓▓▓▓▓▓▓:

$P = 1$
$R = 1$
stable
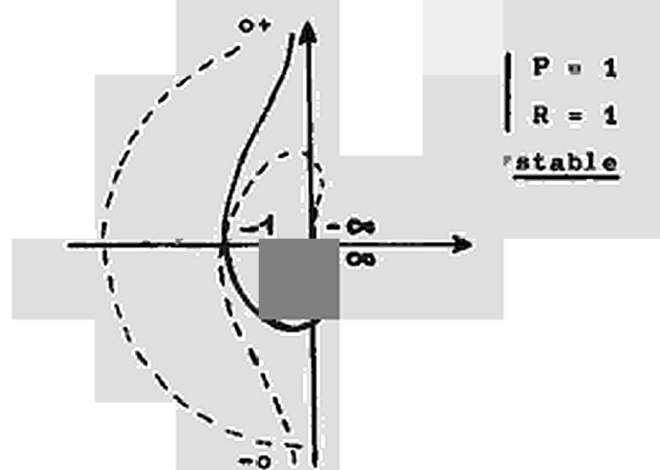
Fig. 3.12.

3.5. Conclusions

They are resumed in the following table:

Transfer function of the control mechanism (inertia = o)	Stability	Stability conditions	Permanent response to a step function δk_i
R_1	stable	$R_1 > \alpha_w$	$\dfrac{\delta n}{n_o} = \dfrac{\delta k_i}{R_1 - \alpha_w}$
R_2/s	stable	stable only in a certain range of amplitude values	$\dfrac{\delta n}{n_o} = o$
$R_1 + R_2/s$	stable	$\dfrac{R_2}{R_1} < \dfrac{1}{\tau} + \dfrac{\beta}{1}$	$\dfrac{\delta n}{n_o} = o$
$R_3 s$	unstable		
$R_1 + R_3 s$	stable	$R_1 > \dfrac{C_o}{D_o}$	$\dfrac{\delta n}{n_o} = \dfrac{\delta k_i}{R_1 - \alpha_w}$
$R_1 + R_2/s + R_3 s$	stable	$\dfrac{R_2}{R_1} < \dfrac{1}{\tau} + \dfrac{\beta}{1}$	$\dfrac{\delta n}{n_o} = o$

It appears that:

- the proportional term is the stabilizing term;

- the integral term leads back the power
  level to its initial value (reset);

- the differential term is without interest
  for stability point of view (it brings
  nothing).

4. STUDY OF THE TRANSIENT RESPONSE OF THE REACTOR WITHOUT CONTROL
TO A REACTIVITY STEP

Let us now search the transient response of the reactor to its noise.

The transfer function of the reactor is the following (Eq. 2.21.):

$$\phi_{RT} G_{RT} = \frac{\delta n(s)/n_o}{\delta k(s)} = \frac{G_o + \dots + G_5 s^5}{H_o + \dots + H_6 s^6}$$

The reactor noise is simulated by a unit-step function of amplitude δk, so that:

$$\delta k(s) = \frac{\delta k}{s}$$

$$\delta n(s)/n_o = \delta k \cdot \frac{G_o + \dots + G_5 s^5}{s(H_o + \dots + H_6 s^6)}$$

The inverse transform of this equation will give the transient response of the reactor.

We have:

$$s(H_o + \dots + H_6 s^6) = s(B_1 + s)(h_o + \dots + h_5 s^5)$$

$$\delta n(s)/n_o = \frac{Z_o}{s} + \frac{Z_1}{s + s_1} + \frac{Z_2}{s + s_2} + \frac{Z_3}{s + s_3} + \frac{Z_4}{s + s_4} + \frac{Z_5}{s + s_5} + \frac{Z_6}{s + s_6}$$

where:

$$s_1 = B_1 > o$$

s_2, s_3, s_4, s_5, s_6 are the roots with reversed signs of the equation $(h_o + \dots + h_5 s^5) = o$

s_2, s_3, s_4, s_5 are positive values and s_6 is a positive value for the unstable core.

The solutions are the following:

For the initial stable core:

$$\delta n(t)/n_o = \delta k (Z_o + \sum_{i=1}^{6} a_i e^{-s_i t})$$

where Z_o is $\dfrac{G_o}{H_o} = -\dfrac{D_o}{C_o} = \dfrac{1}{\alpha_w}$, then:

$$\delta n(t)/n_o = -\frac{\delta k}{\alpha_w} + \delta k \sum_{i=1}^{6} a_i e^{-s_i t}$$

When $t \to +\infty$, $\delta n/n_o \to -\dfrac{\delta k}{\alpha_w}$, we have again the relation (2.22.), as expected.

For the unstable equilibrium core:

$$\delta n(t)/n_o = -\frac{\delta k}{\alpha w} + \delta k \left(\sum_{i=1}^{5} a_i e^{-s_i t} + a_6 e^{-s_6 t} \right) \qquad (4.1.)$$

where s_6 has alone a negative value.

This last case is the most important one and has been studied numerically: the calculation of the roots of the equation $(h_o + \ldots + h_5 s^5) = o$ has allowed to check that the time constants $1/s_1$, $1/s_2$, $1/s_3$, $1/s_4$, $1/s_5$ are inferior to the second and very small with respect to $- 1/s_6$; this signifies that, in expression (4.1.), after a time near but superior to the second, the sum $\sum_{i=1}^{6} a_i e^{-s_i t}$ becomes negligible with respect to the other terms and that the power variation is then only given by:

$$\delta n/n_o \not\# -\frac{\delta k}{\alpha w} + \delta k a_6 e^{-s_6 t} \quad \text{for } t > 1 \text{ sec.}$$

It is verified that the time constant $\Theta = 1/s_6$ is about equal to $- \dfrac{h_1}{h_o} \not\# \dfrac{B_1 D_o}{A_o C_o} = \dfrac{1}{C_2 \alpha_w}$ where C_2 is a constant (for an averaged group of delayed neutrons).

We then have:

$$(\delta n/n_o + \frac{\delta k}{\alpha_w})\#c_1 \quad \delta k \; e^{c_2 \alpha_w t} \quad \text{for } t > 1 \text{ sec.})$$

c_1 and c_2 being two characteristical constants of the reactor, where c_1 must be taken as $1/\beta$ for $\delta k \ll \beta$ (see 2.24.).

In a semi-logarithmic plot, the representation of the quantity ($\delta n/n_o + \delta k/\alpha_w$) as function of the time is then linear, the slope of the representative straight line being proportional to the power coefficient and its ordinate to the origin being proportional to the amplitude step; these properties are checked effectively in Fig. 16 where are reported for the 250 MW-e prototype the power variations (given by the digital DYNOR code) which result from a loss of control simultaneously with a reactivity injection for two power coefficients about double: the searched linearity is verified well until power variations reaching 20%; it must be seen that an overpower of 10% is reached in 15 sec. when the power coefficient is equal to 0.25 pcm/% and in about 12 sec. when this power coefficient is double, this for a reactivity step of 10 pcm.

5. VARIATION OF THE POWER COEFFICIENT IN FUNCTION OF THE COOLANT FLOW

It has been assumed till now that the coolant input temperature and flow are constant. Let us search what is the variation of the power coefficient when the coolant flow is reduced because of the stop of a primary pump.

5.1. The reactor power is constant

At the equilibrium: Δt has increased in an inversely proportional manner to the flow; the difference $(T_U - T_G)$, proportional to the power, remains unchanged; the difference $(T_G - T_C)$ has

increased inversely as the flow (which is the same as assuming the cladding-coolant transfer coefficient to be proportional to the flow).

Using again expression (2.20.) gives:

$$(1_s - 1) = \frac{8}{3} (\frac{T_U{}^0 - T_G{}^0}{\Delta T} + \frac{T_G{}^0 - T_C{}^0}{\Delta T})$$

$$(1_s - 1) \not\equiv C_3 M + C_4$$

where C_3 and C_4 are two constants

then:

$$dl_s = \frac{dM}{M} (1_s - m)$$

$$\text{with } m = (1 + \frac{8}{3} \cdot \frac{T_G{}^0 - T_G{}^0}{\Delta T}) \tag{5.1.}$$

The differentiation of expression (2.23.) giving α_w leads finally, after reducing, to the following relation, valid for small flow variations:

$$\alpha_M = - \frac{d \alpha_w / \alpha_w}{d M / M} = \frac{1 + \frac{\alpha_u}{\alpha_c} m}{1 + \frac{\alpha_u}{\alpha_c} l_s} \tag{5.2.}$$

m being given by (5.1.).

5.2. The reactor power varies like the flow

At equilibrium, Δt is unchanged; the drop $(T_U - T_G)$ varies like the power; the drop $(T_G - T_C)$ is unchanged if the heat transfer coefficient varies directly as the flow; the same expression is found for dl_s, the stability limit not being related to the power.

Finally, we obtain the following relation giving the relative variation of the power coefficient for small variations of flow:

$$\alpha_{MW} = -\frac{d\alpha_W/\alpha_W}{d\,M/M} = \frac{-\frac{\alpha_u}{\alpha_c}\,(\,l_s - m)}{1 + \frac{\alpha_u}{\alpha_c}\,l_s} \qquad (5.3.)$$

For the initial core of the 250 MWe prototype, to a decrease in flow of 10% corresponds a relative variation of α_M and α_{MW}, of about 2.5%. For the equilibrium core, to a decrease in flow of 10% corresponds a double value for the power coefficient.

5.3. Discussion

α_M and α_{MW} have been plotted in Fig. 17 in the logarithmic plan of the temperature coefficients for a **negative** decrement dM of flow.

- **If the reactor is unstable:**

The plot shows that α_M and α_{MW} are positive: $d\alpha_W/\alpha_W$ is then positive like $d\alpha_W$ since α_W is positive in the unstable zone: the new value of the power coefficient has then the same sign and a greater absolute value; <u>the reactor instability can only increase in the event of a flow decrement</u>, and this the more the nearer the running point in the temperature coefficient plan is located to the stability limit.

- **If the reactor is stable:**

Let us consider the case where α_M and α_{MW} are negative, then $d\alpha_W$ is positive since α_W is negative in the stable zone: α_W and $d\alpha_W$ having inversed signs, the reactor stability decreases and even, if the absolute value of $d\alpha_W$ becomes superior to that of α_W, the reactor initially stable can become unstable; in reality, this can happen only if the reactor stability is very weak; indeed, to obtain $d\alpha_W/\alpha_W = +1$ corresponding to a flow decrement of 10% for example, it is

necessary to take α_M or $\alpha_{MW} = - 10$ and it can be seen in Fig.17 that the running point is located very near to the stability limit.

In the case where α_M is positive, the reactor stability increases weakly in the event of flow decrement, but this variation is not significant.

We can conclude that, generally, a flow decrement makes the reactor more unstable or less stable that the simultaneous effect of the power is not significant   and that it is always of interest to take a couple of temperature coefficients not too closely situated to the stability limit.

6. CONCLUSIONS

In the following, we give the main results obtained in this study.   The stability condition of the reactor is given by:

$$- \alpha_c / \alpha_u < l_s$$

where

$$l_s = \frac{8}{3} \cdot \frac{T_U - T_C}{\Delta T} + 1$$

T_U and T_C are the averaged temperatures of fuel and coolant in the representative channel;   a good approximation is to take T_U and T_C as averaged temperatures of the averaged channel. ΔT is the coolant temperature span.   The axial neutron flux is a cosine flux.

The reactor power coefficient is:

$$\alpha_w = 10^{-2} \cdot \frac{\Delta T}{2} \; (\alpha_c + \alpha_u l_s)$$

with α_w in pcm/% when α_c and α_u are in pcm/°C;   in the temperature coefficients plan, α_w is constant on any parallel to the stability limit given by $- \alpha_c / \alpha_u = l_s$.

A proportional term R_1 in the control system
is necessary to <u>stabilize</u> the unstable core. R_1 must be adjusted
in order to obtain for the reactor a negative power coefficient
of desired value α'_w so that:

$$R_1 = \alpha_w - \alpha'_w$$

The inertia time constant of the bar is not
a sensitive parameter for stability point of view. Usually, the
thermal time constant of the fuel rod has not a significant
influence on the inertia time constant of the control rod.

When the proportional term and the time constant
of the bar are adjusted, an integral term R_2 is necessary to lead
back the power level to its initial value.

In the case of the 100 and the 250 MWe studied
prototypes, an optimum value for the ratio R_2/R_1 is about 1/10.

A differentiel term is <u>without interest</u> for
stability point of view.

In case of control loss with a simultaneous
injection of reactivity, the power of the unstable core after
a time of about one second increases exponentially with a time
constant varying inversely as the power coefficient.

A reduction of the coolant flow makes the
reactor less stable or more unstable.
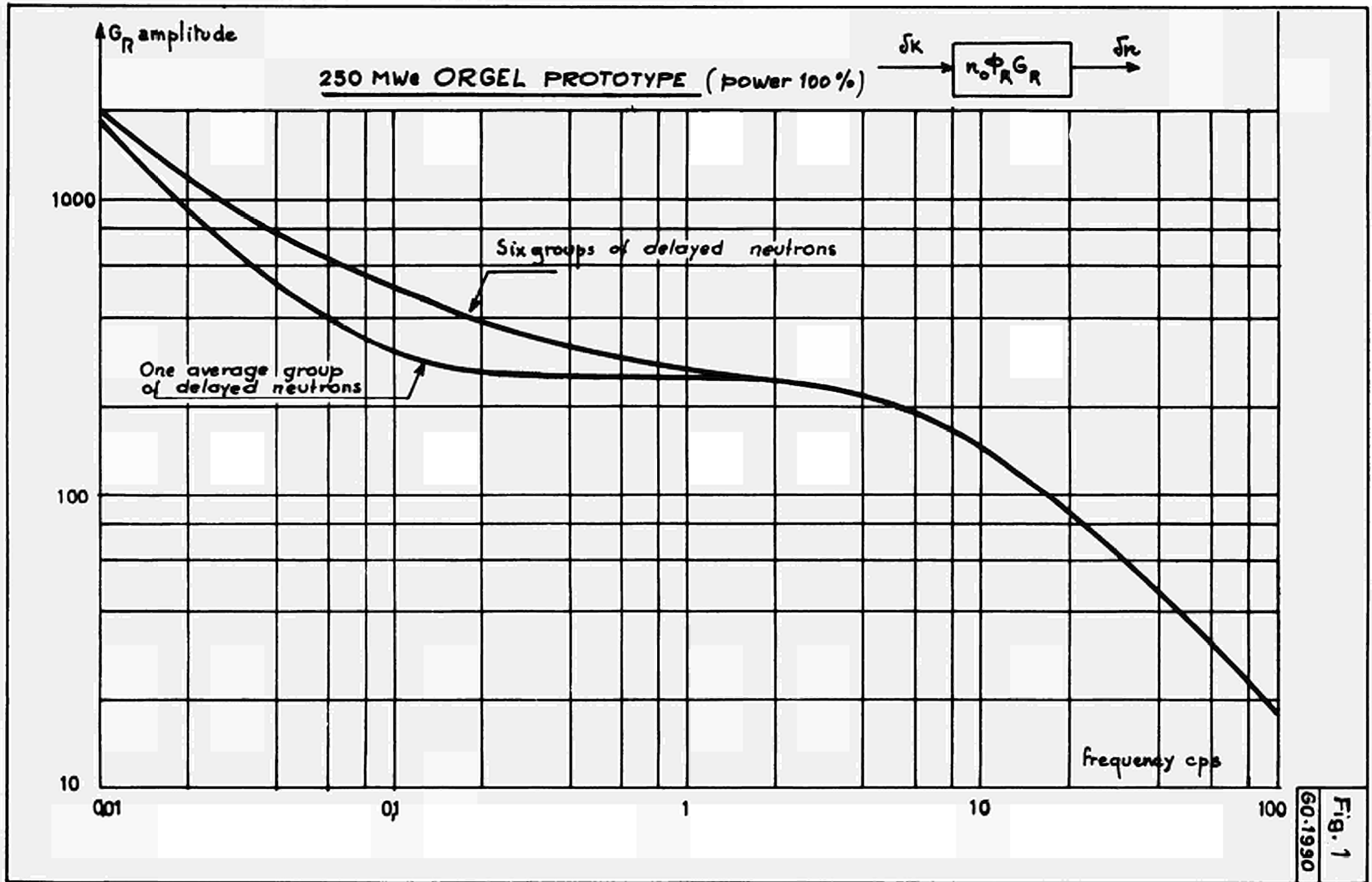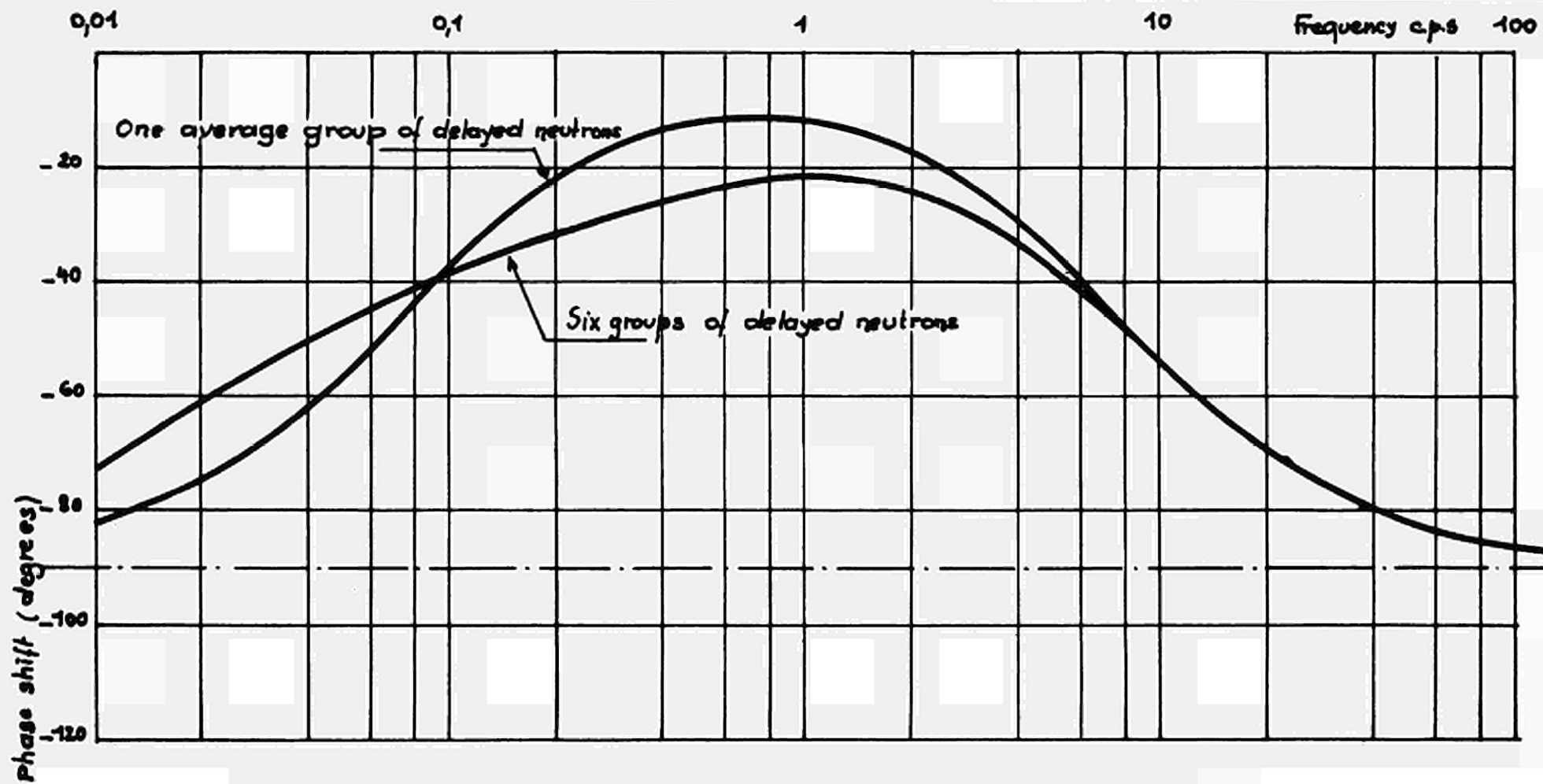
250 MWe ORGEL PROTOTYPE (power 100%)

Fig. 1
60.1990

Fig. 2
G0·1991

Fig. 3
GO·1992

250 MWe ORGEL PROTOTYPE

1. Initial core

2. Equilibrium core

250 MWe ORGEL PROTOTYPE

1. Initial core
2. Equilibrium core

Fig. 4
60-1993

Fig. 5
AGO-1984

Fig. 6

250 MWe ORGEL PROTOTYPE

1. Initial core
2. Equilibrium core

G_{RT} amplitude

frequency c.p.s.

Fig. 7
GO-1996

Fig. 6

250 MWe ORGEL PROTOTYPE

1. Initial core
2. Equilibrium core

Phase shift ϕ_{RT} (degrees)

frequency c.p.s.

60.1997

Fig. 9
60.1998
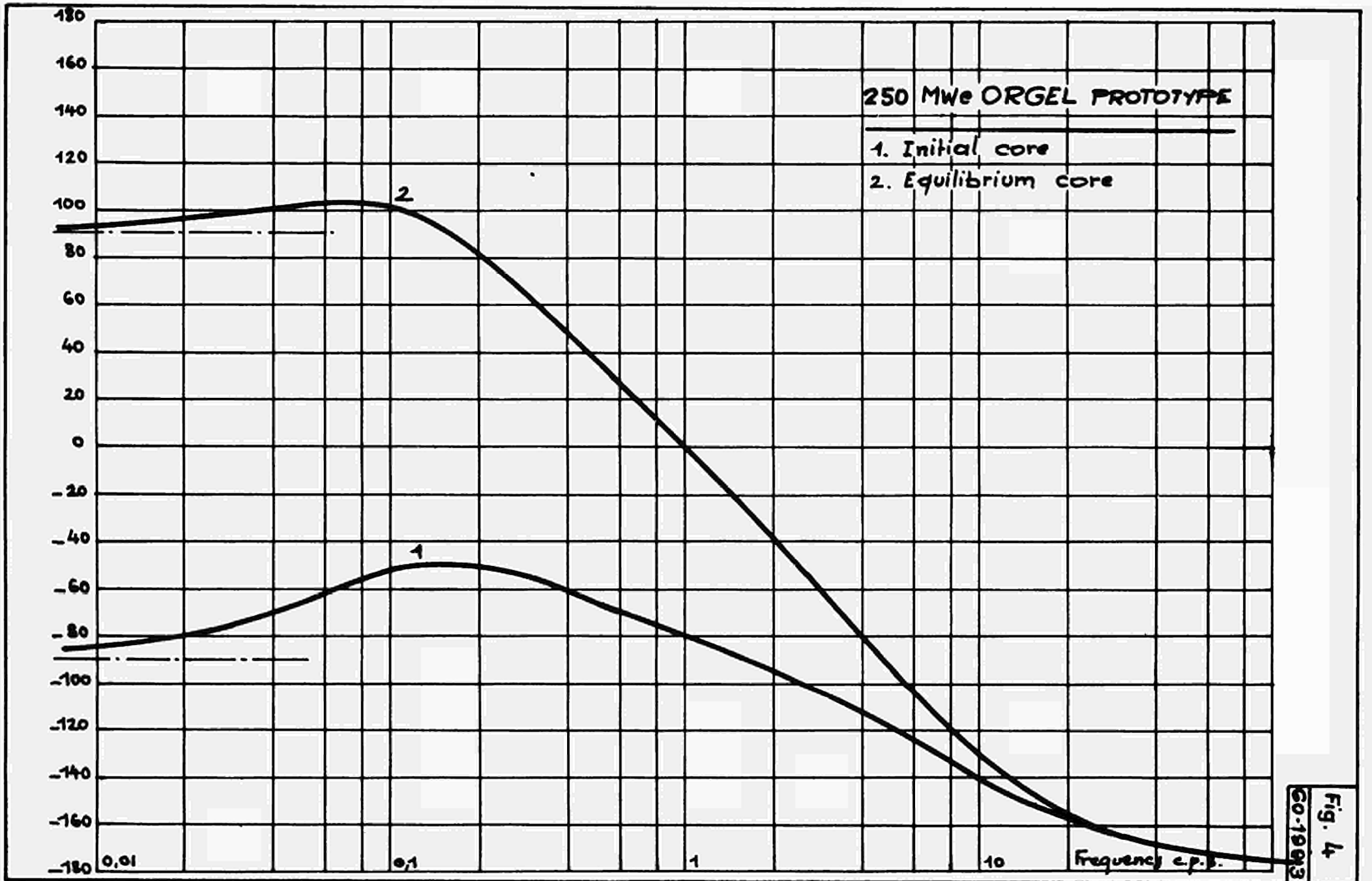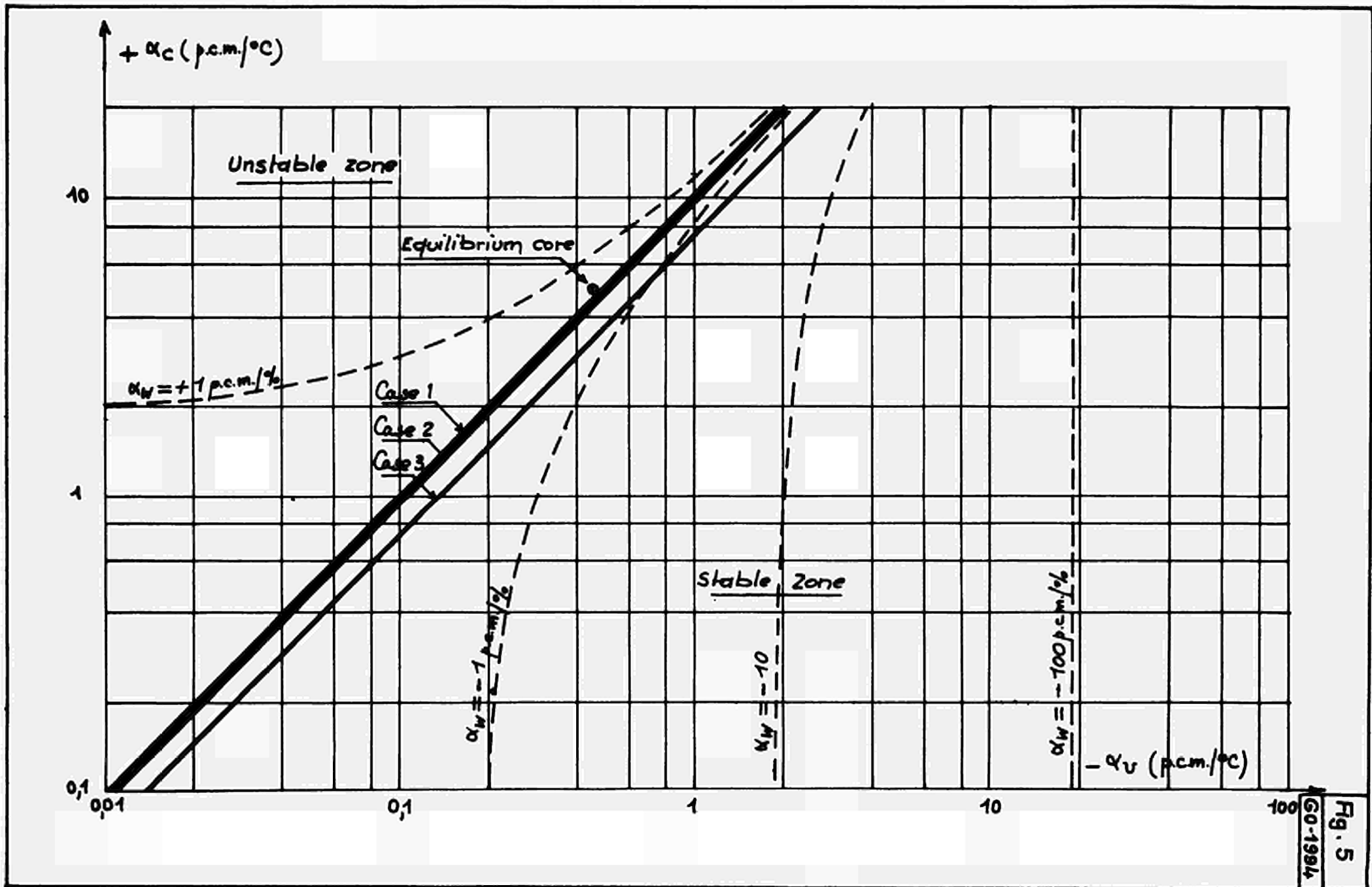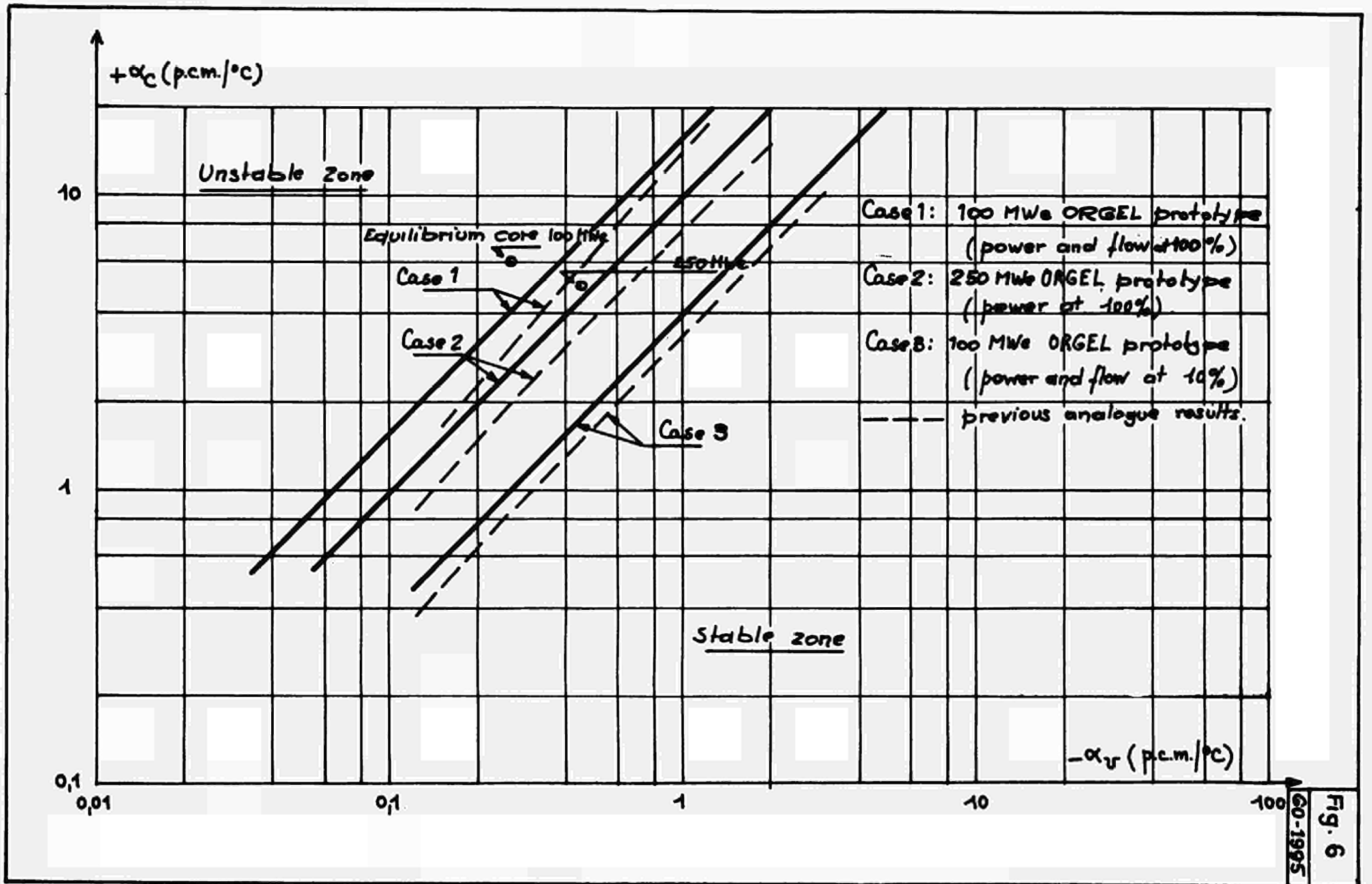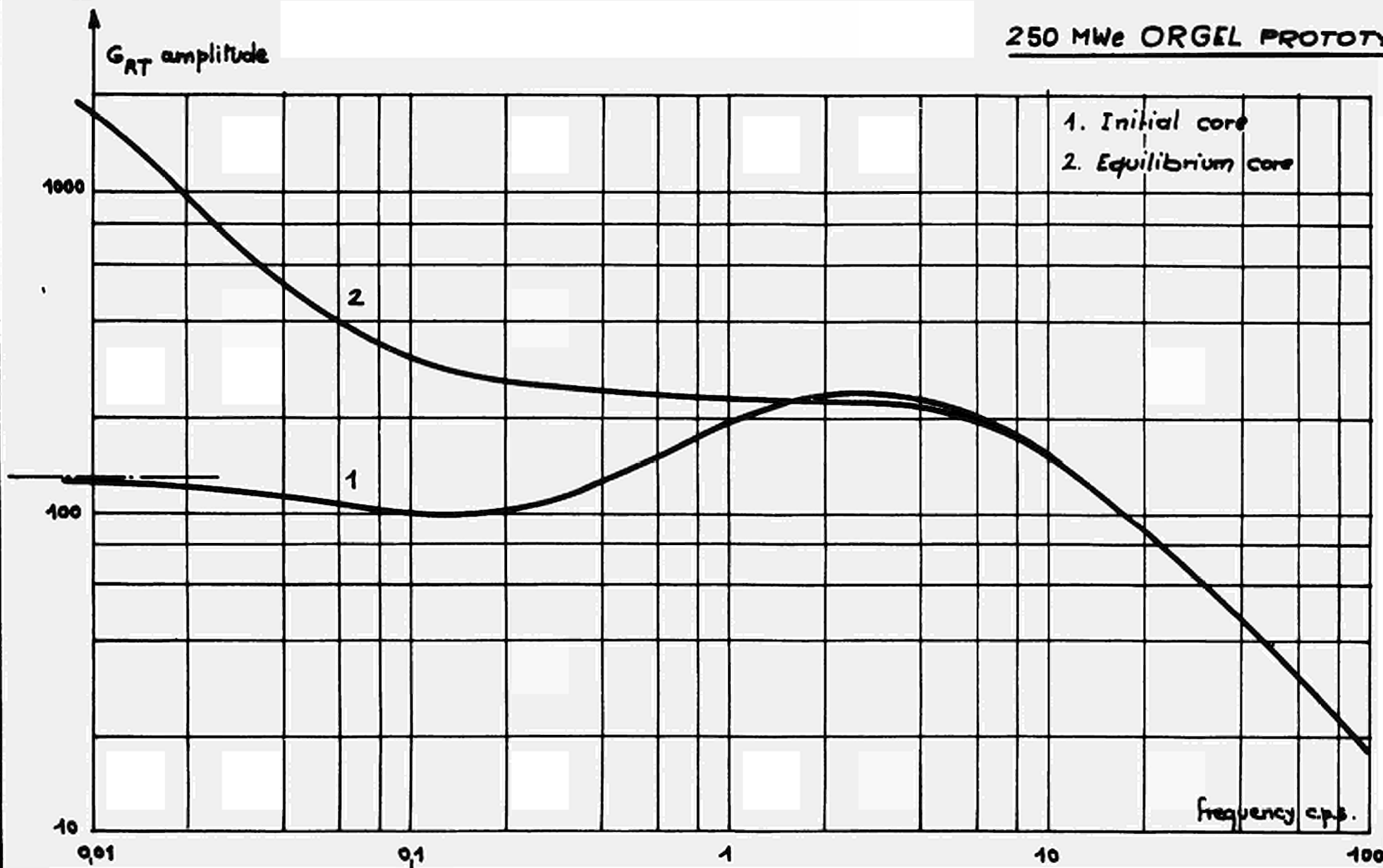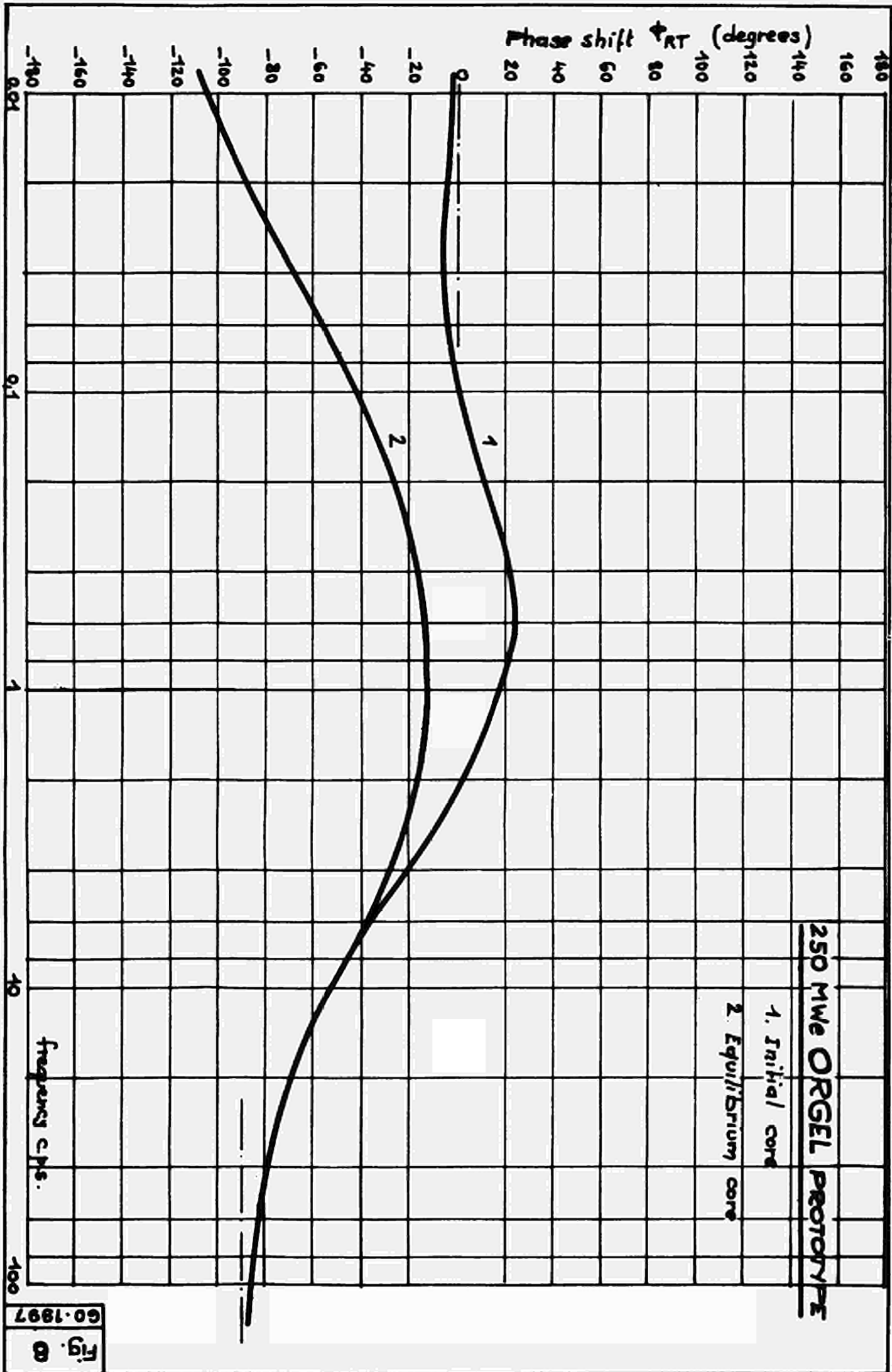
250 MWe ORGEL PROTOTYPE

Analogue responses to a like step function of 10 p.c.m
Reactor alone without heat. exchanger

$\delta n_{max}/n_o = \dfrac{\delta k}{\beta - \delta k}$
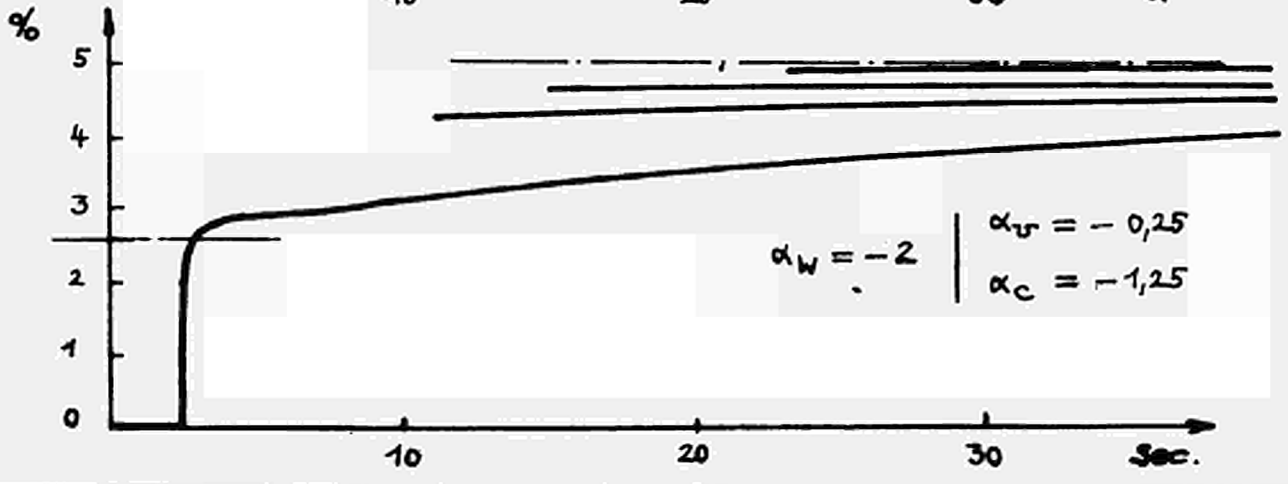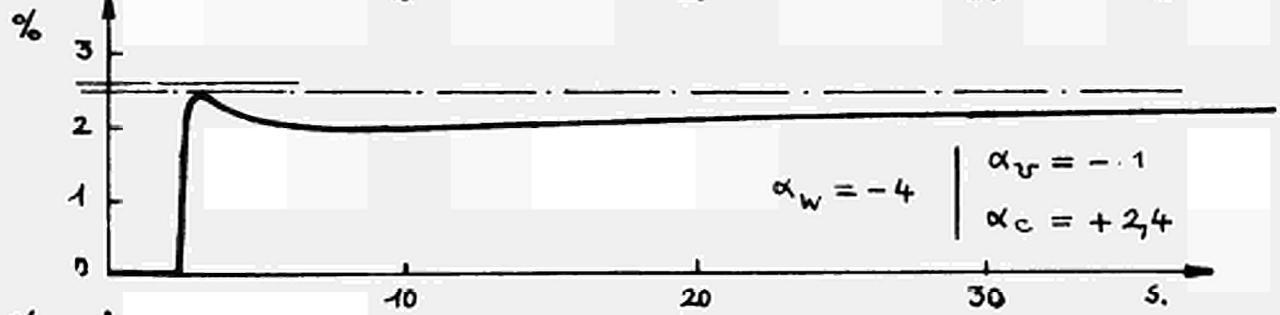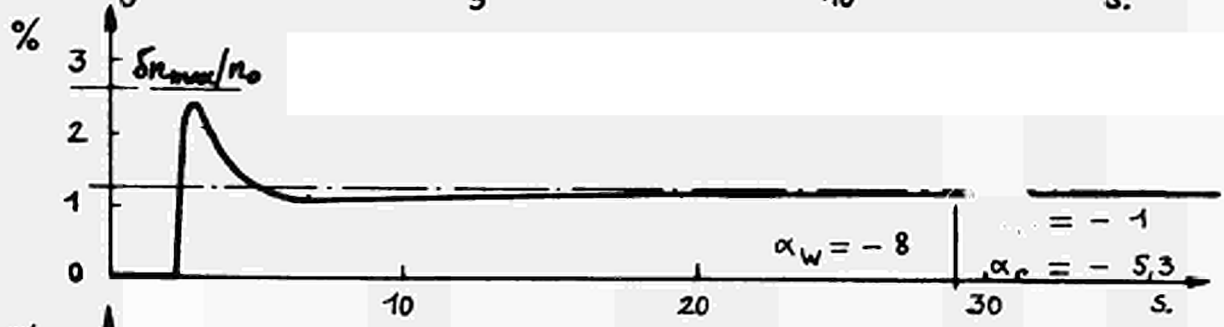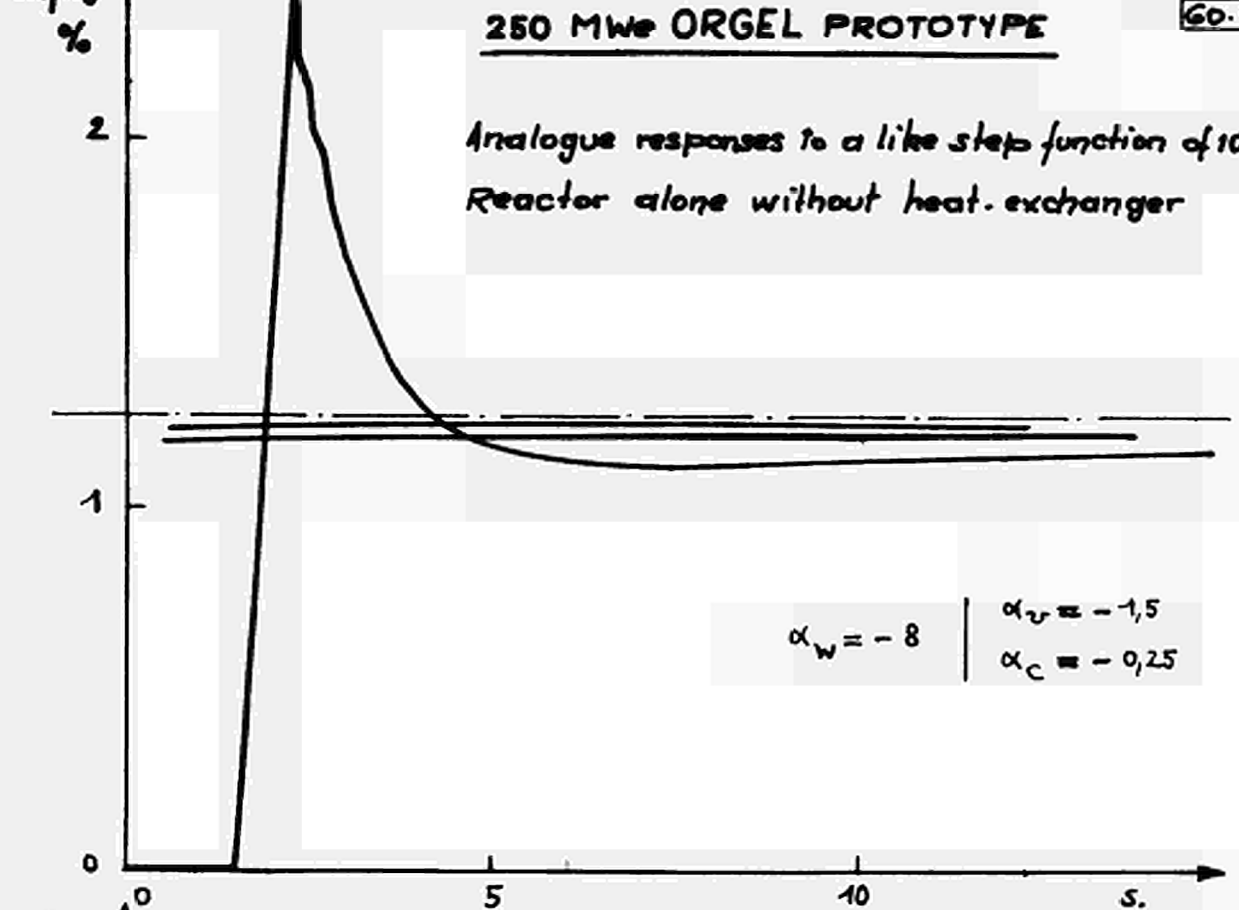
$\alpha_W = -8$ | $\alpha_U = -1,5$
$\alpha_C = -0,25$

$\alpha_W = -8$ | $= -1$
$\alpha_C = -5,3$

$\alpha_W = -4$ | $\alpha_U = -1$
$\alpha_C = +2,4$

$\alpha_W = -2$ | $\alpha_U = -0,25$
$\alpha_C = -1,25$

Fig. 10
6.0.1989

250 MWe ORGEL PROTOTYPE

amplitude $G_c G_{RT}$

Proportional term: $R_1 = 10^{-2}$

$\tau = 1$ sec.

$\tau = 10$ sec.

frequency c.p.s.
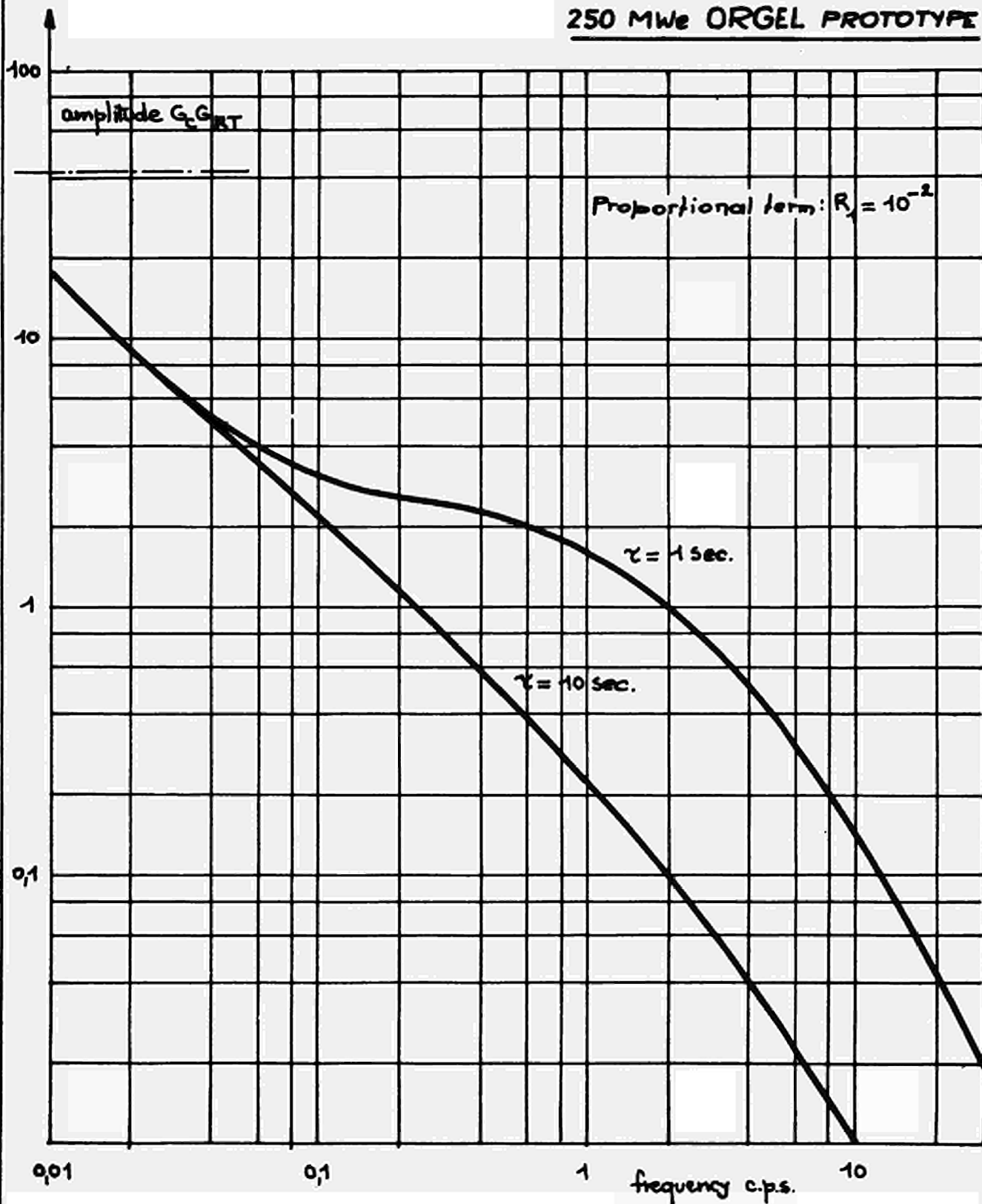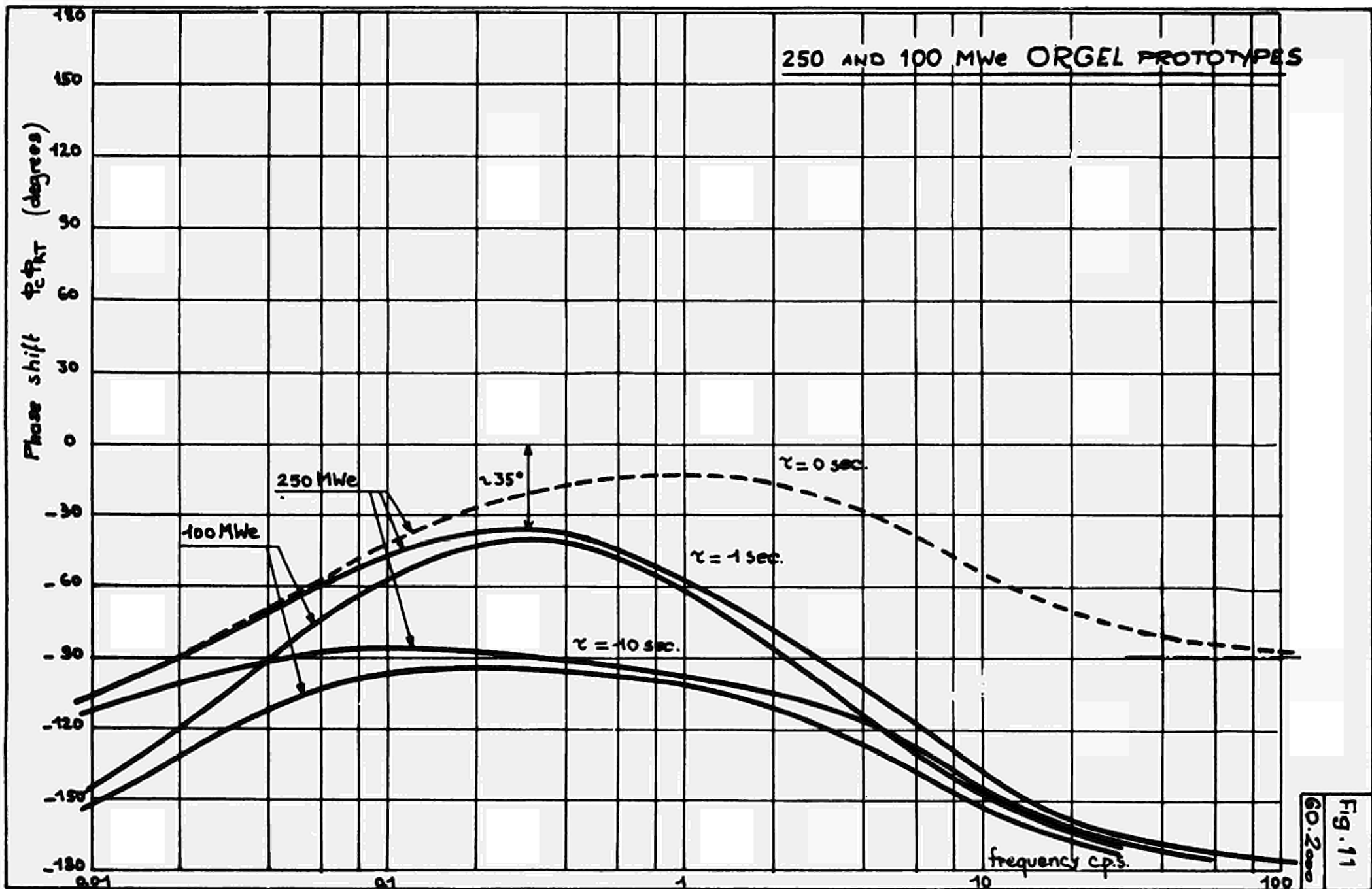
Fig. 11
60.2sec

Fig. 12
G.0.2001

250 MWe ORGEL PROTOTYPE

Unstable equilibrium core

Responses to a step function of 50 p.c.m.
with proportional and integral terms
(digital results)
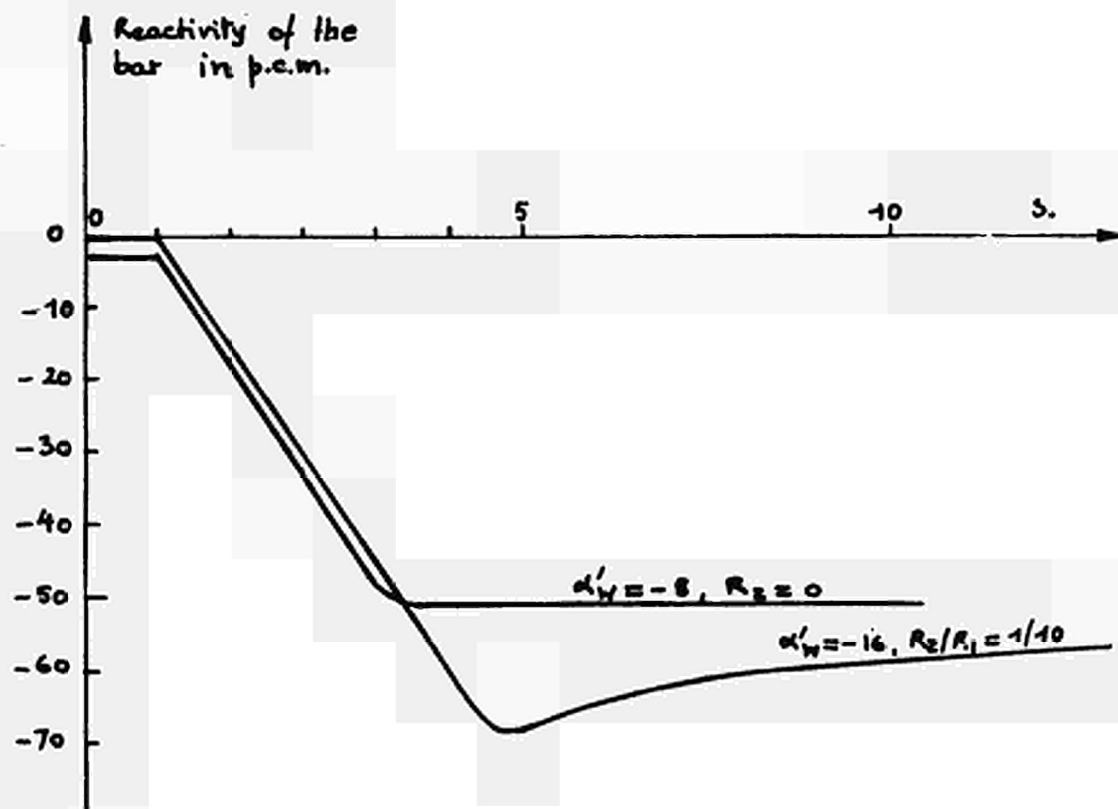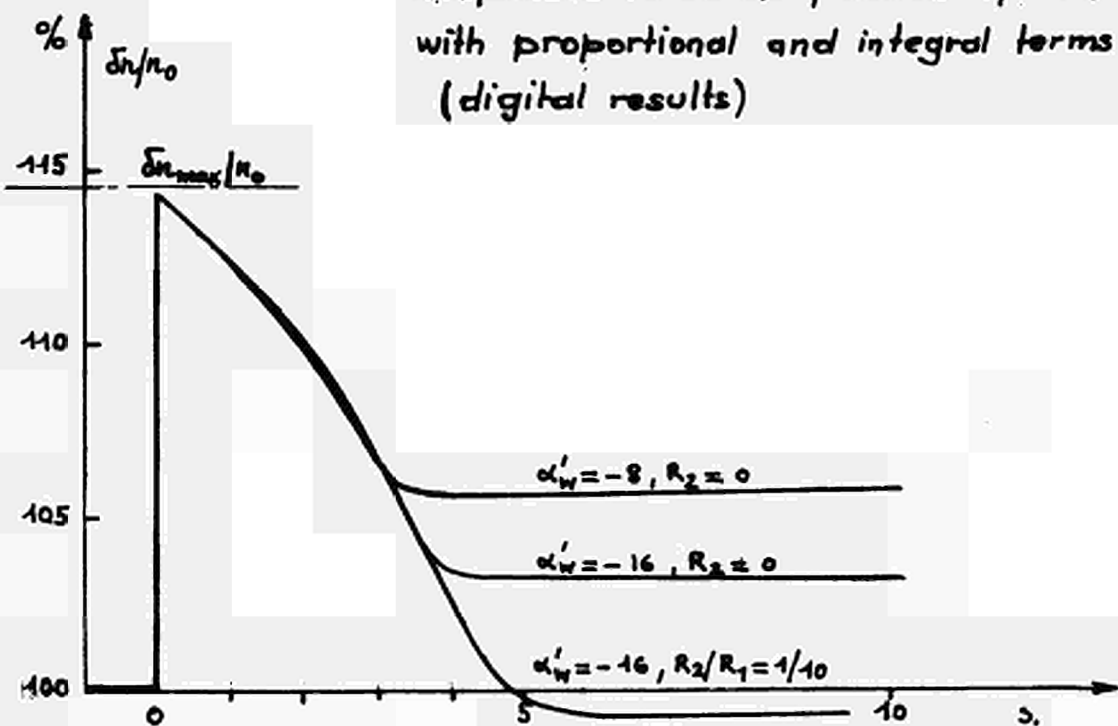
Fig. 13
G.0·2002

250 MWe ORGEL PROTOTYPE

amplitude $G_c G_{RT}$

Proportional and integral terms

$R_1 = 5 \cdot 10^{-2}, R_1 / R_2 = 1/5$

$R_1 = 10^{-2}, R_1 / R_2 = 1/5$

$R_1 = 10^{-2}, R_1 / R_2 = 1/10$

$\tau = 1$ sec.

$\tau = 10$ sec.

frequency c.p.s.

Fig. 14
GO-2003

250 Mwe ORGEL PROTOTYPE

Fig. 15
G.O. 2004

250 MWe ORGEL PROTOTYPE

Fig. 16
GO.2005
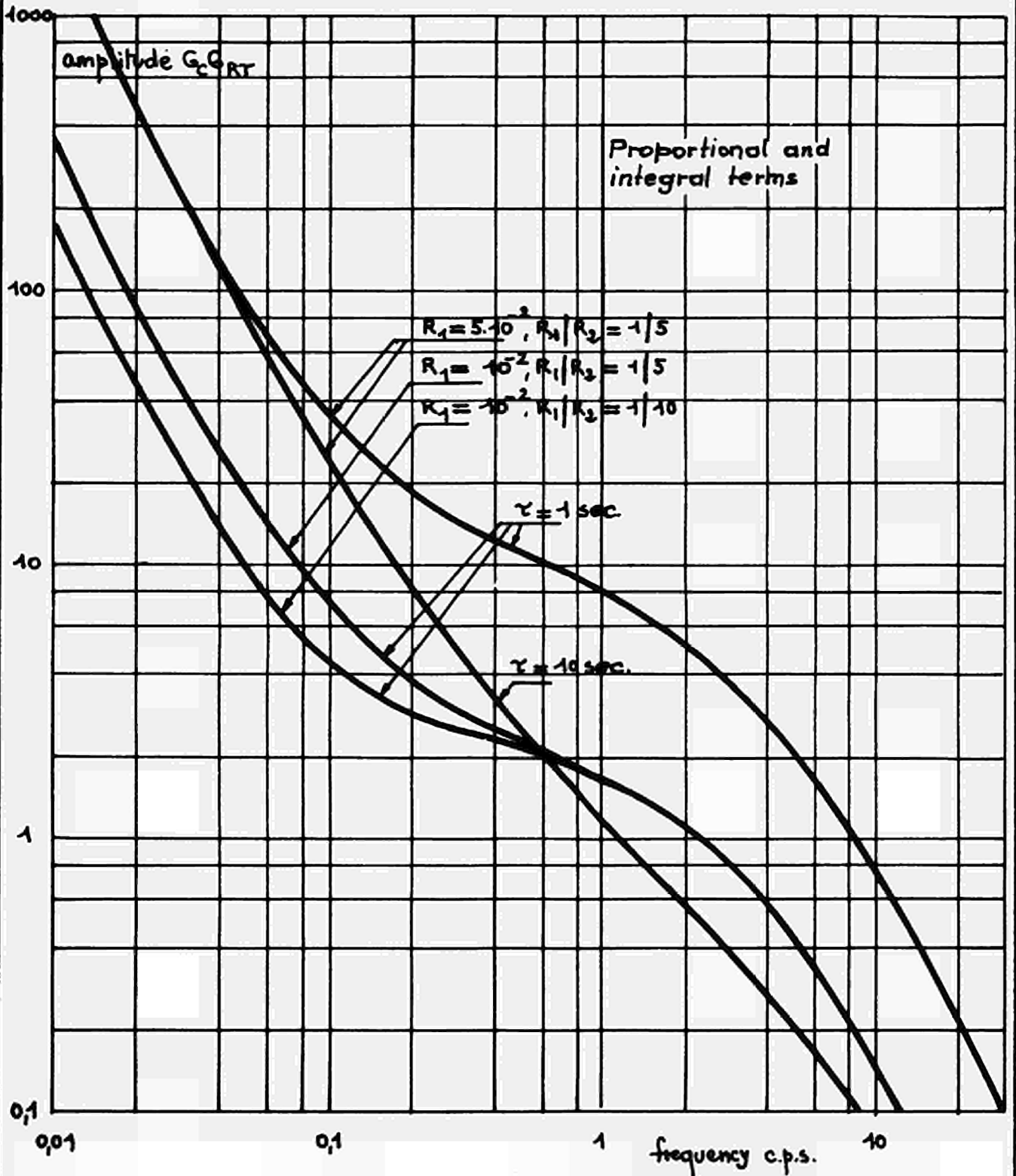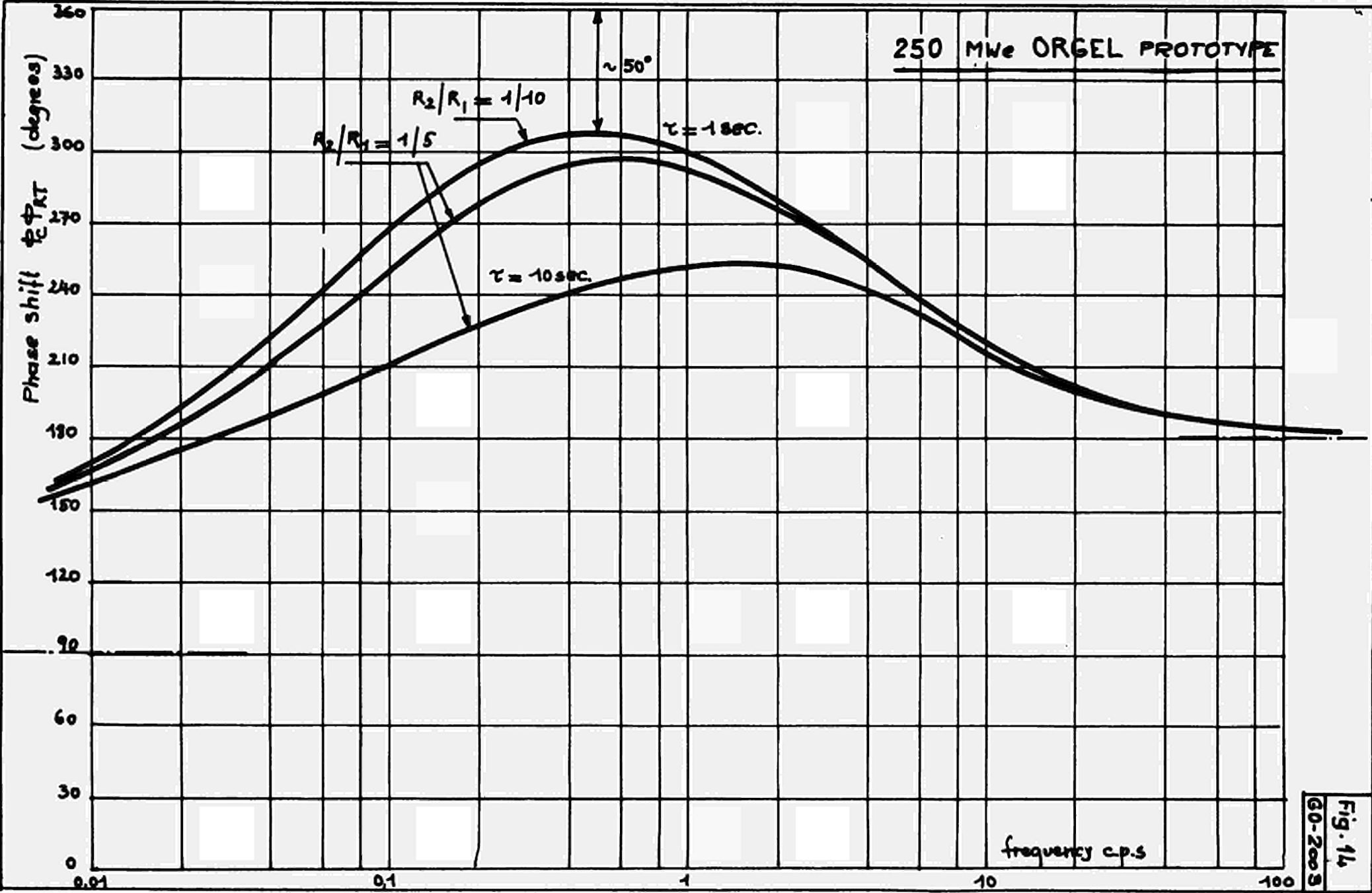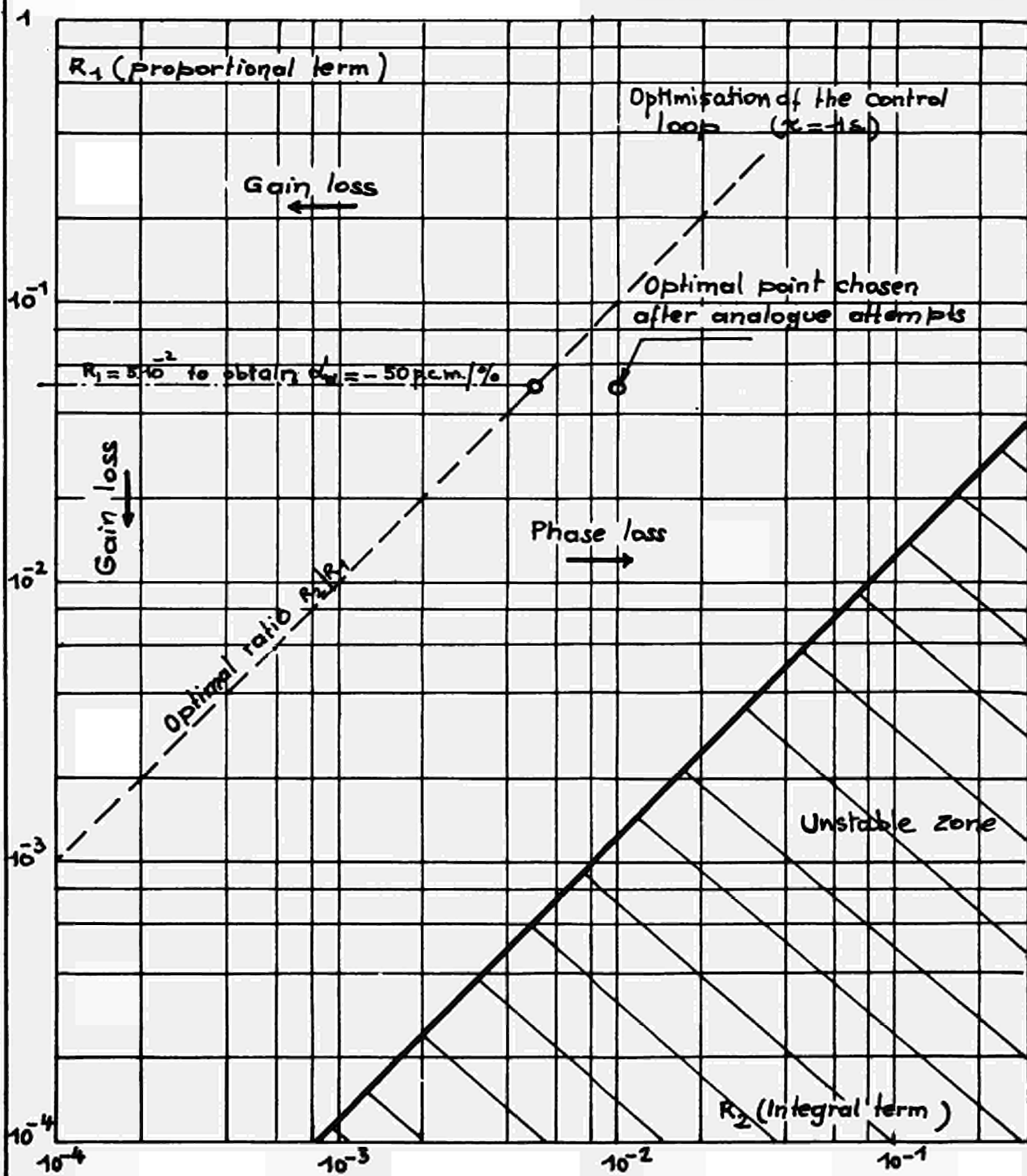
250 MWe ORGEL PROTOTYPE

Simultaneous control loss and reactivity step for variable power coefficients.
Digital results

Step of 10 p.c.m.

$\alpha_W = +0,57$

$\alpha_W = +0,25$

$\alpha_W = +0,25$

$\alpha_W = +0,57$

$(\delta n/n_o + \frac{\delta K}{\alpha_W}) \%$

$\delta n/n_o \%$

time (sec)

Stable period : $T = \frac{\beta - \delta K}{\lambda \, \delta K} \neq 9$ min.
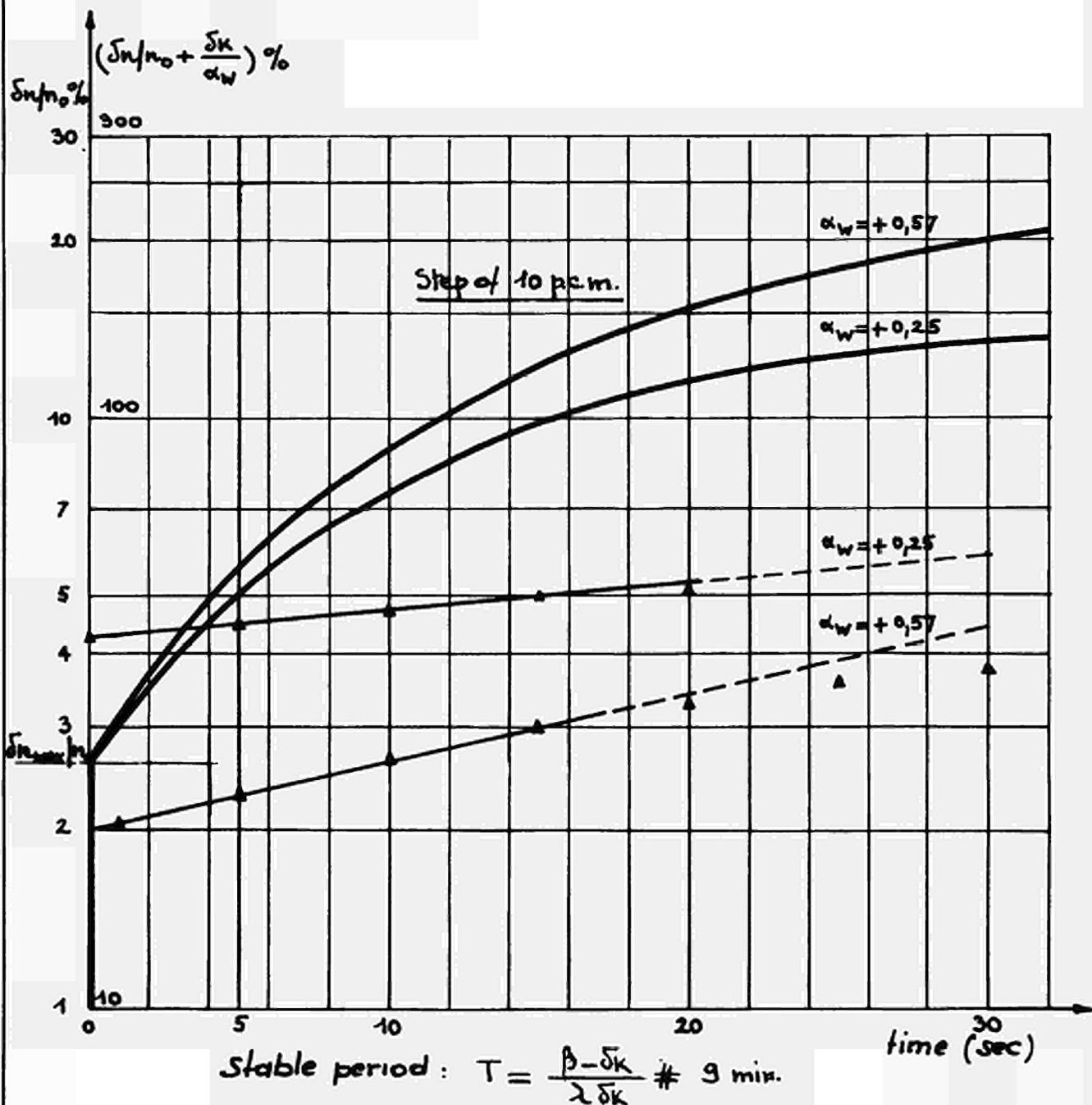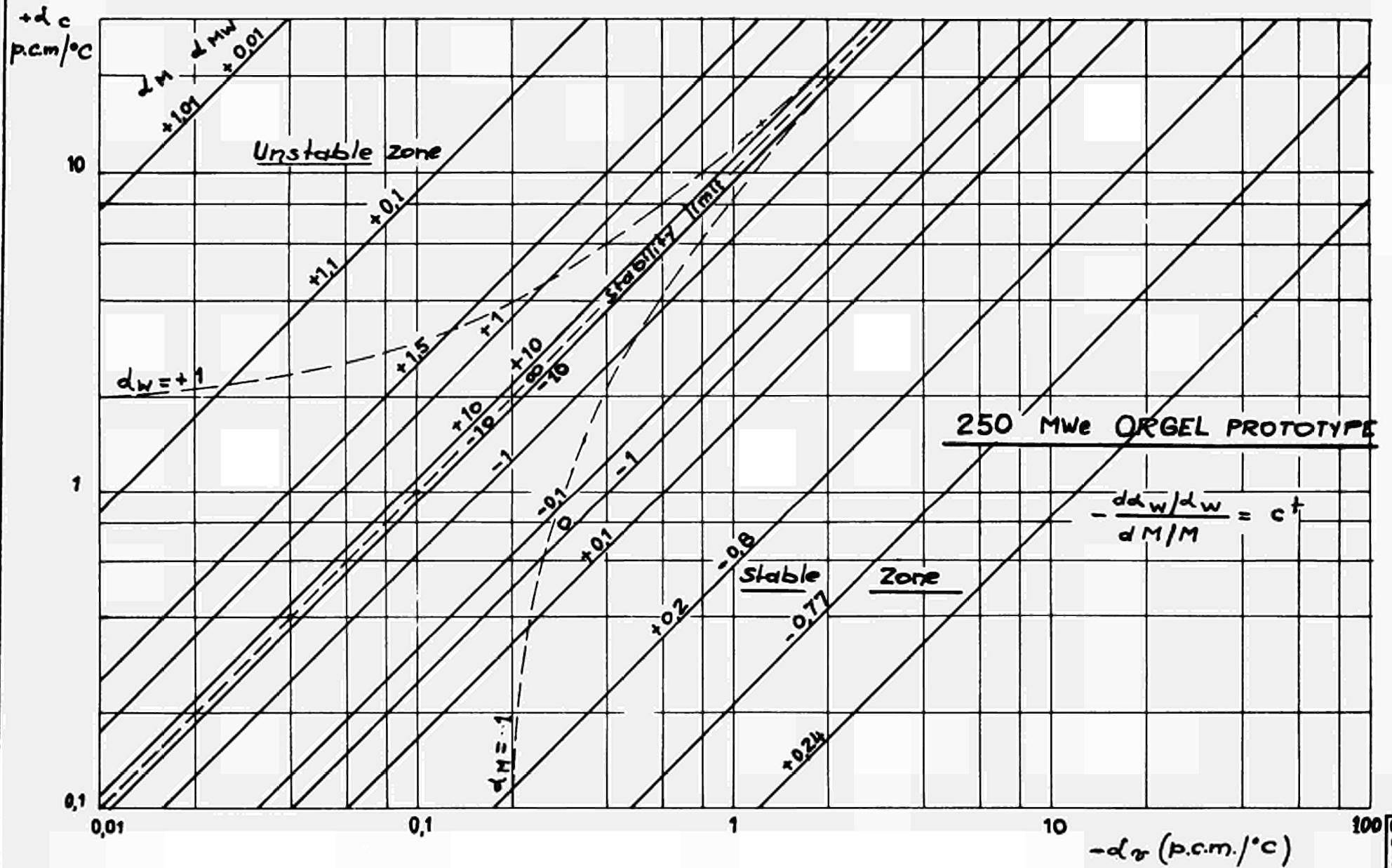
Fig. 17
60.2006

APPENDIX B

D Y N O R

A numerical program for the DYNamic simulation of an ORGEL power plant

1. INTRODUCTION

The DYNOR code was made with the intention to investigate the behavior of an ORGEL power station under a great variety of circumstances, such as:

- variation of power level;
- reactivity, temperature or coolant flow disturbances;
- different temperature coefficients;
- different regulator arrangements;
- different arrangements of the heat exchanger;
  etc.

For this reason, the DYNOR code was written using the more general simulation program SAHYB 2 (Ref. 2), which accepts the problem description in a language close to the mathematical formulae, and handles integration and input-output in a standard way.

As a consequence. DYNOR is made of 10 subroutines, which are called by SAHYB-2. Changes in the formulation corresponding to the required investigations are done modifying some of these routines which contain substantially the physical formulae.

The description which follows will thus refer to a standard version of DYNOR that will be modified according to the investigation needed. The standard DYNOR, given in Appendix II, computes the dynamical evolution towards a steady state.

2. GENERAL ORGANIZATION OF DYNOR

The block diagram of the power station is given in Fig. B-1; as in all programs using an integration routine, the integrated variables are expressed in vector notation X_i or $X(I)$. The correspondence between the $X(I)$ and the physical variables is given in the following sections and is resumed in Fig. 1. In all subroutines, the derivatives are noted $DX(I)$ and time is noted T. A differential equation is thus noted:

$$DX(I) = \ldots\ldots \text{expression}$$

The correspondence between physical parts of the system and the subroutines of DYNOR is also given in Fig. 1.

The reader should note the exact correspondence between Fig. 3.1. and Fig. 1.21a. The finite differences partition of the heat exchanger is identical to the one described in 1.3.

3. THE SUBROUTINE DER

This subroutine contains the description of the reactor and of the primary loop, including the wall equations of the heat exchanger.

DER only is called by the program SAHYB-2, and all other routines of DYNOR are called by DER, directly or indirectly.

The arguments of DER are:

T   the time (independent variable)

X   the integrated vector

DX   the vector of the derivatives

PAR   a parameter vector, not utilized here*

The first part of DER, up to the statement 200 CONTINUE,
is executed only once, and contains the physical parameters**
and intermediate computations.

The equations following statement number 200 are equations***
(1.1.),(1.2.),(1.8.),(1.9.), (1.10.), (1.27.) for the reactor, and
(1.29.), (1.30.) for the heat exchanger.

Equation (1.1.) has been approximated by a sequence of
equilibrium states, assuming the derivative always equal to zero.
This is necessary to ensure numerical stability with reasonable
long integration steps, since this equation has very fast time
constants.

The subroutine DER calls subroutines VARIAT, SECOND, REGUL,
to be explained later.

The functions DELAY and SIGMAP are standard SAHYB-2
functions, performing respectively delay simulation and multiple
summation (see SAHYB-2 operating manual).

The use of indices for the vectors X and DX can clarly
be understood examining Fig. B-1.

PAR is a vector of parameters (maximum 100) that can be read in
the input data (see section 9).   It has not been used in the
standard DYNOR because the parameters are too numerous, and the
input data deck must be kept reasonably short.   Now suppose e.g.
that a certain number of computations is wanted varying temperature
coefficients AU and AC.   The use of DYNOR should then compile
subroutine DER replacing instructions n°510 and 520 (of Appendix II)
by the following: AU=PAR(1), AC=PAR(2) and then read PAR(1) and
PAR(2) in the input data as explained in section 9.
The meaning of symbols is given in Appendix I.
All equation numbers refer to paragraph 1.

4. THE SUBROUTINE REGUL

This subroutine is called by DER, and contains the description of the regulator, as described in section 1.4. The first section introduces parameters, and after statement number 100 are described equations (1.43.) and (1.44.).

If different control systems need to be tested with the power plant, a new REGUL subroutine may be introduced in DYNOR.

The arguments are the same as for DER.

The function COMPAR is a standard SAHYB-2 function*
which introduces the non-linearities (limitations of speed and displacement). COMPAR is used here in a similar way as a comparator in an analogue set-up.

5. THE SUBROUTINE SECOND

This routine is called by DER, and contains the equations of the secondary side of the heat exchanger, except the super - heater equations, which are in subroutine SUPHTR, called by SECOND.

As in DER and REGUL, the first section, up to statement number 300, contains the parameter definitions and preliminary computations which are executed only once.

The equations are those given in Figs. 1.8. and 1.10. and Eqs. (1.33.), (1.34.), (1.36.), (1.37.), (1.39.), (1.40.) and (1.41.).

COMPAR(A,i) is equal to 1 when A is positive, and zero for A negative; when the transition from one state to another occurs, this is indicated in the output, and COMPAR resets the starting procedure of the integration routine, avoiding the errors due to the discontinuity.

The economizer equations (Fig. 1.8.) are solved for their equilibrium state, assuming the derivative always equal to zero, in order to ensure numerical stability with a reasonable long integration step (as for Eq. 1.1.).

The approximation given in section 1.3. for the thermo-dynamical functions (saturation temperature, enthalpies and specific volume) are linked with the scaling range of the analogue computation; in DYNOR, these functions have been evaluated by accurate formulae (see section 8).

The subroutine SECOND calls also subroutine RECORD, which is a control on input-output operation. The arguments of second are the same as in DER.

6. THE SUBROUTINE SUPHTR

This subroutine is called by SECOND. It solves the energy conservation equations for the superheater (Fig. 1.18.) as a sequence of equilibrium states (to ensure numerical stability). The equations are solved for the enthalpy of superheated steam H(J) by iterations; this requires the evaluation of the steam temperature, which is function of pressure and enthalpy.

The evaluation of temperature by accurate formulae would require long computer times; the temperature function is there-fore stored in tables for a wide range of pressures and enthalpies, and is read by the function FTWOV (which is a standard SAHYB-2 function) which uses linear interpolation (see section 10 and appendix IV). The accuracy of this procedure is maintained within a one percent; if, by any chance, the computed temperature goes outside the stored range, computation is stopped and a diagnostic is given by SAHYB-2.

7. THE SUBRØUTINE RECORD

This subroutine is called by SECOND (which is called by DER) and contains the standard SAHYB-2 statements for read-out; they have been grouped here in order to allow a change of the output without modifying or recompiling the other DYNOR sub - programs.

The subroutines that may be called by RECORD to print out results are:

CALL ØUTPUT (arg 1, arg 2, ...)

This subroutine enables to print out, either the complete integrated vector and the derivatives, or some of them. Specified labels (given in the input data) are printed out near the results. The arguments are integers, and are the indexes of components which must be printed out.

CALL WRITE (arg$_{11}$, arg$_{12}$, ... arg$_{i1}$, arg$_{i2}$, ...)

This subroutine prints out variables other than the integrated vector components. These variables must appear at least once in a left-hand side term in the subroutine DER. They are printed out for the same interval as in OUTPUT. The number of arguments is variable with a minimum of two; they are always in pairs, the first one specifying the label, the second one the variable name.

arg$_{i1}$ is a Hollerith field of a maximum of 6 characters, which specify the label that should be printed near the variable;

arg$_{i2}$ is a name of a variable which must be printed out.

In addition, plots may be obtained on the CALCOMP, calling in RECORD the following subroutines:

<u>CALL DRAW (arg$_{11}$, arg$_{12}$, arg$_{i1}$, arg$_{i2}$, ...)</u>

plots the results as a function of the independent
variable T. The arguments have the same arrangement as for
WRITE. The subroutine DRAW may be called repeatedly, with
different arguments. For each CALL, the curves relative to the
arguments will be drawn on the same plot.

<u>CALL DRAWXY (arg$_{11}$, arg$_{12}$, ... arg$_{i1}$, arg$_{i2}$)</u>

plots the results in a phase plane, taking as abscissa
the first variable (first two arguments) and as ordinate the
successive. The routine may be called repeatedly to obtain
different plots in a similar way as DRAW.

For further details on the output procedures, the reader
should refer to the SAHYB-2 operating manual. When writing a
new RECORD to change the output, care should be taken to see
that the variables to be recorded appear in one of the COMMONS.

7. THE SUBROUTINE VARIAT

As it has been illustrated to this point, DYNOR contains
a system of differential equations describing the power station;
integration would, if carried on a sufficient time, lead to the
steady state at nominal power. As the purpose of DYNOR is to
allow transient computation under a variety of circumstances,
the SUBROUTINE VARIAT has been introduced as an easy way to
insert variations (or disturbances) without modifying and
recompiling th other DYNOR subroutines. As given in appendix
II, VARIAT is a dummy and has no influence. A comment indicates
which are the variables that may be programmed in VARIAT:
disturbances in reactivity, temperature or flow; variation of
power demand, variation on the regulation programs for pressure
and temperatures when the power is changed. Since all these
inputs have frequently the shape of a step, a pulse or a ramp,
SAHYB-2 provides, as a standard feature, the three following
functions:

STEP (T)

PULSE (T)

RAMP (T1, T2)

simulating respectively a step of unit amplitude, a pulse of unit surface occurring at time T, or a ramp of unity rate (1 unit/second) between times T1 and T2. The synchronisation of the discontinuity with the integration routine is automatically ensured.

For example, a 100 pcm reactivity occurring at time = 5 sec. would need this instruction in VARIAT:

CTØ = 1. + 100.E - 5* (STEP (5))

A temperature disturbance of 5°C/sec. during 2 seconds in the inlet temperature of the heat exchanger would be simulated by:

TF = 190. + 5.* (RAMP (0.,2.))

As another example, consider a power demand variation following the regulation program given in 1.4.3. and Figs. 1.22. and 1.23.*

The required instructions for VARIAT would be:

PØWVAR = 1. - 0.0008333* (RAMP(0.,900.))

TAVZ   = 318. - 0.02222* (RAMP(300.,900.))

When using VARIAT, it must obviously be verified that the variable to be changed is in the common.

Power demand from 100% to 25% in 15 minutes (900 seconds) varying thus of 5% a minute (0.0008333/second). The average temperature must remain constant from 100% to 75% of full power (thus during 300 seconds), and then decrease of 20° in the next 10 minutes (0.02222°C/second).

8. SUBPROGRAMS FOR EVALUATING THERMODYNAMIC QUANTITIES

The functions utilized by DYNOR are:

FUNCTION TLSAT(P)   gives the temperature of saturation, in degrees Centigrades, if P is the pressure in kg/cm2;

FUNCTION VSVAP (P,TEMP)   gives the specific volume of steam, in m3/kg, if P is the pressure in kg/cm2 and TEMP is the temperature in degrees Centigrades;

FUNCTION EVSAT (TSAT)   gives the enthalpy of saturated steam, in Kcal/kg, if TSAT is the saturation temperature in degrees Centigrades;

FUNCTION ELSAT (TSAT)   gives the enthalpy of water at saturation, in Kcal/kg, if TSAT is the saturation temperature in degrees Centigrades.

These functions are called by SUBROUTINE SECOND.

9. INTEGRATION SUBROUTINES

These are the standard routines used by SAHYB-2.

Three options may be used, which give comparable results: (the choice of the desired option is made through the input data, see § 10).

Option 4: fixed step 4th order RUNGE-KUTTA integration.   Use a time step of about 0.1 second.

Option 1: fixed step predictor-corrector integration.   Use a time step of about 0.1 second.

Option 2: variable step predictor corrector. The following
characteristics should give a reasonable compromise
between accuracy and speed:

MAXIMUM ERROR	10^{-5}
MINIMUM TIME STEP	10^{-3} sec.
MAXIMUM TIME STEP	10^{2} sec.
VARIATION FACTOR	0.5
LIMIT BETWEEN ABS. AND RELATIVE ERROR	100
LOWER BOUND TO ERROR	50

Generally, the variable step option will be preferred.

10. INPUT DATA

These follow the standard arrangement for SAHYB-2,
adapted to the particular case of DYNOR.

The first card is a comment intended to identify the
problem; the first 15 letters of this comment are written on
the CALCOMP plots for identification. On the following, there
is one numerical information per card: columns 1 to 40 may be
used for any comment to be reproduced on the output listing
(usually the meaning of that particular datum). The numerical
information is contained in column 41 to 50, in fixed or floating-
point notation*.

The data cards are, in order:

1)   identification and comments;

2)   number of differential equations N (fixed point) N = 31
        for the standard DYNOR, but may be modified if equations
        are added;

For fixed point, the reading format is: I 10. For floating
point, the reading format is: E 10.6. Thus, for fixed point,
the unities should be in column 50; for floating, if the
decimal point is explicit, the number may be written in any
desired way in columns 41 to 47; column 48 contains eventually
the sign of the exponent of 10, columns 49 and 50 this exponent.
Blanks are taken as zeroes.

3)   number of parameters PAR;   equal zero, if PAR is not used*

4)   number of tables to be read in input: N = 7 for the
        standard DYNOR;

5)   final time for integration (floating);

6)   initial or constant integration step (floating);   a value
        around 0.1 is convenient;

7)   time step for output (floating);

8)   integration option (see section 9);   the numerical
        information in column 50 should be:
        1 for fixed step predictor-corrector
        2 for variable step predictor-corrector
        3 for variable step predictor-corrector using standard
          error characteristics**
        4 for 4th order Runge-Kutta integration

9, 1)   initial condition for X(1) in floating;   the first six -
        characters of the comment are taken as label on the
        standard output;

        ....

9, n)   initial condition for X(n);

10-i)   PAR(i) value, with the same format of initial conditions
        (only if datum 3 is different than zero)***

Then the following cards (11 to 16) must be placed only when
integration option is 2 on datum n.8.

---

11)   maximum relative error (floating);

12)   minimum time step (floating);

13)   maximum time step (floating);

14)   variation factor (floating);

15)   level below which the absolute error is considered for step variation (floating);

16)   error factor, specifying a lower bound for which a longer step length is taken (floating);

17)   number of points in table 1 (100, fixed point);

18-1)   the following cards contain the abscissae and ordinates of table one: six numbers, per card;   respectively x_1, y_1, x_2, y_2, x_3, y_3 on the first card, etc.   Each number is expressed in floating and uses 10 columns. Thus columns 1 to 60 are used on these cards.

19)   number of points in table 2 (fixed point)

20)   abscissae and ordinates of table two
         etc.

And so on for the desired number of tables.   The last card must always contain END in the first three columns.   If the data need to be changed, follow the SAHYB-2 operating manual.

The tables referred to in data 4, 17, 18, 19 etc. are the values of temperature of superheated steam versus enthalpy, for several values of pressure:

Table 1 corresponds to		40	kg/cm2
" 2	"	60	"
" 3	"	80	"
" 4	"	100	"
" 5	"	130	"
" 6	"	160	"
" 7	"	200	"

These tables are given in appendix 4;   they limit the validity domain of the program (see section 5);   an example of data deck is given in appendix 3.

APPENDIX I

Definition of symbols

SUBROUTINE DER

X(1) = TU	temperature of uranium
X(2) = TG	temperature of cladding
X(3) = TC	temperature of coolant
X(4) to X(9)	delayed neutrons (6 groups)
X(12) = TORG 1 to X(19) = TORG 8	organic temperatures in the primary of the heat exchanger (eight zones, from the hot to the cold end)
X(20) = TWALL 1 to X(27) = TWALL 8	wall temperatures in the heat exchanger
PNTR	neutron power
CT	total reactivity
UU, UA, UC	heat capacity per unit of volume of uranium, cladding and coolant
AA, BBB	heat transfer coefficients uranium-cladding and cladding-coolant
CC	transport coefficient
GU, GC	are γ_u, γ_c defined by (2.25.) and (2.22.)
BETA = β	delayed neutrons fraction
VL = ℓ	neutron lifetime
B(i)	β_i / ℓ
AU = α_u	uranium temperature coefficient
AC = α_c	coolant temperature coefficient

SUBROUTINE REGUL

ERROR	actuating error signal
X(10) = INTE	integrated error
X(11) = ROCON	control rods reactivity
TAV	average temperature of organic
TAVZ	reference average temperature
PNOM	nominal power
R4	gain of integrated feedback
R5	gain of proportional feedback

AINERT	inverse of inertia time constant
SPEED	reactivity speed of control rods
SPDLI	speed limit for control rods
UPLI	upper limit for reactivity (mechanical stop of control rod)
DOWNLI	lower limit

SUBROUTINES SECOND and SUPHTR

TSEC(i)	temperature in the secondary (eight zones, from hot to cold)
X(28) - = P	steam pressure
X(29= RO	steam density in the boiler
X(30) = XX	steam quality in the boiler
X(31) = IDOW	enthalpy in the downcomer
H(i)	enthalpy in the superheater (three zones, from hot to cold)
I	enthalpy in the boiler
ISAT	enthalpy of saturated steam
ILIQ	enthalpy of saturated water
TSAT	temperature of saturation
WREQ	mass flow in the secondary
WR	mass flow in the riser
WC	condensation flow
VS	specific volume of liquid
ROSAT	density of saturated steam
VSPEC	specific volume of steam
POWER	nominal power demand
POWVAR	variation factor for power demand
ROLVE	density of water in the economizer
CLVE	specific heat of water in the economizer
TF	inlet temperature in the economizer
VLIQ	specific volume of water
ROD	density in the downcomer
TAU 1, TAU 2	time delays between reactor and heat exchanger
WOL	organic mass flow
WOLVAR	mass flow variation factor
TOUT	outlet temperature of the reactor
TIN	inlet temperature of the reactor

TOL	inlet temperature of the primary
TOUTEC	oulet temperature of the primary
ALTZE, B, S	height of the economizer, boiler and superheater
VLORE, B, S	volume, organic
VLTUE, B, S	volume, tubes
SPORE, B, S	surface, organic side
SPVAE, B, S	surface, secondary side
V	volume upper dome
LR, LD	height of riser and downcomer
VLDO	volume downcomer
HLOE, B, S	heat transfer coefficient organic side for economizer, boiler, superheater
HLVE, B, S	heat transfer coefficient secondary side for economizer, boiler, superheater
ROLOE, B, S	density of organic for economizer, boiler, super - heater
ROPE, B, S	density of wall for economizer, boiler, superheater
CLOE, B, S	specific heat of organic for economizer, boiler, superheater
CPE, B, S	specific heat of wall for economizer, boiler, superheater

APPENDIX II

Program and deck arrangement

DYNOR may be used with the FORTRAN-4 7090 or FORTRAN-360 monitor, in the following arrangement:

      1)   DYNOR CARDS

      2)   SAHYB-2 CARDS

      3)   DATA CARDS

The DYNOR programs for the 7090 and the 360/60 will practically be identical.

The SAHYB-2 decks are different.

The standard DYNOR is given in the following pages only to facilitate understanding; as in all digital programs changes or corrections could be introduced after publication of the present report.

```
      SUBROUTINE DER(T,X,DX,PAR)                                DYN00010
      COMMON/VARVAR/TF,CTO,POWVAR,WOLVAR,PNVAR,DERROR,TAVZ       DYN00020
      COMMON/SECVAR/TSEC(8),PNTR,ERROR,REG,TAV,CT,TOUT,          DYN00030
     1TOL,TIN,TSAT,POWER                                        DYN00040
      COMMON/SECPAR/PLVE,PLVB,PLVS,HLVE,HLVB,HLVS,LECO,ALVE,ALVB,ALVS,ADDYN00050
     1,AR,LSUR,LEVA,V,LD,LR,VLDO                                DYN00060
      DIMENSION X(100),DX(100),PAR(100)                         DYN00070
      DIMENSION C1(8),C2(8),C3(8),D1(8),D2(8),D3(8),VLA(9),B(9) DYN00080
      DIMENSION ROSEC(3)                                        DYN00090
      REAL LSUR,LEVA,LECO,LR,LD                                 DYN00100
      LOGICAL SWITCH                                            DYN00110
      IF(SWITCH(1)) GO TO 200                                   DYN00120
C                                                               DYN00130
C                                                               DYN00140
C        ****************** PARAMETERS **************************DYN00150
C                                                               DYN00160
      REACTOR                                                   DYN00170    ,1      ,2      ,3
                                                                DYN00180    ,4
      UU=3.1E4                                                  DYN00190    ,5
      UA=1.5E4                                                  DYN00200    ,6
      UC=1.9E4                                                  DYN00210    ,7
      AA=3.E4                                                   DYN00220    ,8
      BBB=4.5E4                                                 DYN00230    ,9
      CC=1.6E4                                                  DYN00240    ,10
      A11=0.95/UU                                               DYN00250    ,11
      A12=CC/UU                                                 DYN00260    ,12
      A32=2.*BBB/UC                                             DYN00270    ,13
      A31= AA/UC                                                DYN00280    ,14
      A22= AA/UA                                                DYN00290    ,15
      A21=CC/UA                                                 DYN00300    ,16
      GU=4./3.                                                  DYN00310    ,17
      GC=1.                                                     DYN00320    ,18
      CTO=1.00                                                  DYN00330    ,19
      BETA=0.003955                                             DYN00340    ,20
      BB=1.-BETA                                                DYN00350    ,21
      VL=5.4E-4                                                 DYN00360    ,22
      VLA(4)=3.01                                               DYN00370    ,23
      VLA(5)=1.14                                               DYN00380    ,24
      VLA(6)=0.301                                              DYN00390    ,25
      VLA(7)=0.111                                              DYN00400    ,26
      VLA(8)=0.0305                                             DYN00410    ,27
      VLA(9) =0.0124                                            DYN00420    ,28
      B(4) =.000169/VL                                         DYN00430    ,29
      B(5) =.000431/VL                                         DYN00440    ,30
      B(6) =.001482/VL                                         DYN00450    ,31
      B(7) =.000792/VL                                         DYN00460    ,32
      B(8) =.000096/VL                                         DYN00470    ,33
      B(9) =.000131/VL                                         DYN00480    ,34
      DTUO=X(1)                                                 DYN00490
      DTCO=X(3)                                                 DYN00500    ,35
      TEMPERATURE COEFF FOR IRRADIATED CASE                    DYN00510    ,36
      AU=-0.45E-5                                               DYN00520
      AC=+5.64E-5                                               DYN00530
C                                                               DYN00540
C                                                               DYN00550    ,37
C     DELAY LINES
```

```
TAU1=12.25                                                   DYN00560    ,38
ST1=2.                                                        DYN00570    ,39
TAU2=13.                                                      DYN00580    ,40
ST2=2.                                                        DYN00590    ,41
TOUTEC=266.00                                                 DYN00600    ,42
TIN=TOUTEC                                                    DYN00610    ,43
TOUT=2.*X(3)-TIN                                              DYN00620    ,44
TOL=TOUT                                                      DYN00630
                                                             DYN00640
GEOMETRIC PARAMETERS                                         DYN00650
*********************************************************** DYN00660
          ALTZE,B,S=HEIGT OF ECONOMISER,BOILER AND SUPERHEATER DYN00670
          VLORE,B,S=VOLUME ,ORGANIC                          DYN00680
          VLTUE,B,S=VOLUME ,    TUBES                        DYN00690
          SPORE,B,S=SURFACE,ORGANIC SIDE                     DYN00700
          SPVAE,B,S=SURFACE,SECONDARY SIDE                   DYN00710
          V = VOLUME UPPER DOME                              DYN00720
          LR,LD = HEIGHT OF RISER,DOWNCOMER                  DYN00730
          VLDO = VOLUME DOWNCOMER                            DYN00740
*********************************************************** DYN00750    ,45
ALTZE  =  2.725                                              DYN00760    ,46
ALTZB  =  7.22                                               DYN00770    ,47
ALTZS  =  2.25                                               DYN00780    ,48
VLORE  =  1.34                                               DYN00790    ,49
VLORB  =  4.3                                                DYN00800    ,50
VLORS  =  1.72                                               DYN00810    ,51
VLTUE  =  0.03                                               DYN00820    ,52
VLTUB  =  4.44                                               DYN00830    ,53
VLTUS  =  0.15                                               DYN00840    ,54
VLVAE  =  0.03                                               DYN00850    ,55
VLVAB  =  8.23                                               DYN00860    ,56
VLVAS  =  0.3                                                DYN00870    ,57
SPORE  =  419.                                               DYN00880    ,58
SPORB  =  1881.                                              DYN00890    ,59
SPORS  =  636.                                               DYN00900    ,60
SPVAE  =  295.                                               DYN00910    ,61
SPVAB  =  1519.                                              DYN00920    ,62
SPVAS  =  519.                                               DYN00930    ,63
V= 6.                                                        DYN00940    ,64
LR=7.22                                                      DYN00950    ,65
LD=7.22                                                      DYN00960    ,66
VLDO= 4.                                                     DYN00970
                                                             DYN00980
GEOMETRIC  DEFINITIONS                                       DYN00990
                                                             DYN01000    ,67
ALOE = VLORE / ALTZE                                         DYN01010    ,68
ALOB = VLORB / ALTZB                                         DYN01020    ,69
ALOS = VLORS / ALTZS                                         DYN01030    ,70
APE = VLTUE / ALTZE                                          DYN01040    ,71
APB = VLTUB / ALTZB                                          DYN01050    ,72
APS = VLTUS / ALTZS                                          DYN01060    ,73
ALVE = VLVAE / ALTZE                                         DYN01070    ,74
ALVB = VLVAB / ALTZB                                         DYN01080    ,75
ALVS = VLVAS / ALTZS                                         DYN01090    ,76
LECO = ALTZE / 2.                                            DYN01100    ,77
LEVA = ALTZB / .3                                            DYN01110    ,78
```

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```
      LSUR = ALTZS  / 3.                          DYN01120      ,79
      PLOE = SPORE /ALTZE                         DYN01130      ,80
      PLOB = SPORB /ALTZB                         DYN01140      ,81
      PLOS = SPORS /ALTZS                         DYN01150      ,82
      PLVE = SPVAE /ALTZE                         DYN01160      ,83
      PLVB = SPVAB /ALTZB                         DYN01170      ,84
      PLVS = SPVAS /ALTZS                         DYN01180      ,85
      AD=VLDO/LR                                  DYN01190      ,86
      AR=VLVAS/LR                                 DYN01200
C                                                 DYN01210
C                                                 DYN01220
C     THERMAL AND HYDRAULIC PARAMETERS            DYN01230      ,87
                                                  DYN01240      ,88
      HLOE= 0.696                                 DYN01250      ,89
      HLOB= 0.601                                 DYN01260      ,90
      HLOS= 0.460                                 DYN01270      ,91
      HLVE= 5.461                                 DYN01280      ,92
      HLVB= 3.561                                 DYN01290      ,93
      HLVS= 0.593                                 DYN01300      ,94
      ROLOE=898.                                  DYN01310      ,95
      ROLOB=872.                                  DYN01320      ,96
      ROLOS=823.                                  DYN01330      ,97
      ROPE=7860.                                  DYN01340      ,98
      ROPB=7860.                                  DYN01350      ,99
      ROPS=7860.                                  DYN01360      ,100
      CLOE=.544526                                DYN01370      ,101
      CLOB=.573203                                DYN01380      ,102
      CLOS=.600907                                DYN01390      ,103
      CPE=0.12                                    DYN01400      ,104
      CPB=0.12                                    DYN01410
      CPS=0.12                                    DYN01420
C                                                 DYN01430
C                                                 DYN01440      ,105
C     ORGANIC FLOW                                DYN01450      ,106
                                                  DYN01460
      WOL =722.8                                  DYN01470
      WOLVAR=1.0                                  DYN01480
C                                                 DYN01490
C                                                 DYN01500
      INTERMEDIATE VALUES                         DYN01510      ,107
C                                                 DYN01520      ,108
C      ORGANIC SIDE                               DYN01530      ,109
      CS1=ALOS*RCLOS*CLOS                         DYN01540      ,110
      CS2=CLOS/LSUR*WOL                           DYN01550      ,111
      CS3=FLOS*PLOS                               DYN01560      ,112
      CB1=ALOB*RCLOB*CLOB                         DYN01570      ,113
      CB2=CLOB/LEVA*WOL                           DYN01580      ,114
      CB3=HLOB*PLOB                               DYN01590      ,115
      CE1=ALOE*RCLOE*CLOE                         DYN01600
      CE2=CLOE/LECO*WOL                           DYN01610      ,116
      CE3=HLOE*PLOE                               DYN01620      ,117
C      WALL                                       DYN01630      ,118
      DS1=APS*ROPS*CPS                            DYN01640      ,119
      DS2=FLOS*PLOS                               DYN01650      ,120
      DS3=HLVS*PLVS                               DYN01660      ,121
      DB1=APB*ROPB*CPB                            DYN01670      ,122
      DB2=FLOB*PLOB
      DB3=FLVB*PLVB
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      DE1=APE*ROPE*CPE                                      DYN01680    ,123
      DE2=FLOE*PLOE                                         DYN01690    ,124
      DE3=FLVE*PLVE                                         DYN01700
C                                                           DYN01710
C     TOTAL THERMAL COEFFICIENTS                            DYN01720
C                                                           DYN01730
C       SUPERHEATER                                         DYN01740    ,125
      DO 100 J=1,3                                          DYN01750    ,126
      C2(J)=CS2/CS1                                         DYN01760    ,127
      C3(J)=CS3/CS1                                         DYN01770    ,128
      D1(J)=DS2/DS1                                         DYN01780    ,129
      D2(J)=(-DS2-DS3)/DS1                                  DYN01790    ,130
      D3(J)=DS3/DS1                                         DYN01800    ,131
  100 CONTINUE                                              DYN01810
C       BOILER                                              DYN01820    ,132   ,133
      DO 110 J=4,6                                          DYN01830    ,134
      C2(J)=CB2/CB1                                         DYN01840    ,135
      C3(J)=CB3/CB1                                         DYN01850    ,136
      D1(J)=DB2/DB1                                         DYN01860    ,137
      D2(J)=(-DB2-DB3)/DB1                                  DYN01870    ,138
      D3(J)=DB3/DB1                                         DYN01880    ,139
  110 CONTINUE                                              DYN01890
C       ECONOMISER                                          DYN01900    ,140   ,141
      DO 120 J=7,8                                          DYN01910    ,142
      C2(J)=+CE2/CE1                                        DYN01920    ,143
      C3(J)=CE3/CE1                                         DYN01930    ,144
      D1(J)=DE2/DE1                                         DYN01940    ,145
      D2(J)=(-DE2-DE3)/DE1                                  DYN01950    ,146
      D3(J)=DE3/DE1                                         DYN01960    ,147
  120 CONTINUE                                              DYN01970
C                                                           DYN01980
C                                                           DYN01990
C                                                           DYN02000
C                                                           DYN02010
C                                                           DYN02020
C     ******************** EQUATIONS ********************************* DYN02030
C                                                           DYN02040    ,148   ,149
  200 CONTINUE                                              DYN02050    ,150
      CALL VARIAT                                           DYN02060    ,151
      CALL SECCND(T,X,DX,PAR)                               DYN02070
C                                                           DYN02080
C     DELAY LINES                                           DYN02090
C                                                           DYN02100    ,152
      TIN=DELAY( 9,TAU2/WOLVAR,ST2,X(12))                   DYN02110    ,153
      TOUT=2.*X(3)-TIN                                      DYN02120    ,154
      TOL=DELAY(10,TAU1/WOLVAR,ST1,TOUT)                    DYN02130
C                                                           DYN02140
C     REACTOR KINETICS                                      DYN02150
C                                                           DYN02160    ,155
      CT=CTO+AC*GC*(X(3)-DTCO)+AU*GC*(X(3)-DTCO)+AU*GU*(X(1)-DTUO-X(3)+DDYN02170
     1TCO) +X(11)                                           DYN02180    ,156
      TRET=SIGMAP(VLA,X,4,9)                                DYN02190    ,157
      PNTR=-(TRET*VL) / (CT*BB-1.)                          DYN02200
C                                                           DYN02210
C     REGULATOR EQUATIONS                                   DYN02220    ,158
      CALL REGUL(T,X,DX,PAR)                                DYN02230
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C                                                            DYN02240
C        REACTOR THERMAL EQUATIONS                           DYN02250
C                                                            DYN02260    ,159
      DX(1)=A11*PNTR-A12*(X(1)-X(2))                         DYN02270    ,160
      DX(2)=A21*(X(1)-X(2))-A22*(X(2)-X(3))*WOLVAR           DYN02280    ,161
      DX(3)=A31*WOLVAR*(X(2)-X(3))-A32*(X(3)-TIN )           DYN02290
C                                                            DYN02300
C        DELAYED NEUTRONS                                    DYN02310
C                                                            DYN02320
      B(I)=BETA(I)/VL                                        DYN02330    ,162
      DO 220 I=4,9                                           DYN02340    ,163
  220 DX(I)=-X(I)*VLA(I)+PNTR*CT*B(I)                        DYN02350
C                                                            DYN02360
C                                                            DYN02370
C        HEAT EXCHANGER ORGANIC SIDE                         DYN02380
C                                                            DYN02390    ,164    ,165
      DX(12)=(-C3(1)-C2(1)*WOLVAR)*X(12)+C2(1)*TOL*WOLVAR+C3(1)*X(20)  DYN02400    ,166
      DO 230 I=13,19                                         DYN02410    ,167
      J=I-11                                                 DYN02420    ,168
      K=I+8                                                  DYN02430    ,169
  230 DX(I)=(-C3(J)-C2(J)*WOLVAR)*X(I)+C2(J)*X(I-1)*WOLVAR+C3(J)*X(K)  DYN02440
C                                                            DYN02450
C        WALL EQUATION                                       DYN02460
C                                                            DYN02470    ,170    ,171
      DO 240 I=20,27                                         DYN02480    ,172
      K=I-8                                                  DYN02490    ,173
      J=I-19                                                 DYN02500    ,174
  240 DX(I)=D1(J)*X(K)+D2(J)*X(I)+D3(J)*TSEC(J)              DYN02510    ,175    ,176
      RETURN                                                 DYN02520    ,177
      END                                                    DYN02530    ,178
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      SUBROUTINE REGUL(T,X,DX,PAR)                          DYN02550
C     REGULATOR                                             DYN02560
      DIMENSION X(100),DX(100),PAR(100)                     DYN02570
      COMMON/VARVAR/TF,CTO,POWVAR,WOLVAR,PNVAR,DERROR,TAVZ  DYN02580
      COMMON/SECVAR/TSEC(8),PNTR,ERROR,REG,TAV,CT,TOUT,     DYN02590
     1TOL,TIN,TSAT,POWER                                    DYN02600
      LOGICAL SWITCH                                        DYN02610
      IF(SWITCH(3)) GO TO 100                               DYN02620
C                                                           DYN02630
C                                                           DYN02640
C     REGULATOR PARAMETERS                                  DYN02650   ,1      ,2    ,3
      DERROR=0.0                                            DYN02660   ,4
      PNVAR=1.0                                             DYN02670   ,5
      AINERT=2.                                             DYN02680   ,6
      PNOM=4.0086E6                                         DYN02690   ,7
      PNTR=PNOM                                             DYN02700   ,8
      TAVZ=318.00                                           DYN02710   ,9
      PRESN=62.                                             DYN02711   ,10
      R1=1./PNOM                                            DYN02720   ,11
      R2=1./TAVZ                                            DYN02730   ,12
      R3=0.5/PRESN                                          DYN02731   ,13
      R4=1.E-2                                              DYN02740   ,14
      R5=2.5E-2                                             DYN02750
C     MECHANICAL LIMITS OF CONTROL RODS                     DYN02760   ,15
      UPLI=200.E-5                                          DYN02770   ,16
      DOWNLI=-200.E-5                                       DYN02780   ,17
      SPDLI=15.E-5                                          DYN02790   ,18
  100 CONTINUE                                              DYN02800
C     EQUATIONS                                             DYN02810
C                                                           DYN02820   ,19
      TAV=0.5*(TOL+X(19))                                   DYN02830   ,20
      ERROR=-R1*(PNTR-PNOM*PNVAR)-R2*(TAV-TAVZ)-R3*(X(28)-PRESN)+DERROR DYN02840 ,21
      DX(10)=R4*ERROR                                       DYN02850   ,22
      REG=X(10)+R5*ERROR                                    DYN02860   ,23
      SPEED=AINERT*(REG-X(11))                              DYN02870   ,24
      DSPEED=ABS(SPEED)-SPDLI                               DYN02880   ,25
      COMP10=COMPAR(DSPEED,10)                              DYN02890   ,26
      IF(SPEED)110,120,120                                  DYN02900   ,27
  110 SPEED=SPEED*(1.-COMP10)-SPDLI*COMP10                  DYN02910   ,28
      GO TO 130                                             DYN02920   ,29
  120 SPEED=SPEED*(1.-COMP10)+SPDLI*COMP10                  DYN02930   ,30
  130 DX(11)=SPEED                                          DYN02940   ,31
      COMP9 =COMPAR(X(11)-UPLI,9)                           DYN02950   ,32
      COMP8 =COMPAR(DOWNLI-X(11),8)                         DYN02960   ,33
      X(11)=X(11)*(1.-COMP9 -COMP8 )+UPLI*COMP9 +DOWNLI*COMP8  DYN02970 ,34
      RETURN                                                DYN02980   ,35
      END                                                   DYN02990   ,36
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      SUBROUTINE SECOND(T,X,DX,PAR)                              DYN03010
                      EQUATIONS SECONDARY SIDE                   DYN03020
C     ***********************************************************DYN03030
C     COMMON/VARVAR/TF,CTO,POWVAR,WOLVAR,PNVAR,DERROR,TAVZ        DYN03040
      COMMON/SUPHT/I,H(4),WREQ,G2                                 DYN03050
      COMMON/SECVAR/TSEC(3),PNTR,ERROR,REG,TAV,CT,TOUT,          DYN03060
     1TOL,TIN,TSAT,POWER                                         DYN03070
      COMMON/SECPAR/PLVE,PLVB,PLVS,HLVE,HLVB,HLVS,LECO,ALVE,ALVB,ALVS,ADDYN03080
     1,AR,LSUR,LEVA,V,LD,LR,VLDO                                 DYN03090
      COMMON/RECRD/WP,WC,VS,VSPEC,ISAT,ILIQ,ROSAT                DYN03100
      DIMENSION X(100),DX(100),PAR(100)                          DYN03110
      REAL I,ISAT,ILIQ,LECO,LR,LD,K2,LSUR,HLVS                   DYN03120
      LOGICAL SWITCH                                             DYN03130
      IF(SWITCH(2)) GO TO 300                                    DYN03140
C                                                                DYN03150
C     ***************PARAMETERS*********************************DYN03160
C                                                                DYN03170
C                                                                DYN03180
C     MISCELLANEOUS PARAMETERS                                   DYN03190
C                                                                DYN03200      ,1       ,2      ,3
      WCK=0.1                                                    DYN03210      ,4
      WC=0.0                                                     DYN03220      ,5
      WREQO=79.22                                                DYN03230      ,6
      AVS=-0.25874                                               DYN03240      ,7
      BVS=-0.4209E-3                                             DYN03250      ,8
      POWER=173.505E06                                           DYN03260      ,9
      POWVAR=1.0                                                 DYN03270      ,10
      RR=15.                                                     DYN03280      ,11
      PZERO=X(30)                                                DYN03290      ,12
      VSO=AVS+BVS*PZERO                                          DYN03300      ,13
      K2=((RR*WREQO)**2)*(VLIQ+VSO/(RR+1.))/(VSO/(RR+1.))        DYN03310      ,14
      ROLVE=750.                                                 DYN03320      ,15
      CLVE=1.1                                                   DYN03330      ,16
      TF=190.                                                    DYN03340      ,17
      CLVE=1.1                                                   DYN03350      ,18
      BIPRO=103.                                                 DYN03360      ,19
      AI=461.84                                                  DYN03370      ,20
      BIL=1.194                                                  DYN03371      ,21
      BLAT=-1.51514                                              DYN03372      ,22
      VLIQ=0.0013930                                             DYN03380      ,23
      ROD=1./0.00136                                             DYN03390      ,24
      E1=(PLVE*HLVE)/(ALVE*ROLVE*CLVE)                           DYN03400      ,25
      E2=CLVE/(ALVE*ROLVE*CLVE*LECO)                             DYN03410      ,26
      FF1=1./(AR*LR)                                             DYN03420      ,27
      F1=(PLVB*LR*HLVB)/(3.*AR*LR)                               DYN03430      ,28
      F2=1./(AD*LD*ROD)                                          DYN03440      ,29
      F3=1./(V*BIPRO)                                            DYN03450      ,30
      F4=1./V                                                    DYN03460
C                                                                DYN03470
C     PARAMETERS SUPERHEATER                                     DYN03480
C                                                                DYN03490      ,31
      G2=PLVS*LSUR*HLVS                                          DYN03500
C     TENTATIVE INITIAL ENTHALPIES                              DYN03510      ,32
      H(1)=730.                                                  DYN03520      ,33
      H(2)=713.                                                  DYN03530      ,34
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          H(3)=692.                                               DYN03540
C                                                                 DYN03550
C         READ OUT SUBROUTINE                                     DYN03560      ,35
          CALL RECORD(T,X,DX)                                     DYN03570
C                                                                 DYN03580
C         ****************************EQUATIONS**************************************DYN03590
C                                                                 DYN03600      ,36
      300 CONTINUE                                                DYN03610
C                                                                 DYN03620
C         SECONDARY FLOW EQUATIONS                                DYN03630
C                                                                 DYN03640      ,37
          DH=H(1) -CLVE*TF                                        DYN03650      ,38
          WREQ=POWER*POWVAR/(4187.*DH)                            DYN03660
C                                                                 DYN03670
C                                                                 DYN03680
C         BOILER AND UPPER DOME                                   DYN03690
C                                                                 DYN03700      ,39
          TSAT=TLSAT(X(28))                                       DYN03710      ,40
          VS=VSVAP(X(28),TSAT)                                    DYN03720      ,41
          ISAT=EVSAT(TSAT)                                        DYN03730      ,42
          ILIQ=ELSAT(TSAT)                                        DYN03740      ,43
          VSPEC=VLIQ+X(30)*VS                                     DYN03750      ,44
          WR=SQRT(K2*(X(30)*VS/VSPEC))                            DYN03760      ,45
          I=AI+BIPRO*(X(28)/X(29))                                DYN03770      ,46
          CLAT=ISAT-ILIQ                                          DYN03780      ,47
          ROSAT=1./VS                                             DYN03790
C                                                                 DYN03800
C         SECONDARY TEMPERATURES                                  DYN03810
C                                                                 DYN03820
C          BOILER                                                 DYN03830      ,48
          DO 310 IK=4,6                                           DYN03840      ,49
      310 TSEC(IK)=TSAT                                           DYN03850
C                                                                 DYN03860
C          ECONOMISER                                             DYN03870      ,50        ,51
          EE2=E2*WREQ                                             DYN03880      ,52
          EE1=1./(E1+EE2)                                         DYN03890      ,53
          TSEC(8)=(E1*X(27)+EE2*TF)*EE1                           DYN03900      ,54
          TSEC7  =(E1*X(26)+EE2*TSEC(3))*EE1                      DYN03910      ,55
          COMP2=COMPAR(TSEC7-TSAT,2)                              DYN03920      ,56
          TSEC(7)=TSEC7*(1.-COMP2)+TSAT*COMP2                     DYN03930
C                                                                 DYN03940
C         CONDENSATION RATE                                       DYN03950      ,57
          WCC=X(29)-ROSAT                                         DYN03960      ,58
          WC=WCK*WCC*(COMPAR(WCC,1))                              DYN03970
C                                                                 DYN03980      ,59
          SOMMA=F1*(X(23)+X(24)+X(25)-3.*TSAT)+(CLVE*WREQ*TSEC(7)+WR*X(31)- DYN03990
         1(WR+WREQ)*(ILIQ+X(30)*CLAT))*FF1                        DYN04000
C                                                                 DYN04010      ,60
          PDER=(-AI*(X(30)*(WREQ+WR)-WREQ-WC)+ISAT*(X(30)*(WREQ+WR))-WREQ*I-DYN04020
         1ILIQ*WC)*F3                                             DYN04030
C                                                                 DYN04040
C          X(28)=P   STEAM PRESSURE                               DYN04050      ,61
          DX(28)=PDER                                             DYN04060
C                                                                 DYN04070
C          X(29)=RO  BOILING MIX.DENSITY                          DYN04080      ,62
          DX(29)=F4*((X(30)*(WREQ+WR))-WREQ-WC)                   DYN04090
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C                                                              DYN04100
C     X(30)=XX STEAM QUALITY                                   DYN04110    ,63
      DX(30)=(VSPEC/CLAT)*SOMMA-((BIL+BLAT*X(30))*PDER)/CLAT   DYN04120
C                                                              DYN04130
C     X(31)=IDOW ENTHAL.DOWNCOMMER                             DYN04140    ,64
      DX(31)=F2*WR*(ILIQ-X(31))                                DYN04150
C                                                              DYN04160
C     ENTHALPY EQUATIONS SUPERHEATER                           DYN04170
C                                                              DYN04180    ,65
      CALL SUPHTR(X)                                           DYN04190    ,66
      RETURN                                                   DYN04200    ,67
      END                                                      DYN04210    ,68
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      SUBROUTINE SUPHTR(X)                                 DYN04230
C                                                          DYN04240
C     SUPERHEATER SECONDARY SIDE                           DYN04250
C     H(J) ENTHALPY OF SUPERHEATED STEAM IN CELL J         DYN04260
C                                                          DYN04270
      DIMENSION GH(3),ABE(3),E(3),EOLD(3),STPP(3),X(1  )   DYN04280
      REAL I                                               DYN04290
      LOGICAL GH                                           DYN04300
      COMMON/SECVAR/TSEC(3),PNTR,ERROR,REG,TAV,CT,TOUT,    DYN04310
     1TOL,TIN,TSAT,POWER                                   DYN04320
      COMMON/SUPHT/I,H(4),WREQ,G2                          DYN04330
      DIMENSION   VP(7)                                    DYN04340
      DATA (VP(L),L=1,7)/40.,60.,80.,100.,130.,160.,200./  DYN04350
C     NZ NUMBER OF ZONES FINITE DIFFERENCES                DYN04360
C     TOLERANCE OF ONE PER CENT ON H(J)                    DYN04370
      DATA TOLER,NZ,NZP1/16.,3,4/                          DYN04380
C                                                          DYN04390
      DO 5 J=1,3                                           DYN04400    ,1
      GH(J)=.FALSE.                                        DYN04410    ,2
    5 STPP(J)=16.                                          DYN04420    ,3      ,4
      H(4)=I                                               DYN04430
C                                                          DYN04440
C     MAIN ITERATION LOOP                                  DYN04450    ,5
      DO 100 JJ=1,NZ                                       DYN04460    ,6
      J=NZP1-JJ                                            DYN04470    ,7
      JK=J+19                                              DYN04480    ,8
   10 CONTINUE                                             DYN04490    ,9
      EOLD(J)=E(J)                                         DYN04500
C                                                          DYN04510
C     X(28) STEAM PRESSURE                                 DYN04520    ,10
      TSEC(J)= FTWOV(1,7,H(J),X(28),VP)                    DYN04530
C                                                          DYN04540
C     ENTHALPY EQUILIBRIUM EQUATION                        DYN04550    ,11
      E(J)=       (H(J+1)-H(J))+G2*(X(JK)-TSEC(J))/WREQ    DYN04560
C                                                          DYN04570    ,12
      ABE(J)=ABS(E(J))                                     DYN04580    ,13
      IF(ABE(J).LT.TOLER) GO TO 100                        DYN04590
C                                                          DYN04600    ,14    ,15    ,16
      IF(E(J).GT.0.) GO TO 20                              DYN04610    ,17    ,18    ,19
      IF(EOLD(J).GT.0.) STPP(J)=STPP(J)*0.5                DYN04620    ,20    ,21    ,22
      H(J)=H(J)-STPP(J)                                    DYN04630    ,23
      GO TO 10                                             DYN04640    ,24
   20 IF(EOLD(J).LE.0.) STPP(J)=STPP(J)*0.5                DYN04650    ,25    ,26    ,27
      H(J)=H(J)+STPP(J)                                    DYN04660    ,28
      GO TO 10                                             DYN04670    ,29
  100 CONTINUE                                             DYN04680    ,30    ,31
      RETURN                                               DYN04690    ,32
      END                                                  DYN04700    ,33
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      SUBROUTINE VARIAT                                            DYN04720
      COMMON/VARVAR/TF,CTO,POWVAR,WOLVAR,PNVAR,DERROR,TAVZ         DYN04730
                                                                  DYNC4740
      INSERT HERE VARIATION LAWS FOR                              DYN04750
      TF FEEDWATER TEMPERATURE IN DEGREES                         DYN04760
      CTO REACTIVITY=1. AT EQUILIBRIUM                            DYN04770
      POWVAR SECONDARY POWER VARIATION=1. AT NOMINAL POWER        DYN04780
      WOLVAR ORGANIC FLOW VARIATION=1. AT N.P.                    DYN04790
      PJVAR REACTOR POWER=1. AT N.P.                              DYN04800
      DERROR DISTURBANCE ON REGULATOR=0. AT EQUILIBRIUM           DYN04810
      TAVZ REFERENCE ORGANIC MEDIUM TEMPERATURE IN DEGREES        DYN04820
                                                                  DYN04830
      RETURN                                                      DYN04840      ,1
      END                                                         DYN04850      ,2
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      SUBROUTINE RECORD(T,X,DX)                                   DYN04870
      DIMENSION X(150),DX(150)                                    DYN04880
      COMMON/VARVAR/TF,CTO,POWVAR,WOLVAR,PNVAR,DERROR,TAVZ        DYN04890
      COMMON/SUPHT/I,H(4),WREQ,C2                                 DYN04900
      COMMON/SECVAR/TSEC(8),PJTP,ERROR,REG,TAV,CT,TOUT,           DYN04910
     1TOL,TIN,TSAT,POWER                                          DYN04920
      COMMON/SECPAR/PLVE,PLVB,PLVS,HLVE,HLVB,HLVS,LECO,ALVE,ALVB,ALVS,ADDYN04930
     1,AR,LSUR,LEVA,V,LD,LP,VLDO                                  DYN04940
      COMMON/RECRD/WR,WC,VS,VSPEC,ISAT,ILIQ,ROSAT                 DYN04950
                                                                  DYN04960
      READ OUT STATEMENTS OF SAHYB ARE GROUPED HERE               DYN04970
                                                                  DYN04980
      CALL WRITE(4HPNTR,PJTR,5HERROR,ERROR,3HREG,REG,3HTAV,TAV,2HCT,CT, DYN04990
     14HTOUT,TCUT,5HTOL,TOL,3HTIN,TIN,4HTSAT,TSAT,4HWREQ,WREQ,2HWR,WR, DYN05000
     22HWC,WC,5HTSEC1,TSEC(1),5HTSEC2,TSEC(2),5HTSEC3,TSEC(3),4HH(1), DYN05010
     3H(1),4HH(2),H(2),4HH(3),H(3),2HVS,VS,5HVSPEC,VSPEC,4HISAT,ISAT, DYN05020
     44HILIQ,ILIQ,5HROSAT,ROSAT,5HTSEC7,TSEC(7),5HTSEC8,TSEC(8)) DYN05030     ,1
      CALL OUTPUT(1,2,3,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24, DYN05040
     125,26,27,28,29,30,31)                                      DYN05050
                                                                  DYN05060      ,2
      RETURN                                                      DYN05070      ,3
      END                                                         DYN05080      ,4
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```
      FUNCTION VSVAP(P,T)                                      DYN05100
      DATA(R,A,B,C,D,E,F,CP,DP,EP)/1.34992E-02,4.7321E-03,2.239453-03,4.DYN05110
1355075-02,6.75156E-04,3.173605E-05,8.06835+E-05,1.55118,1.26591,1.32DYN05120
2735/                                                         DYN05130
      SIGMA=P*4.4516E-03                                       DYN05140      ,1
      TAU=(T+273.15)*1.54495-03                                DYN05150      ,2
      TAU1=TAU**2.32                                           DYN05160      ,3
      SIGMA1=SIGMA*SIGMA/(TAU**14)                             DYN05170      ,4
      VSVAP=R*TAU/SIGMA-A/TAU1+E*(CP-SIGMA)*TAU1-SIGMA1*(B-(DP*SIGMA-TAUDYN05180
1**3)*D*SIGMA+C/(TAU**18))-(1.-EP*SIGMA)*F*TAU                DYN05190      ,5
      RETURN                                                   DYN05200      ,6
      END                                                      DYN05210      ,7
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      FUNCTION TLSAT(P)                                        DYN05230
      DOUBLE PRECISION A                                       DYN05240
      DIMENSION A(15)                                          DYN05250
      DATA (A(I),I=1,10)/-4.9024542910-2,-4.268563510-7,1.5343731340-6,2DYN05260
1.2071711770-5,1.974175510D-4,-3.7393548425D-4,1.32337729D-3,2.12968DYN05270
22011D-2,2.1377004650-1,2.575357647,2.705424215D+1,9.909271199D+1/    DYN05280
      PP=ALOG(P)                                               DYN05290      ,1
      S=A(1)*PP+A(2)                                           DYN05300      ,2
      DO 10 I=3,12                                             DYN05310      ,3
      S=S*PP+A(I)                                              DYN05320      ,4
10    CONTINUE                                                 DYN05330      ,5      ,6
      TLSAT=S                                                  DYN05340      ,7
      RETURN                                                   DYN05350      ,8
      END                                                      DYN05360      ,9
```

```
      FUNCTION EVSAT(T)                                              DYN05380
      DOUBLE PRECISION A                                             DYN05390
      DIMENSION A(10)                                                DYN05400
      DATA (A(I),I=1,7)/2.45672819830-1,-2.252469249,6.681529737,-1.02838DYN05410
     1362D+1,3.76167557D+0,4.3351603990+1,5.97257040060+2/           DYN05420
      TT=T*0.01                                                      DYN05430        ,1
      S=A(1)*TT+A(2)                                                 DYN05440        ,2
      DO 10 I=3,7                                                    DYN05450        ,3
      S=S*TT+A(I)                                                    DYN05460        ,4
   10 CONTINUE                                                       DYN05470        ,5        ,6
      EVSAT=S                                                        DYN05480        ,7
      RETURN                                                         DYN05490        ,8
      END                                                            DYN05530        ,9
```

```
      FUNCTION ELSAT(T)                                              DYN05520
      DOUBLE PRECISION A                                             DYN05530
      DIMENSION A(15)                                                DYN05540
      DATA (A(I),I=1,10)/6.6072979780D-2,-0.465226031D-1,5.700027955,-1.8DYN05550
     16838884D+1,3.62372223D+1,-4.10863442D+1,2.885444361D+1,-1.06332556DYN05560
     21D+1,1.01485241D+2,-1.135706422D-2/                          DYN05570
      TT=T*0.01                                                      DYN05580        ,1
      S=A(1)*TT+A(2)                                                 DYN05590        ,2
      DO 10 I=3,1:                                                   DYN05600        ,3
      S=S*TT+A(I)                                                    DYN05610        ,4
   10 CONTINUE                                                       DYN05620        ,5        ,6
      ELSAT=S                                                        DYN05630        ,7
      RETURN                                                         DYN05640        ,8
      END                                                            DYN05650        ,9
```

APPENDIX III

1) Example of input

The input should be done for each case following section 10.

This example should be considered as indicative; the initial conditions represent an equilibrium state which has been verified with the analogue computation.

The tables have been extracted from standard steam tables* and may be considered as a permanent part of DYNOR, unless the range of pressures or temperatures need to be extended.

2) Example of output

Equilibrium at 100% of nominal power and after 418 seconds of problem time; these figures are indicative, since they may be altered modifying the references' values to the regulator.

---

*   Ernst SCHMIDT VDI:

VDI Wasserdampftafeln, Ausgabe A (kcal-at),

R. Oldenbourg, Muenchen, 1963

See also appendix IV

DATA (Zones de 10 colonnes)

| PROBLEM | DATE | PAGE | 1 | OF | 2 |

IDENTIFICATION		STANDARD DYNOR	
NUMBER OF DIFFERENTIAL EQUATIONS			37
N. OF PAR			0
N. OF TABLES			7
FINAL TIME (SECONDS)		500.	
(INITIAL) INTEGRATION STEP		0.1	
OUTPUT STEP		5.	
INTEGRATION OPTION (ADAMS-MOULTON)			2
TU	TEMP.OF URANIUM	X1	682.661
TG	TEMP.OF CLADDING	X2	384.253
TC	TEMP.OF COOLANT	X3	324.572
C1	DEL.NEUTR.GROUP 1	X4	5.22557+05
C2	2	X5	3.43709+06
C3	3	X6	4.58242+07
C4	4	X7	6.64070+07
C5	5	X8	2.92937+08
C6	6	X9	9.82904+07
INTE	INTEGRATED ERROR	X10	-3.0158-04
ROCON	CONTROL REACTIVITY	X11	-3.0158-04
TORG 1	ORGANIC TEMPERATURE	X12	373.622
TORG 2		X13	368.697
TORG 3		X14	361.454
TORG 4		X15	322.776
TORG 5		X16	300.703
TORG 6		X17	288.106

DATA (Zones de 10 colonnes)

TORG 7	ORGANIC TEMPERATURE	X18	282.223
TORG 8	' '	X19	271.521
TWALL1	WALL TEMPERATURE	X20	355.805
TWALL2		X21	346.764
TWALL3		X22	329.193
TWALL4		X23	280.250
TWALL5		X24	276.434
TWALL6		X25	274.257
TWALL7		X26	266.341
TWALL8		X27	242.633
P	PRESSURE	X28	57.3496
RO	DENSITY	X29	28.9309
XX	STEAM QUALITY	X30	7.73244-02
IDOW	DOWN. ENTHALPY	X31	2.84596+02
DATA FOR N.S. INTEGR. MAX. ERROR			1. E-05
MIN. T. STEP			0.001
MAX. T. STEP			100.
VARIATION FACTOR			0.5
LIMIT FOR RELATIVE ERROR			100.
LOWER BOUND TO ERROR			50.
TABLE 1 (40 ATM.) N. OF POINTS			18
258.198 249.172 669.465 250.			670.204 260.
679.095 270. 687.132 280.			694.574 290.
etc .... (all the steam tables)			
END			

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TIME = 4.18595E 02   TIME STEP = 1.00C00E-C1

```
X(  1) = TU     =  6.82653E 02      DER(TU    ) =  4.19617E-05      PNTR   =  5.02568E 06
X(  2) = TG     =  3.84253E 02      DER(TG    ) =  2.67029E-05      ERROR  =  1.89897E-06
X(  3) = TC     =  3.24573E 02      DER(TC    ) = -3.43323E-05      REG    = -3.01616E-04
X(  4) = C1     =  5.22543E 05      DER(C1    ) = -2.18750E 00      TAV    =  3.24573E 02
X(  5) = C2     =  3.43699E 06      DER(C2    ) = -3.46875E 00      CT     =  1.00000E 00
X(  6) = C3     =  4.58228E 07      DER(C3    ) =  1.97500E 01      TOUT   =  3.77622E 02
X(  7) = C4     =  6.64049E 07      DER(C4    ) =  5.16875E 01      TOL    =  3.77622E 02
X(  8) = C5     =  2.92921E 08      DER(C5    ) =  4.52875E 02      TIN    =  2.71524E 02
X(  9) = C6     =  9.82621E 07      DER(C6    ) =  7.41859E 02      TSAT   =  2.71366E 02
X( 10) = INTE   = -3.61664E-04      DER(INTE  ) =  1.89897E-08      WREQ   =  8.77777E 01
X( 11) = ROCON  = -2.61659E-04      DER(ROCON ) =  8.64093E-08      WR     =  9.64025E 02
X( 12) = TORG 1 =  3.73622E 02      DER(TORG 1) =  2.86102E-06      WC     =  1.17571E 02
X( 13) = TORG 2 =  3.68698E 02      DER(TORG 2) = -1.90735E-06      TSEC1  =  3.38872E 02
X( 14) = TORG 3 =  3.61455E 02      DER(TORG 3) = -1.90735E-06      TSEC2  =  3.25917E 02
X( 15) = TORG 4 =  3.22778E 02      DER(TORG 4) = -4.00543E-05      TSEC3  =  2.98530E 02
X( 16) = TORG 5 =  3.00706E 02      DER(TORG 5) = -7.05719E-05      H(1)   =  7.???E 02
X( 17) = TORG 6 =  2.88109E 02      DER(TORG 6) = -7.82013E-05      H(2)   =  7.130?E 02
X( 18) = TORG 7 =  2.82226E 02      DER(TORG 7) = -7.34329E-05      H(3)   =  6.920?E 02
X( 19) = TORG 8 =  2.71523E 02      DER(TORG 8) = -5.53151E-05      VS     =  3.47042E-02
X( 20) = TWALL1 =  3.55807E 02      DER(TWALL1) = -3.81470E-05      VSPEC  =  4.765?E-03
X( 21) = TWALL2 =  3.46766E 02      DER(TWALL2) = -3.05176E-05      ISAT   =  6.65960E 02
X( 22) = TWALL3 =  3.29196E 02      DER(TWALL3) = -4.57764E-05      ILIQ   =  2.946?E 02
X( 23) = TWALL4 =  2.80253E 02      DER(TWALL4) = -7.24792E-05      ROSAT  =  2.88149E 01
X( 24) = TWALL5 =  2.76438E 02      DER(TWALL5) = -7.62939E-05      TSEC7  =  2.53463E 02
X( 25) = TWALL6 =  2.74260E 02      DER(TWALL6) = -7.24792E-05      TSEC8  =  2.374?6E 02
X( 26) = TWALL7 =  2.66743E 02      DER(TWALL7) = -0.
X( 27) = TWALL8 =  2.42635E 02      DER(TWALL8) = -6.10352E-05
X( 28) = P      =  5.73526E 01      DER(P     ) = -6.78758E-05
X( 29) = RO     =  2.89325E 01      DER(RO    ) = -3.51627E-05
X( 30) = XX     =  7.73249E-02      DER(XX    ) = -8.84594E-07
X( 31) = IDOW   =  2.84600E 02      DER(IDOW  ) = -1.06279E-04
```

APPENDIX IV

Superheater steam tables:

Temperature versus enthalpy, for different values of pressure.

(Note that the first point of each table is the enthalpy of saturated water).

TABLE 1   40 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   1   = 18 **

2.5819800E 02	2.4917200E 02
6.6946499E 02	2.4917200E 02
6.7020399E 02	2.5000000E 02
6.7909599E 02	2.6000000E 02
6.8713199E 02	2.7000000E 02
6.9457399E 02	2.8000000E 02
7.0158799E 02	2.9000000E 02
7.0828499E 02	3.0000000E 02
7.1474199E 02	3.1000000E 02
7.2101199E 02	3.2000000E 02
7.2713299E 02	3.3000000E 02
7.3313599E 02	3.4000000E 02
7.3904300E 02	3.5000000E 02
7.4487099E 02	3.6000000E 02
7.5063300E 02	3.7000000E 02
7.5633999E 02	3.8000000E 02
7.6200200E 02	3.9000000E 02
7.6762600F 02	4.0000000E 02

TABLE 2   60 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   2   = 15 **

2.8817400E 02	2.7428100E 02
6.6525199E 02	2.7428100E 02
6.7145599E 02	2.8000000E 02
6.8141499E 02	2.9000000E 02
6.9043199E 02	3.0000000E 02
6.9875000F 02	3.1000000E 02
7.0653799E 02	3.2000000E 02
7.1391700E 02	3.3000000E 02
7.2097600E 02	3.4000000E 02
7.2778000E 02	3.5000000E 02
7.3437999E 02	3.6000000F 02
7.4081299F 02	3.7000000E 02
7.4711099E 02	3.8000000E 02
7.5329500E 02	3.9000000E 02
7.5938599F 02	4.0000000E 02

TABLE 3   80 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   3   = 13 **

3.1264499E 02	2.9361900E 02
6.5899299E 02	2.9361900E 02
6.6702999E 02	3.0000000E 02
6.7842395E 02	3.1000000E 02
6.8665899E 02	3.2000000E 02
6.9800899E 02	3.3000000E 02
7.0667799E 02	3.4000000E 02
7.1481100E 02	3.5000000E 02
7.2252199E 02	3.6000000E 02
7.2989500E 02	3.7000000E 02
7.3699395E 02	3.8000000E 02
7.4386999E 02	3.9000000E 02
7.5056199E 02	4.0000000E 02

TABLE 4   100 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   4   = 12 **

3.3404900E 02	3.0953999E 02
6.5174499E 02	3.0953999E 02
6.5239899E 02	3.1000000E 02
6.6629599E 02	3.2000000E 02
6.7855499E 02	3.3000000E 02
6.8956000E 02	3.4000000E 02
6.9959099E 02	3.5000000E 02
7.0685799E 02	3.6000000E 02
7.1752099E 02	3.7000000E 02
7.2570099E 02	3.8000000E 02
7.3349000E 02	3.9000000E 02
7.4096299E 02	4.0000000E 02

TABLE 5   130 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   5   = 10 **

3.3630950E 00	3.2930700E 02
6.4013199E 02	3.2930700E 02
6.4100899E 02	3.3000000E 02
6.5722400E 02	3.4000000E 02
6.7143499E 02	3.5000000E 02
6.8408599E 02	3.6000000E 02
6.9551299E 02	3.7000000E 02
7.0597099E 02	3.8000000E 02
7.1565400E 02	3.9000000E 02
7.2471495E 02	4.0000000E 02

TABLE 6   160 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   6   =   8 **

3.9084200E 02	3.4572900E 02
6.2845395E 02	3.4572900E 02
6.3558800E 02	3.5000000E 02
6.5312600E 02	3.6000000E 02
6.6850600E 02	3.7000000E 02
6.8218600E 02	3.8000000E 02
6.9451900E 02	3.9000000E 02
7.0577395E 02	4.0000000E 02

TABLE 7 200 ATM   N. OF POINTS   ** NUMBER OF POINTS IN TABLE   7   =   6 **

4.2922195E 02	3.6407000E 02
6.1366255E 02	3.6407000E 02
6.2340500E 02	3.7000000E 02
6.4313295E 02	3.8000000E 02
6.6034499E 02	3.9000000E 02
6.7560995E 02	4.0000000E 02
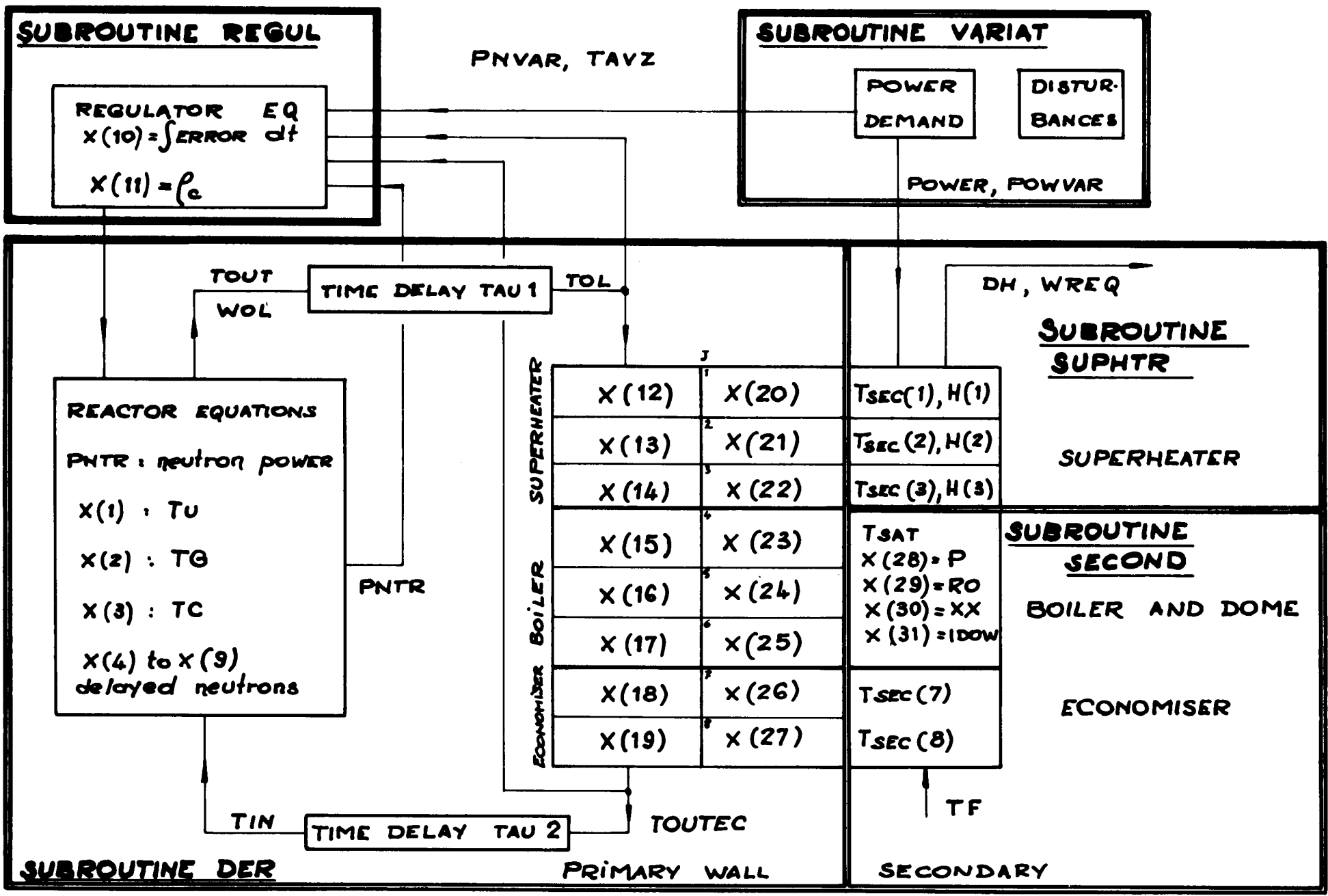
Fig. 1

R E F E R E N C E S

(1)   Control of Nuclear Reactors and Power Plants
       M.A. Schultz
       McGraw-Hill Book Company, Inc.

(2)   SAHYB-2: A Program for the Solution of Differential
       Equations using an Analogue-Oriented Language
       H. d'Hoop, R. Monterosso
       EUR 3622e
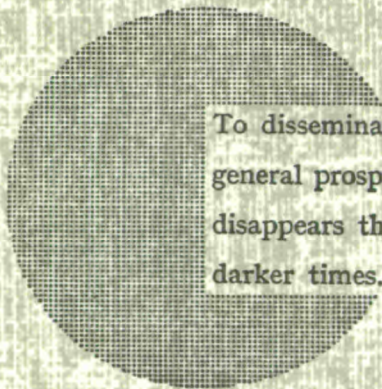
To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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