AE-341
UDC 621.039.526:
621.311.2.001.57

AE-341

Nonlinear Dynamic Model of Power Plants with Single-Phase Coolant Reactors

H. Vollmer

AKTIEBOLAGET ATOMENERGI
STOCKHOLM, SWEDEN 1968

NONLINEAR DYNAMIC MODEL OF POWER PLANTS WITH SINGLE-PHASE COOLANT REACTORS

by

Heinz Vollmer

ABSTRACT

The traditional way of developing dynamic models for a specific nuclear power plant and for specific purpose seems rather uneconomical, as much of the information often cannot be utilized if the plant design or the required accuracy of the calculation is desired to be changed. It is therefore suggested that the model development may be made more systematic, general and flexible by

- applying the "box of bricks" system, where the main components of a nuclear power plant are treated separately and combined afterwards according to a given flow scheme,
- a dynamic determination of the components which is as general as possible without taking into account those details which have a minor influence on the overall dynamics,
- providing approximations of the more rigorous solution sufficient to meet the user's requirements on accuracy,
- proper use of computers.

A dynamic model for single-phase coolant reactor plants is established along these lines. By separation of the nonlinear and linear parts of the system, application of Laplace transformation and proper approximations, and the use of a hybrid computer it seems possible to determine the (nonlinear) dynamic behaviour of such a plant for perturbations which are not so large that phase changes of physical parameters occur, e.g. fuel does not melt.

The model is applied to a steam cooled fast reactor power plant.

Printed and distributed in December 1968.

LIST OF CONTENTS

1. INTRODUCTION

The dynamic behaviour of nuclear power plants has received growing interest and has been investigated by the use of numerous models. The reason for the diversity of these models originates from the variety of plant systems, the different objectives and accuracy of the calculations, and, last but not least, the different types and capacities of the available computers.

When studying a new system, often little use is made of the existing specific models, and instead a new model is developed to suit the requirements and objectives stated for this problem. This procedure is both time-consuming and uneconomical, and will be prohibitive in view of the steadily increasing importance and number of future dynamic investigations.

Therefore the question arises whether the model development can be made more systematical, general and flexible. To answer this question a clear statement of the objectives for dynamic studies and the design of the various plants is necessary, since it is obvious that a common model for all systems and all purpose would neither be possible nor economical.

The practical tasks to be solved by dynamic models concern mainly

- stability
- investigation of the behaviour of the system when subject to perturbations at full or part load, in particular load changes, reactivity insertions and possible flow variations
- accident behaviour (loss of coolant, loss of flow, failure of plant components)
- design and performance studies of control systems.

These types of investigation deal with transients in the, say, 0.1 sec to several minutes range and with variations of the physical quantities that do not lead to phase changes e.g. of fuel or cladding.

We shall assume that other transients either causing large excursions or slow variations (e.g. Xe-poisoning) are best treated by separate models.

Although there is a large variety of nuclear plants these consist of a few main components only:

- except for a few designs the core consists of cylindrical clad fuel rods,
- heat exchanger (of direct or indirect contact type),
- circulator (pumps or blowers),
- turbine,
- plenum,
- valves and pipes.

The limited number of components and objectives stated above render possible a more general model development, as will be shown in this report. This investigation will be confined to single-phase coolant reactor plants such as PWRs and fast breeders. The study of two-phase systems introduces further complications and may be seen as a development task.

In order to become independent of a specific design and application purpose, it is suggested that the "box of bricks system" be used, the (few) plant components being dealt with separately and combined afterwards according to the flow scheme. Further, a relative general mathematical description of the individual components is necessary as well as different approximations of the rigorous description. The user of the model then chooses the approximation from the "library" which suits his requirements.

Both the general solution, its approximation and the proper use of the computers will be discussed in the following sections. As an example, a dynamic model of a steam cooled fast reactor power is given.

2. GENERAL APPROACH TO MODEL DEVELOPMENT

The recipes for developing a general and effective model were mentioned in the previous section. They will be described here in more detail.

2.1 Box of bricks system

Separate mathematical description of the various plant components makes the model independent of the specific plant design. The transient behaviour of each component is determined as a function of all physical variables by which it is affected (input variables). The output variables are then the input variables of the succeeding component.

2.2 General description of the components with options for approximations

The objective is to find a mathematical description of the main plant components which is so general that it includes the main design possibilities without taking into account details of subordinate influence on the dynamic behaviour. This compromise is not quite well defined but leaves little choice when treating the individual plant components. See section 3.

Only very rarely is a rigorous solution of the problem necessary. Moderate requirement on accuracy or limited capacity often demand an approximate solution. It is therfore necessary to develop approximation techniques. The following procedure is suggested.

First, find out the main non-linearities and try to separate them from the linear system. An example is the calculation of coolant enthalpy, see 3.2.5.

Second, if the non-linearity is of a "slow or weak" type, apply a quasi-linear description which is up-dated at longer time intervals.

Third, solve the linear system analytically as far as possible. Special advantage may be taken of the application of Laplace transformation by which partial differential equations are transferred into ordinary differential equations and their solutions are backed up with the formalisms developed for these equations and the Laplace transformations.

As a result one obtains a set of ordinary equations for the (physical) variables, the coefficients being the so-called transfer functions.

Fourth, approximate these rigorous transfer functions by the aid of computer programmes, e.g. Ref. [1], according to the specified requirements of accuracy.

This procedure offers several advantages. First, it is non-iterative, which saves computation time. Second, the computer capacity may be utilized more effectively due to the separation technique. Both the linear part of the problem and the approximation may be treated prior to the actual calculation of the transients. Thus, the entire computer capacity can be used for both purposes at times. Third, the precedure is backed up with well developed techniques and provides a systematical and wide range of suitable approximations.

2.3 Adequate use of computers

The first question to be answered concerns the type of computer. A pure digital simulation of a power reactor plant results in computation times of around 20 to 50 times the problem speed. The corresponding number for analog simulation is 0.1. The use of a digital computer alone seems prohibitive when considering the large number of runs necessary for designing the plant and the control system (some thousands). The main disadvantages of the pure analog computer originate from the limited capacity and logical facilities. It is therefore concluded that only the combined use of both type of computers is successful. It is further concluded that the analog and digital computers must be used both in both parallel and serial modes. An effective way of using the computers is sketched in Fig. 1.

The input information consists of data on the design and operation at time 0 and the transient perturbation to be imposed on the system. This information is used to determine the transfer functions of the linear part of the system which is approximated according to prescribed accuracy requirements. The results are inputs to the digital

computer programme determining the potentiometer settings of the analog computer and initialising the digital part of the hybrid computer. It may be appropriate to have some sort of check programme testing the hybrid computer. The actual transient calculation is performed on the hybrid computer with possible up-dating of the transfer functions for very large transients and the results are recorded directly and/or processed on a digital computer (Fourier analysis etc.).

The decision which part of the problem should be solved on the analog and which on the digital computer has to be made on the basis of the type of the problem. Integrations are best performed on the analog computer, nonlinearities and logical operations are better suited for the digital computer. In practice the division will be influenced by the capacities of the computers and their interface equipment.

3. DYNAMIC BEHAVIOUR OF THE MAIN PLANT COMPONENTS

3.1 Objective

It is the objective of this section to calculate the dynamic behaviour of the main components as generally as seems adequate for the application purposes. At the same time an attempt is made to provide various approximations of the rigorous solutions such as to satisfy different requirements on accuracy and computer capacity which will arise when the components are combined according to the specified flow scheme. Frequent reference will be made to a linear model developed previously, see Ref. [2], which may be considered as basis for the present work.

3.2 Core

In most reactors the core consists of cylindrical fuel rods in cladding material. It seems that 2 representative rods are required to simulate large cores, in most cases only one rod is sufficient. There is an intermediate solution of this problem by having one representative rod and one or several "slave channels" which have no feedback on the system reactivitywise.

3.2.1 Nuclear power

The nuclear power consists of two parts which are determined by the kinetic equations and relationship for decay heat N''.

$$N = N' + N'' \tag{1}$$

$$\frac{dN'}{dt} = [k(1 - \beta) - 1] \frac{N'}{\ell} + \Sigma \lambda_j^* C_j^* + S^* \tag{2}$$

$$\frac{dC_j^*}{dt} = - \lambda_j^* C_j^* + \beta_i k \frac{N'}{\ell} \qquad , j = 1, \ldots \tag{3}$$

N'' and S* are specified externally. The nomenclature is the same as in Ref. [2] and summarized on page 21 et seq.

3.2.2 Reactivity

The effective multiplication factor and reactivity changes depend on cross section and spectrum changes which, in their turn, may change directly or indirectly due to temperature and density changes in the core. Reactivity which is approximated as k - 1, k being close to unity, is therefore written as

$$k - 1 = \delta k_1 + \delta k_3 + \delta k_4 + \delta k_{ext} \tag{4}$$

$$\delta k_1 = \sum_j \frac{\partial k^{(j)}}{\partial T_1} \delta T_1^{(j)}(t) \tag{5}$$

$$\delta k_3 = \sum_j \frac{\partial k^{(j)}}{\partial T_3} \delta T_3^{(j)}(t) \tag{6}$$

$$\delta k_4 = \sum_j \frac{\partial k^{(j)}}{\partial \rho_4} \delta \rho_4^{(j)}(t) \tag{7}$$

δk_{ext} represents externally inserted reactivity and slow reactivity effects such as Xe-poisoning which may be separated from the actual problem.

As reactivity is an integral quantity, the definition of local reactivity coefficients for each region (j) is incorrect. This description becomes a good approximation for small perturbations or for large perturbations if the reactivity effects are linear.

Considering the uncertainties encountered in the determination of reactivity coefficients the local coefficients may often be related to the uniform and integral coefficients as

$$\frac{\partial k^{(j)}}{\partial T_1} = g_1^{(j)} \frac{\partial k}{\partial T_1}(T_1, \rho_4)$$

$$\frac{\partial k^{(j)}}{\partial T_3} = g_3^{(j)} \frac{\partial k}{\partial T_3}(T_3)$$

$$\frac{\partial k^{(j)}}{\partial \rho_4} = g_4^{(j)} \frac{\partial k}{\partial \rho_4}(\rho_4)$$

$\frac{\partial k}{\partial T_1}(T_1, \rho_4)$ specified (by a table or an analytical expression)

$\frac{\partial k}{\partial T_3}(T_3)$ specified

$\frac{\partial k}{\partial \rho_4}(\rho_4)$ specified

The g's are constant weighting factors and in the integral coefficients only the main dependences are indicated.

3.2.3 Fuel and cladding temperature

Thermal conductivity is temperature dependent and introduces a nonlinearity in the calculation of fuel temperature. It is felt that this nonlinearity may be disregarded for the following reasons.

- Fuel temperature becomes of great interest if it rises, because of the risk of melting. In the regions of large temperatures the thermal conductivity is constant.
- Uncertainties in the thermal conductivity are still large so that sophisticated models may not be justified.
- The actual fuel temperature field is uncertain due to uncertainties in fuel performance.

Consequently we assume constant material properties in fuel (and cladding) so that the results of Ref. [3] may be used directly.

$$\delta T_1^{(j)}(s) = \frac{1}{C_1^{(j)}} Y_5 \, \delta N^{(j)}(s) + \frac{1}{Y_2} \delta T_3^{(j)}(r_3, s) \tag{8}$$

$$\delta T_3^{(j)}(s) = \frac{1}{C_3^{(j)}{}_s} [\delta N^{(j)}(s) - \delta q_3^{(j)}(s)] - \frac{C_1^{(j)}}{C_3^{(j)}} \delta T_1^{(j)}(s) \tag{9}$$

The transfer functions Y_2 and Y_5 depend upon material properties and the function y_{ik} and are determined by the computer code DYROTE as described in Appendix A. Local temperatures in fuel and cladding may be calculated separately as functions of $\delta N(s)$ and $\delta T_3(r_3, s)$, see Ref. [3], which may be advantageous from the viewpoint of computer capacity.

3.2.4 Heat flow to coolant

The heat flow to coolant may be expressed as a function of power and canning surface temperature, using the results of Ref. [3].

$$\delta q_3^{(j)}(s) = Y_3 [\delta N^{(j)}(s) - C_1^{(j)}{}_s \, Y_4 \, \delta T_3^{(j)}(r_3, s)] \tag{10}$$

The transfer functions Y_3 and Y_4 are found in Appendix A. The non-linearity in heat transfer from canning to cooling may in general not be neglected. Thus,

$$\delta T_3^{(j)}(r_3, t) = \delta\left(\frac{q_3^{(j)}(t)}{S_3^{(j)} \alpha_3^{(j)}(t)}\right) + \delta T_4^{(j)}(t) \tag{11}$$

$$q_3^{(j)}(t) = q_3^{(j)}(o) + \delta q_3^{(j)}(t) \tag{12}$$

$$T_3^{(j)}(r_3, t) = T_3^{(j)}(r_3, o) + \delta T_3^{(j)}(r_3, t) \tag{13}$$

$\alpha_3^{(j)}(t)$ may be of the form

$$\alpha_3^{(j)}(t) = \alpha_3^{(j)} \left[\frac{W(t)}{W}\right]^{\mu_1} \left[\frac{c_4^{(j)}(t)}{c_4^j}\right]^{\mu_2} \left[\frac{T_4^{(j)}(t)}{T_3^{(j)}(r_3, t)}\right]^{\mu_3} \left[\frac{T_3^{(j)}(r_3, o)}{T_4^{(j)}(o)}\right]^{\mu_3} \tag{14}$$

For a fast steam cooled reactor the exponents are $\mu_1 = 0.8$, $\mu_2 = 0.4$, $\mu_3 = 0.575$.

3.2.5 Coolant enthalpy

Coolant enthalpy is determined from the mass and energy balance equations. The main ideas to solve the nonlinear problems are:

- Separate the nonlinear perturbation terms from the essentially linear dynamic operator which determines enthalpy.
- Assume space-time separability for the heat flux in the various sub-regions.
- The nonlinearities still neglected are of second order and may be taken into account by updating at longer time intervals.

The power of this procedure is that the effect of different nonlinearities may be checked directly and that large parts of the linear treatment can be utilized directly.

Some details of the mathematical derivation are given in Appendix B. Results for the average and outlet enthalpy of a sub-region j read

$$\delta h_{4o}^{(j)}(s) = Y_{3o}^{(j)}\, \delta F'^{(j)}(s) + Y_{4o}^{(j)}(s)\, f(s) + Y_{5o}^{(j)}(s)\, \delta h_{4i}^{(j)}(s) \tag{15}$$

$$\delta h_4^{(j)} = Y_3^{(j)}\, \delta F'^{(j)}(s) + Y_4^{(j)}(s)\, f(s) + Y_5^{(j)}(s)\, \delta h_{4i}^{(j)} \tag{16}$$

$$\delta F'^{(j)}(t) = \frac{W_4(o)}{W_4(t)} \left(1 + \frac{\delta q_3^{(j)}(t)}{q_3^j}\right) - 1 \tag{17}$$

$$f(t) = \frac{A_4}{W_4(t)} \frac{dp_4}{dt} \tag{18}$$

3.2.6 Coolant temperature and density

Two alternatives exist when determining coolant temperature T and density ρ. First, T is determined from enthalpy and pressure

$$T_4^{(j)} = T(h_4^{(j)}, p_4) \tag{19a}$$

and density is then calculated as a function of T and p

$$\rho_4^{(j)} = \rho_4(T_4^{(j)}, p_4) \tag{20a}$$

In this procedure the corresponding relationships must be given as tables or equations. Second, T and ρ are determined quasi-linearly

$$\delta T_4^{(j)}(t) = \int_o^t \frac{1}{c_{p4}^{(j)}} \left[\frac{dh_4^{(j)}}{dt} + (\nu_{v4}^{(j)} - 1) v_4^{(j)} \frac{dp_4}{dt} \right] dt \tag{19b}$$

$$\delta \rho_4^{(j)}(t) = \int_o^t \frac{\rho_4^{(j)}}{\nu_{\rho 4}^{(j)}} \left[\frac{1}{p_4} \frac{dp_4}{dt} - \frac{\nu_{T4}^{(j)}}{T_4^{(j)}} \frac{dT_{4t}^{(j)}}{dt} \right] dt \tag{20b}$$

The pure by linear description is obtained if all quantities (except the derivatives) are constant and equal the steady state values. Then by updating frequently any degree of nonlinearity may be taken into account.

3.2.7 Coolant pressure and flow

The pressure drop across the core is normally small and may be neglected when calculating the space and time dependent temperature and density. Thus,

$$p_4(t) = \frac{p_{4i} + p_{4o}}{2} \tag{21}$$

For the core flow we assume

$$p_{4i} - p_{4o} = \frac{w_4^2}{\rho_4} \text{const} \tag{22}$$

3.3 Plenum

The equations for the volume, mass and energy balance combined with the equation of state and an equation for the heat losses to the structure material determine the dynamic behaviour of a plenum, see also Ref. [2]. Combination of the balance equations yields

$$h\left[1 + \frac{m}{W_i}\frac{d}{dt}\right] = h_i + \frac{1}{W_i}\left[Q + V\frac{dp}{dt}\right] \tag{23}$$

Note that in this paragraph all quantities are functions of time and the argument is omitted for convenience. $\frac{m}{W_i}$ is the (time dependent) transit time of the coolant through the plenum. Its transient variation is a second order effect and may thus be treated by up-dating the transit time at longer intervals. The mass is calculated from

$$\frac{dm}{dt} = W_i - W_o \tag{24}$$

The temperature is derived from

$$T = T(h, p) \tag{25}$$

or an equivalent equation to (19b).

The pressure is calculated from a similar expression to that obtained for the linear model, see Ref. [2].

$$\frac{dp}{dt} = p\,\frac{\nu_T}{T}\,\frac{dT}{dt} + \frac{\nu_\rho p}{m}\,(\delta W_i - \delta W_o) \tag{26}$$

Again, the variation of the quantities $p\,\frac{\nu_T}{T}$ and $\frac{\nu_\rho p}{m}$ is a second order effect.

The heat exchange with the structure material is

$$Q = -Y_{st}\,T \tag{27}$$

For small temperature changes Y_{st} is of the form

$$Y_{st} = A_{st}\,\alpha_{st}\,\frac{\tau_{st}s}{1 + \tau_{st}s} \quad , \quad \tau_{st} = \frac{m_{st}\,c_{st}}{A_{st}\,\alpha_{st}}$$

The density is calculated from

$$\rho = \frac{m}{V} \tag{28}$$

3.4 Heat exchanger

Heat exchangers in the general sense occur at several positions in a plant scheme, and serve to exchange energy between two media without internal heat sources. One may distinguish between direct and indirect contact heat exchangers. Steam generators are of the former type, condensers of the latter. A variety of designs exists for both types, and it seems necessary to develop a few models which by combination should render possible the general and practicable description of the various designs. This task has not been tackled and is suggested as a further development.

The following are the equations for a steam generator which is designed so that water and steam are in thermal equilibrium. The volume, mass and energy balance equations are found in Ref. [2], and are solved as follows (time argument is omitted):

$$\frac{dm}{dt} = -\frac{1}{v - v^*}\left[m \frac{dv}{dt} + m^* \frac{dv^*}{dt} + v^*(W_i + W_i^* - W_o) \right] \tag{29}$$

$$\frac{dm^*}{dt} = W_i + W_i^* - W_o - \frac{dm}{dt} \tag{30}$$

$$\frac{dp}{dt}\left[mv - m \frac{dh}{dp} - m^* \frac{dh^*}{dp} + mp \frac{dv}{dp} \right] = (h - pv) \frac{dm}{dt} + h^* \frac{dm^*}{dt} -$$

$$- W_i h_i - W_i^* h_i^* + W_o h - Q - Q^* \tag{31}$$

T, v, v^*, h, h^* specified as functions of p. (32)

$$Q = -A_{st} \alpha_{st} \frac{\tau_{st} s}{1 + \tau_{st} s} T \tag{33}$$

The asterisk denotes the water phase.

3.5 Circulator

Pumps, compressors or blowers may be described by the same formulas as already summarized in Ref. [2]. Essentially they consist of two characteristic equations, the equations of energy and momentum conservation and the equation of state.

$$\frac{p_o}{p_i} = \Pi(\xi, \zeta) \tag{34}$$

$$\xi = \frac{W(t)}{W} \frac{p_i}{p_i(t)} \sqrt{\frac{j_i(t)}{j_i}} \tag{35}$$

$$\zeta = \frac{n(t)}{n} \sqrt{\frac{j_i}{j_i(t)}} \tag{36}$$

$$j_i = \frac{\varkappa}{\varkappa - 1} p_i(t)\, v_i(t) \approx \frac{\varkappa}{\varkappa - 1} \text{ const } T_i \tag{37}$$

$$\eta = \eta(\Pi, \zeta) \tag{38}$$

$$h_o - h_i = \frac{1}{\eta} c_{pi} T_i (\Pi^{\frac{\varkappa - 1}{\varkappa}} - 1) \tag{39}$$

$$(J_t + J_c) \frac{dn}{dt} = M_t - M_c - M_\ell \tag{40}$$

$$M_\ell = M_\ell(n) \tag{41}$$

$$M_c = \frac{N_c}{n} \tag{42}$$

$$N_c = W(h_o - h_i) \tag{43}$$

3.6 Turbine

Similar arguments to those for the circulators are valid for the turbines.

$$\frac{p_i}{p_o} = \Pi_t \tag{44}$$

$$\xi = \xi(\Pi_t, \zeta) \tag{45}$$

$$\eta_t = \eta_t(\Pi_t, \zeta) \tag{46}$$

$$h_i - h_o = \eta_t c_{pi} T_i \left[1 - \Pi_t^{\frac{1-\varkappa}{\varkappa}} \right] \tag{47}$$

$$M_t = \frac{N_t}{n} \tag{48}$$

$$N_t = W(h_i - h_o) \tag{49}$$

ξ and ζ have the same meaning as in eqs. (35) and (36).

In the next section we shall consider a flow scheme containing three turbines, see Fig. 2. The drive turbine and the compressor are assumed to have a common shaft so that

$$n_t = n_c \tag{50}$$

For the main turbine n_T may be assumed

$$n_{T1} = n_{T2} = 0 \tag{51}$$

A detailed description of turbine power is necessary only for the drive turbine, and only there may c_p possible be considered as pressure and temperature dependent.

$$c_p = c_p(T, p) \tag{52}$$

3.7 Pipes and valves

In principle the same equations can be applied for pipe and plenum. However, in practice some simplifications may be accepted. Since the valves are normally well insulated we may neglect heat losses, so that

$$\delta h_o(t) = \delta h_i(t - \theta) \tag{53}$$

$$\theta(t) = \theta(o)\ \frac{W(o)}{W(t)} \tag{54}$$

Pressure drops are normally small and may be simulated at other places, e.g. at a preceding or succeeding valve.

$$\delta p_o(t) = \delta p_i(t) \tag{55}$$

Otherwise the drop is calculated from

$$\Delta p = \text{const}\ \frac{W^2}{\rho} \tag{56}$$

Due to the small volume we may further neglect the compressibility.

$$\delta W_o(t) = \delta W_i(t) \tag{57}$$

The mass flow through a valve is

$$W = A\,\Psi(\Pi)\sqrt{2\,\frac{p_i}{v_i}} \tag{58}$$

$$\Pi = \frac{p_o}{p_i} \tag{59}$$

$$\Psi(\Pi) = \begin{cases} \Pi^{\frac{1}{\varkappa}}\sqrt{\frac{\varkappa}{\varkappa-1}\left[1-\Pi^{\frac{\varkappa-1}{\varkappa}}\right]} & \Pi > \left(\frac{2}{1+\varkappa}\right)^{\frac{\varkappa}{\varkappa-1}} \\ \left(\frac{2}{1+\varkappa}\right)^{\frac{1}{\varkappa-1}}\sqrt{\frac{\varkappa}{\varkappa+1}} & \Pi \le \left(\frac{2}{1+\varkappa}\right)^{\frac{\varkappa}{\varkappa-1}} \end{cases} \quad \text{if} \tag{60}$$

A(t) is specified and $\varkappa$ may be assumed constant.

4. DYNAMIC BEHAVIOUR OF THE ENTIRE PLANT

4.1 General procedure of the calculation

If the complete flow scheme and the objective of the dynamic investigation is specified, then the first task will be to choose the main components of interest and combine them in a simplified flow diagram. In this all unessentials are dropped.

The next step concerns the determination of the various components. The objective of the studies and the required accuracy will then determine the approximations acceptable for the mathematical description of the components. Thereby the needed computer capacity is determined, which may be compared to the available capacity. If the required computer capacity is larger than that available, the problem can often be solved by dividing it into different parts. Remedies of this kind are:

- Consider a number of related components as a unit, e.g. core or external plant. Treat the larger blocks separately and approximate them afterwards.
- Treat low and high frequency ranges one at a time.
- Solve the problem only for those variables which have a marked influence on the entire system. Determine the other quantities at a second and separate step with the use of results obtained before. (Hot spot analysis, slave channel).

If the required and available computer capacities match, the remarks made in section 2 will be a guide to determine the proper use of the computers.

4.2 The steam cooled fast reactor power plant

The steam cooled fast reactor power plant will be used to demonstrate a specific application. Its flow diagram is found in Fig. 2. Combining the various components is quite obvious. In addition to the equations given in section 3 we must add several identity statements of the kind: the pressure at the upper plenum equals the pressure at steam generator inlet, drive turbine inlet and turbine admission valve inlet. Further, we need some equations where several lines branch:

$$W_{T2} = W_{T1} + W_t \tag{61}$$

$$h_{T2i} = \frac{W_{T1}}{W_{T2}} h_{T1o} + \frac{W_t}{W_{T2}} h_{vo} \tag{62}$$

$$W_{Do} = W_{gi} + W_t + W_{T1} \tag{63}$$

The complete model is shown in the form of a diagram in Fig. 3. A scheme demonstrating the sampling cycle of the hybrid computer is included in Fig. 4. In this specific case 16 A/D and 8 D/A converters are employed.

To give an idea which computer capacity seems to be necessary it may be mentioned that the above mentioned plant is intended to be simulated on a EAI 640/8800 hybrid computer.

5. FUTURE WORK

It has already been pointed out that the heat exchanger deserves a further and more detailed investigation. Next it would be desirable to study the dynamic nonlinearities of the plant components more quantitatively. A comparison of the nonlinear and linear model for some typical designs and operations would yield the desired information. A similar study should be undertaken for an entire plant. The steam-cooled fast reactor power plant may be taken as an example, as its linear dynamic behaviour was investigated for various plant designs and operations. Finally, it is suggested that the presented model may be extended to apply to studies of two-phase coolant reactor systems.

ACKNOWLEDGEMENT

The author wishes to thank Mr I Ebbsjö for writing the computer programme DYROTE.

NOMENCLATURE

A	area
C	heat capacity
C*	concentration of delayed emitters
c	specific heat
g	weighting function
h	specific enthalpy
J	inertia
k	effective multiplication factor
ℓ	neutron life time
M	torque
m	mass
N	power
n	speed
p	pressure
q	heat flow
r	radius
S	surface
S*	source
s	Laplace variable
T	temperature (absolute)
$T_1(t)$	mean fuel temperature
$T_3(r_3, t)$	surface canning temperature
$T_3(t)$	mean canning temperature
t	time
V	volume
v	specific volume

W	mass flow
Y	transfer function
z	axial coordinate
α	heat transfer coefficient
β	delayed neutron fraction
δ	denotes deviation from steady state
ζ	variable defined by eq. (36)
η	internal efficiency
θ	transit time
$\varkappa$	isentropic exponent
λ^*	decay constant
μ_i	exponents in eq. (14)
ν_T	$\equiv \frac{T}{p}\left(\frac{\partial p}{\partial T}\right)_v$
ν_v	$\equiv \frac{T}{v}\left(\frac{\partial v}{\partial T}\right)_p$
ν_ρ	$\equiv -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_T$
ξ	variable defined by eq. (35)
Π	pressure ratio
ρ	density
τ	time constant

Subscripts:

1 refers to fuel

2 " " gap

3 " " canning

4 " " coolant

i " " inlet

o " " outlet

Superscripts refer to (axial) subregions.

Note: In order to achieve a clear and simple denotation we define the use of arguments as follows.

$f(t)$ time dependent function

$f(s)$ Laplace transform of $f(t)$

$f = f(t = 0)$

LIST OF REFERENCES

1. TOLLANDER B,
The computer programme Anpass. (Private communication.)

2. VOLLMER H,
Linear dynamics model for steam cooled fast power reactors. 1968.
(AE-316).

3. VOLLMER H,
Transient temperature distribution in a reactor core with cylindrical fuel rods and compressible coolant. 1968.
(AE-315).

4. VOLLMER H, and ANDERSSON A J W,
Development of a dynamics model for heavy water boiling reactors and its application to the HBWR. 1964.
(HPR-54).

APPENDIX A

Transfer functions for the fuel rod temperatures

The local and mean fuel and canning temperatures as well as the heat fluxes in the fuel rod were derived in Ref. [3]. It was shown there that these variables may be expressed as functions of nuclear power and heat flux from the fuel pellet to the gap. Naturally other sets of two independent variables could have been used e.g. nuclear power and cladding surface temperature. The latter has the advantage that the nonlinearity occurring in the heat transfer from cladding surface to coolant is better separated from the linear rod temperature calculation. In addition some computational advantages arise. The mean fuel and cladding temperatures and the heat flux from the cladding to coolant were therefore expressed as functions of the above mentioned variables. The transfer functions are readily obtained as

$$Y_1^{-1} = y_{10}\left(\omega_3 r_2, \frac{r_3}{r_2}\right) + 2\,\frac{r_2}{r_1}\,\frac{r_3 \rho_3 c_3}{r_1 \rho_1 c_1}\, y_{11}\left(\omega_3 r_3, \frac{r_2}{r_3}\right)\left[\frac{\lambda_1 \omega_1^2 r_1}{2\alpha_{13}} + y_{01}(r_1 \omega_1, 1)\right]$$

$$Y_2 = \frac{1}{2}\,\frac{\lambda_1}{\lambda_3}\, r_1^2 \omega_1^2\, y_{00}\left(\omega_3 r_3, \frac{r_2}{r_3}\right) + y_{10}\left(\omega_3 r_3, \frac{r_2}{r_3}\right)\left[\frac{\lambda_1 \omega_1^2 r_1}{2\alpha_{13}} + y_{01}(r_1 \omega_1, 1)\right]$$

$$Y_3 = \frac{1}{Y_1 Y_2}\, y_{10}\left(\omega_3 r_3, \frac{r_2}{r_3}\right) - 2\,\frac{r_2}{r_1}\,\frac{r_3 \rho_3 c_3}{r_1 \rho_1 c_1}\, y_{11}\left(\omega_3 r_3, \frac{r_2}{r_3}\right)$$

$$Y_4 = \frac{1}{Y_1 Y_2 Y_3}$$

$$Y_5 = \frac{1}{s}\left[1 - \frac{1}{Y_2}\, y_{10}\left(\omega_3 r_3, \frac{r_2}{r_3}\right)\right]$$

where $\omega_i = \sqrt{\frac{s}{n_i}}$.

$\varkappa_i$ is the thermal diffusivity and the y_{ik}´s are functions defined and calculated in Ref. [3].

The transfer functions Y_1, Y_2, ..., Y_5 were determined by a computer programme DYROTE (Dynamic Rod Temperature) written by Mr I Ebbsjö. The input data to the programme read:

r_1, cm

r_2, cm

r_3, cm

λ_1, $\frac{W}{cm\ ^oC}$

λ_3, "

ρ_1, g/cm^3

ρ_3, "

c_1, $I/g\ ^oC$

c_3, "

α_{13}, $\frac{W}{cm^2\ ^oC}$

frequencies, c/sec.

The print out contains frequency, gain in db and phase in degrees of Y_1 to Y_5.

APPENDIX B

Determination of coolant enthalpy

Omitting the arguments, the mass and energy balance equations read:

$$\frac{\partial}{\partial t} A_4 \rho_4 = - \frac{\partial W_4}{\partial z} \tag{1}$$

$$\frac{\partial}{\partial t} [A_4 \rho_4 (h_4 - p v_4) = 2 \pi r_3 q_3 - \frac{\partial}{\partial z} W_4 h_4 \tag{2}$$

Here $q_3 = q_3(z,t)$ is the local heat flux at height z and time t. Combining eqs. (1) and (2) yields:

$$\frac{\partial h_4}{\partial z} + \frac{1}{u_4} \frac{\partial h_4}{\partial t} = F(z,t) + f(t) \tag{3}$$

where

$$F(z,t) = \frac{2\pi r_3 q_3(z,t)}{W_4(t)} \tag{4}$$

$$f(t) = \frac{A_4}{W_4(t)} \frac{dp_4(t)}{dt} \tag{5}$$

and u_4 is the local and time-dependent coolant velocity. Let us neglect for the time being these dependences; then we see from eq. (3) that the enthalpy is determined from a linear equation where only the perturbation terms are nonlinear.

Laplace transforming and solving eq. (3) yields for the deviations of the variables from their steady states:

$$\delta h_4(z,s) = e^{-\frac{s}{u_4} z} \int_0^z [\delta F(z,s) + f(s)] e^{\frac{s}{u_4} z} dz + e^{-\frac{s}{u_4}} \delta h_{4i}(s) \tag{6}$$

The space dependence of $\delta T(z,s)$ is mainly due to the heat flux which we may assume separable

$$q_3(z,t) = q_3(z,o)\left(1 + \frac{\delta q_3(t)}{q_3}\right) \tag{7}$$

Define

$$\delta F'(t) \equiv \frac{W_4}{W_4(t)}\left(1 + \frac{\delta q_3(t)}{q_3}\right) - 1 \tag{8}$$

and insert the Laplace transforms of eqs. (4), (7) and (8) into eq. (6). Then the integrations involved in eq. (6) can be solved either directly or by reducing the integrals to Laplace transforms of the function $q_3(z,o)$:

$$\delta h_4(z,s) = \delta F'(s) \cdot \frac{2\pi r_3}{W_4}\left[\overline{q_{3z}\left(\frac{s}{u_4}\right)} - \overline{q_3\left(\frac{s}{u_4}\right)} e^{-\frac{s}{u_4}z}\right] +$$

$$+ f(s)\,\frac{u_4}{s}\left(1 - e^{-\frac{s}{u_4}z}\right) + e^{-\frac{s}{u_4}z}\,\delta h_{4i}(s) \tag{9}$$

where

$$\overline{q_{3z}(\sigma)} = L_{z'}\left\{q_3(z - z', o)\right\} \tag{10}$$

$$\bar{q}_3(\sigma) = L_{z'}\left\{q_3(-z', o)\right\} \tag{11}$$

$\sigma = \frac{s}{u_4}$ may be considered as a Laplace variable, z' as a time variable. The principle of the solution is the same as given in Appendix B of Ref. [4].

Considering z as the coordinate determining the outlet of a (sub-) region, the outlet enthalpy is determined by 3 transfer functions:

$$Y_{3o} = \frac{2\pi r_3}{W_4}\left[\overline{q_{3z}\left(\frac{s}{u_4}\right)} - \bar{q}_3\left(\frac{s}{u_4}\right) e^{-\frac{s}{u_4}z}\right] \tag{12}$$

$$Y_{4o} = \frac{u_4}{s}\left(1 - e^{-\frac{s}{u_4}z}\right) \tag{13}$$

$$Y_{5o} = e^{-\frac{s}{u_4}z} \tag{14}$$

A further integration of the local temperature is needed for the average temperature of a (sub-) region. The corresponding transfer functions turn out to be related to the above mentioned as:

$$Y_3 = \left[\frac{q_3}{W_4} - Y_{3o}\right]\frac{u_4}{zs} \tag{15}$$

$$Y_4 = \left[z - Y_{4o}\right]\frac{u_4}{zs} \tag{16}$$

$$Y_5 = \left[1 - Y_{5o}\right]\frac{u_4}{zs} \tag{17}$$

Note that for the functions defined by eqs. (12) to (17) z is the length of the (sub-) region and therefore a given value.

In the results derived above, the coolant velocity was assumed space- and time-independent. If the space dependence is appreciable it may be taken into account in a way similar to that used in Ref. [4]. This implies essentially that a (z,τ) coordinate transformation is applied according to

$$\tau = \int_0^z \frac{dz'}{u_4(z',o)} \tag{18}$$

In doing so expressions are obtained which are of the same type as those for constant velocity.

Neglecting the time dependence of the velocity in eq. (3) introduces an error of second order. Therefore, it is acceptable to consider u_4 constant in different time intervals. By up-dating it from time to time the solution may be made as accurate as required.

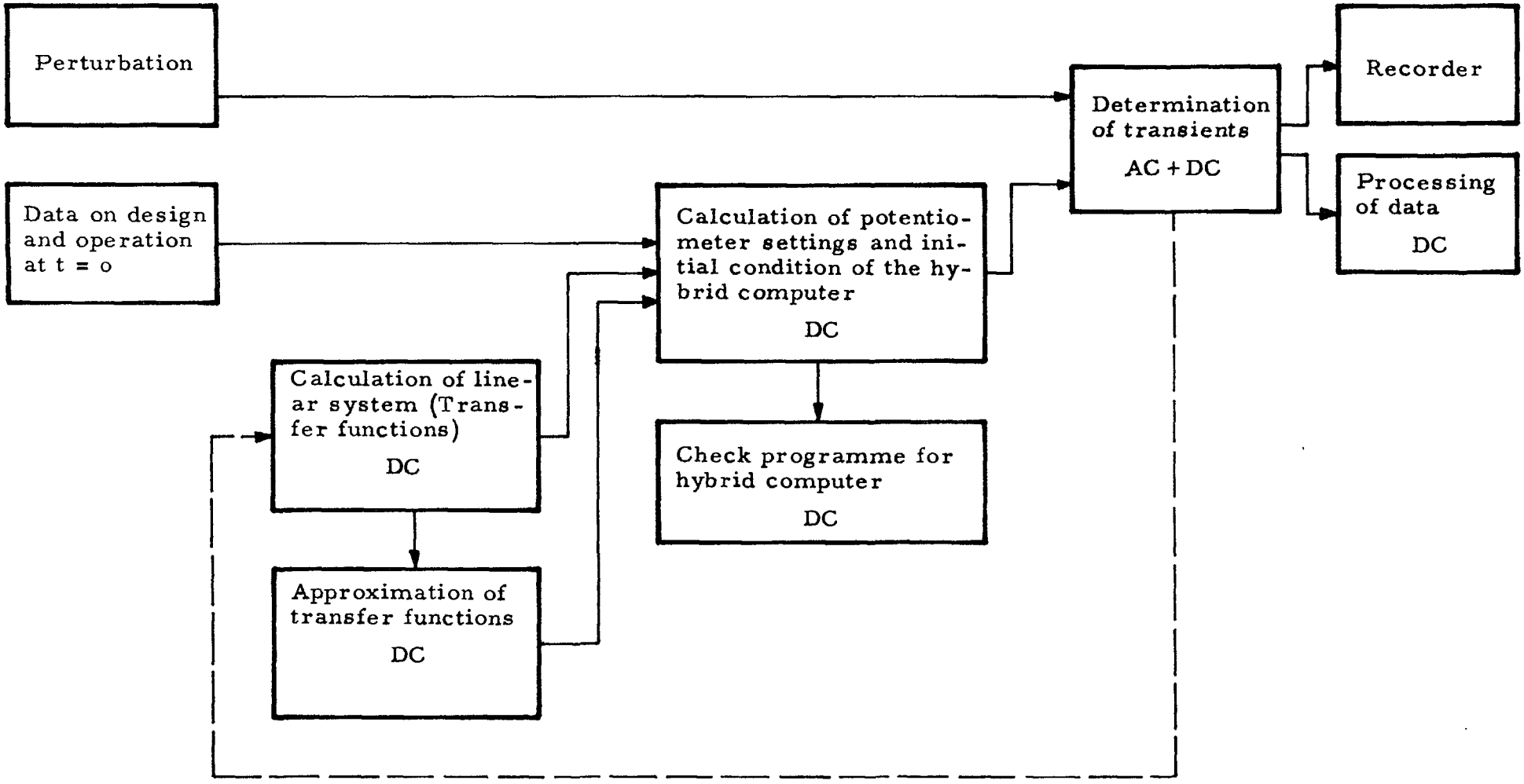
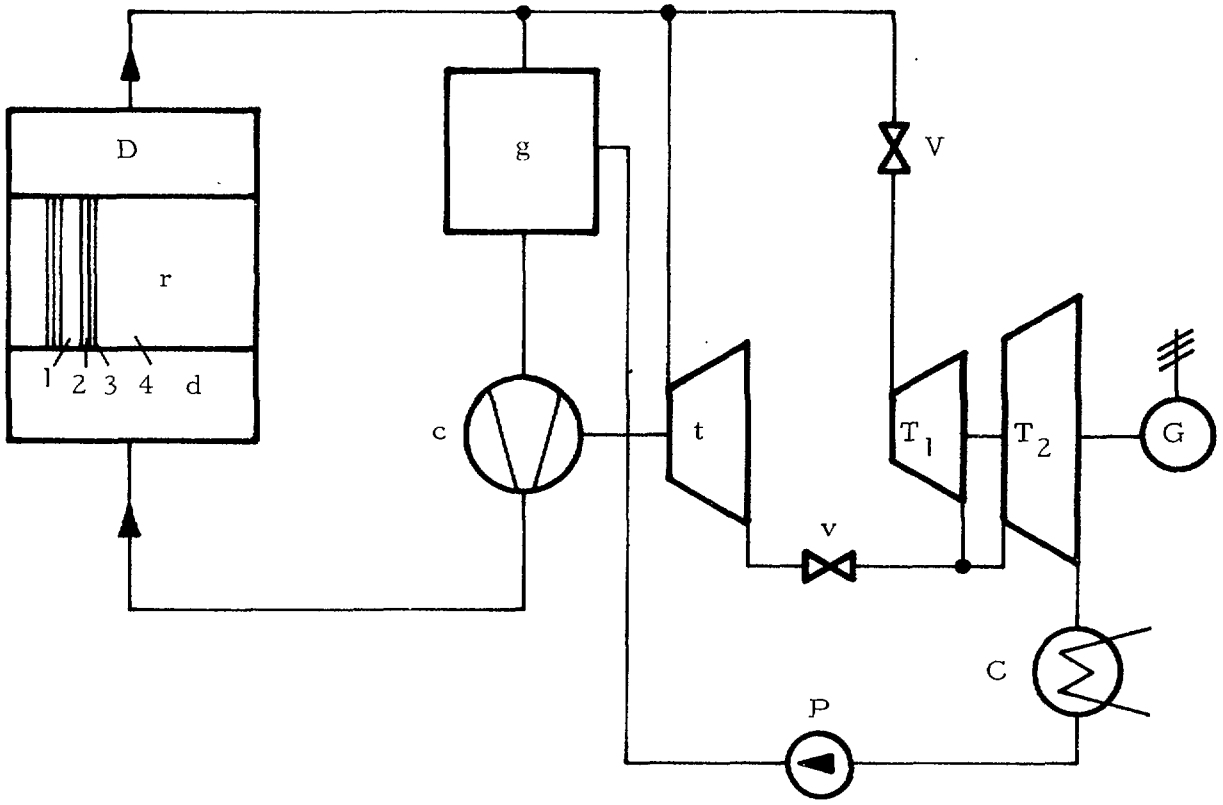


Fig. 1 Proper use of digital (DC) and analog computer (AC) in dynamic investigations

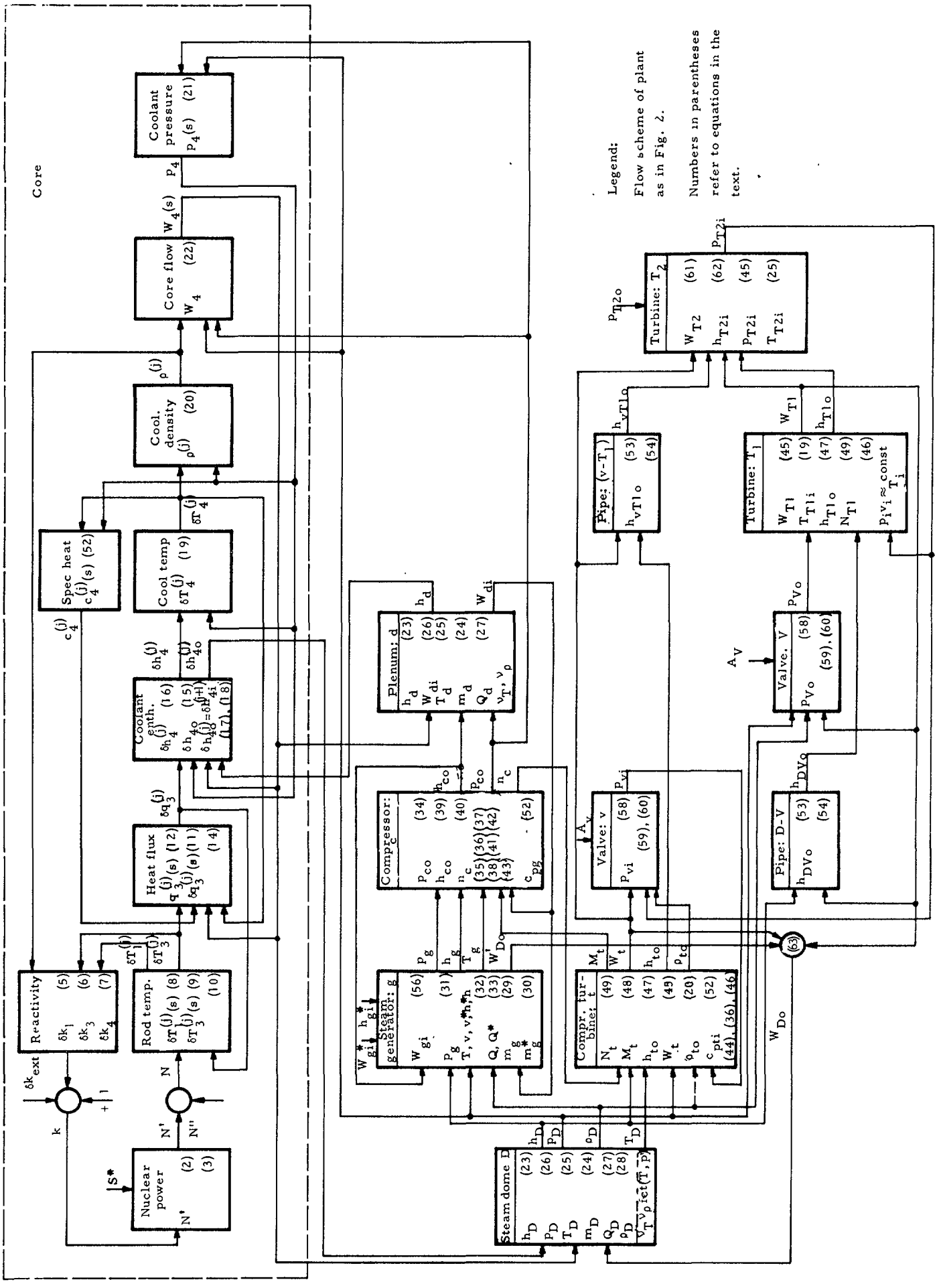


Legend:

C	condenser
c	compressor
D, d	plenum at core outlet, inlet
G	generator
g	steam generator
P	pump
r	reactor core; 1, 2, 3, 4, refer to fuel, gap, canning, coolant, respectively
T	main turbine
t	compressor drive turbine
V, v	valves

Fig. 2 Flow diagram of a steam cooled fast reactor power plant

Fig. 3 Block diagram of a dynamic model of a steam cooled fast reactor power plant



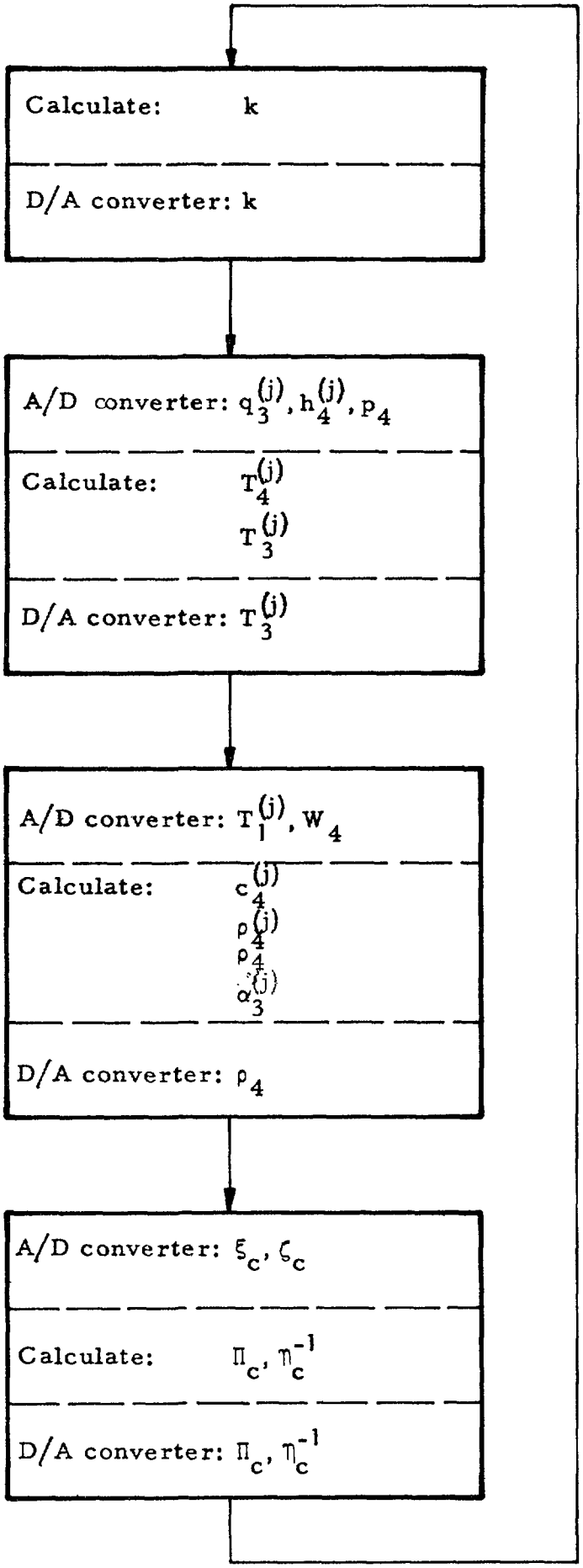


Fig. 4 Sampling cycle of the hybrid computer. The block scheme indicates the sequence of the digital computation.

LIST OF PUBLISHED AE-REPORTS

1–260. (See the back cover earlier reports.)

261. On the attenuation of neutrons and photons in a duct filled with a helical plug. By E. Aalto and Å. Krell. 1966. 24 p. Sw. cr. 8:–.

262. Design and analysis of the power control system of the fast zero energy reactor FR-0. By N. J. H. Schuch. 1966. 70 p. Sw. cr. 8:–.

263. Possible deformed states in ^{115}In and ^{117}In. By A. Bäcklin, B. Fogelberg and S. G. Malmskog. 1967. 39 p. Sw. cr. 10:–.

264. Decay of the 16.3 min. ^{182}Ta isomer. By M. Höjeberg and S. G. Malmskog. 1967. 13 p. Sw. cr. 10:–.

265. Decay properties of ^{147}Nd. By A. Bäcklin and S. G. Malmskog. 1967. 15 p. Sw. cr. 10:–.

266. The half life of the 53 keV level in ^{197}Pt. By S. G. Malmskog. 1967. 10 p. Sw. cr. 10:–.

267. Burn-up determination by high resolution gamma spectrometry: Axial and diametral scanning experiments. By R. S. Forsyth, W. H. Blackladder and N. Ronqvist. 1967. 18 p. Sw. cr. 10:–.

268. On the properties of the $s_{1/2} \longrightarrow d_{3/2}$ transition in ^{199}Au. By A. Bäcklin and S. G. Malmskog. 1967. 23 p. Sw. cr. 10:–.

269. Experimental equipment for physics studies in the Ågesta reactor. By G. Bernander, P. E. Blomberg and P.-O. Dubois. 1967. 35 p. Sw. cr. 10:–.

270. An optical model study of neutrons elastically scattered by iron, nickel, cobalt, copper, and indium in the energy region 1.5 to 7.0 MeV. By B. Holmqvist and T. Wiedling. 1967. 20 p. Sw. cr. 10:–.

271. Improvement of reactor fuel element heat transfer by surface roughness. By B. Kjellström and A. E. Larsson. 1967. 94 p. Sw. cr. 10:–.

272. Burn-up determination by high resolution gamma spectrometry: Fission product migration studies. By R. S. Forsyth, W. H. Blackadder and N. Ronqvist. 1967. 19 p. Sw. cr. 10:–.

273. Monoenergetic critical parameters and decay constants for small spheres and thin slabs. By I. Carlvik. 1967. 24 p. Sw. cr. 10:–.

274. Scattering of neutrons by an anharmonic crystal. By T. Högberg, L. Bohlin and I. Ebbsjö. 1967. 38 p. Sw. cr. 10:–.

275. The $|\Delta K| = 1$, E1 transitions in odd-A isotopes of Tb and Eu. By S. G. Malmskog, A. Marelius and S. Wahlborn. 1967. 24 p. Sw. cr. 10:–.

276. A burnout correlation for flow of boiling water in vertical rod bundles. By Kurt M. Becker. 1967. 102 p. Sw. cr. 10:–.

277. Epithermal and thermal spectrum indices in heavy water lattices. By E. K. Sokolowski and A. Jonsson. 1967. 44 p. Sw. cr. 10:–.

278. On the $d_{5/2} \leftrightarrow g_{7/2}$ transitions in odd mass Pm nuclei. By A. Bäcklin and S. G. Malmskog. 1967. 14 p. Sw. cr. 10:–.

279. Calculations of neutron flux distributions by means of integral transport methods. By I. Carlvik. 1967. 94 p. Sw. cr. 10:–.

280. On the magnetic properties of the K=1 rotational band in ^{189}Re. By S. G. Malmskog and M. Höjeberg. 1967. 18 p. Sw. cr. 10:–.

281. Collision probabilities for finite cylinders and cuboids. By I. Carlvik. 1967. 28 p. Sw. cr. 10:–.

282. Polarized elastic fast-neutron scattering of ^{12}C in the lower MeV-range. I. Experimental part. By O. Aspelund. 1967. 50 p. Sw. cr. 10:–.

283. Progress report 1966. Nuclear chemistry. 1967. 26 p. Sw. cr. 10:–.

284. Finite-geometry and polarized multiple-scattering corrections of experimental fast-neutron polarization data by means of Monte Carlo methods. By O. Aspelund and B. Gustafsson. 1967. 60 p. Sw. cr. 10:–.

285. Power disturbances close to hydrodynamic instability in natural circulation two-phase flow. By R. P. Mathisen and O. Eklind. 1967. 34 p. Sw. cr. 10:–.

286. Calculation of steam volume fraction in subcooled boiling. By S. Z. Rouhani. 1967. 26 p. Sw. cr. 10:–.

287. Absolute E1, $\Delta K = 0$ transition rates in odd-mass Pm and Eu-isotopes. By S. G. Malmskog. 1967. 33 p. Sw. cr. 10:–.

288. Irradiation effects in Fortiweld steel containing different boron isotopes. By M. Grounes. 1967. 21 p. Sw. cr. 10:

289. Measurements of the reactivity properties of the Ågesta nuclear power reactor at zero power. By G. Bernander. 1967. 43 p. Sw. cr. 10:–.

290. Determination of mercury in aqueous samples by means of neutron activation analysis with an account of flux disturbances. By D. Brune and K. Jirlow. 1967. 15 p. Sw. cr. 10:–.

291. Separtaion of ^{51}Cr by means of the Szilard-Chalmers effect from potassium chromate irradiated at low temperature. By D. Brune. 1967. 15 p. Sw. cr. 10:–.

292. Total and differential efficiencies for a circular detector viewing a circular radiator of finite thickness. By A. Lauber and B. Tollander. 1967. 45 p. Sw. cr. 10:–.

293. Absolute M1 and E2 transition probabilities in ^{233}U. By S. G. Malmskog and M. Höjeberg. 1967. 37 p. Sw. cr. 10:–.

294. Cerenkov detectors for fission product monitoring in reactor coolant water. By O. Strindehag. 1967 56 p. Sw. cr. 10:–.

295. RPC calculations for K-forbidden transitions in ^{183}W. Evidence for large inertial parameter connected with high-lying rotational bands. By S. G. Malmskog and S. Wahlborn. 1967. 25 p. Sw. cr. 10:–.

296. An investigation of trace elements in marine and lacustrine deposits by means of a neutron activation method. By O. Landström, K. Samsahl and C-G. Wenner. 1967. 40 p. Sw. cr. 10:–.

297. Natural circulation with boiling. By R. P. Mathisen. 1967. 58 p. Sw. cr. 10:–.

298. Irradiation effects at 160–240°C in some Swedish pressure vessel steels. By M. Grounes, H. P. Myers and N-E. Hannerz. 1967. 36 p. Sw. cr. 10:–.

299. The measurement of epithermal-to-thermal U-238 neutron capture rate (ρ_{28}) in Ågesta power reactor fuel. By G. Bernander. 1967. 42 p. Sw. cr. 10:–.

300. Levels and transition rates in ^{199}Au. By S. G. Malmskog, A. Bäcklin and B. Fogelberg. 1967. 48 p. Sw. cr. 10:–.

301. The present status of the half-life measuring equipment and technique at Studsvik. By S. G. Malmskog. 1967. 26 p. Sw. cr. 10:–.

302. Determination of oxygen in aluminum by means of 14 MeV neutrons with an account of flux attenuation in the sample. By D. Brune and K. Jirlow. 1967. 16 p. Sw. cr. 10:–.

303. Neutron elastic scattering cross sections of the elements Ni, Co, and Cu between 1.5 and 8.0 mev. By B. Holmqvist and T. Wiedling. 1967. 17 p. Sw. cr. 10:–.

304. A study of the energy dependence of the Th232 capture cross section in the energy region O.1 to 3.4 eV. By G. Lundgren. 1967. 25 p. Sw. cr. 10:–.

305. Studies of the reactivity effect of polythene in the fast reactor FRO. By L. I. Tirén and R. Håkansson. 1967. 25 p. Sw. cr. 10:–.

306. Final report on IFA-10, the first Swedish instrumented fuel assembly irradiated in HBWR, Norway. By J-Å. Gyllander. 1967. 35 p. Sw. cr. 10:–.

307. Solution of large systems of linear equations with quadratic or non-quadratic matrices and deconvolution of spectra. By K. Nygaard. 1967. 15 p. Sw. cr. 10:–.

308. Irradiation of superheater test fuel elements in the steam loop of the R2 reactor. By F. Ravndal. 1967. 94 p. Sw. cr. 10:–.

309. Measurement of the decay of thermal neutrons in water poisoned with the non-1/v neutron absorber cadmium. By. L. G. Larsson and E. Möller. 1967. 20 p. Sw. cr. 10:–.

310. Calculated absolute detection efficiencies of cylindrical NaI (Tl) scintillation crystals for aqueous spherical sources. By. O. Strindehag and B. Tollander. 1968. 18 p. Sw. cr. 10:–.

311. Spectroscopic study of recombination in the early afterglow of a helium plasma. By J. Stevefelt. 1968. 49 p. Sw. cr. 10:–.

312. Report on the personnel dosimetry at AB Atomenergi during 1966. By J. Carlsson and T. Wahlberg. 1968. 10 p. Sw. cr. 10:–.

313. The electron temperature of a partially ionized gas in an electric field. By F. Robben. 1968. 16 p. Sw. cr. 10:–.

314. Activation Doppler measurements on U238 and U235 in some fast reactor spectra. By L. I. Tirén and I. Gustafsson. 1968. 40 p. Sw. cr. 10:–.

315. Transient temperature distribution in a reactor core with cylindrical fuel rods and compressible coolant. By H. Vollmer. 1968. 38 p. Sw. cr. 10:–.

316. Linear dynamics model for steam cooled fast power reactors. By H. Vollmer. 1968. 40 p. Sw. cr. 10:–.

317. A low level radioactivity monitor for aqueous waste. By E. J. M. Quirk. 1968. 35 p. Sw. cr. 10:–.

318. A study of the temperature distribution in UO_2 reactor fuel elements. By I. Devold. 1968. 82 p. Sw. cr. 10:–.

319. An on-line water monitor for low level β-radioactivity measurements. By E. J. M. Quirk. 1968. 26 p. Sw. cr. 10:–.

320. Special cryostats for lithium compensated germanium detectors. By A. Lauber, B. Malmsten and B. Rosencrantz. 1968. 14 p. Sw. cr. 10:–.

321. Stability of a steam cooled fast power reactor, its transients due to moderate perturbations and accidents. By H. Vollmer. 1968. 36 p. Sw. cr. 10:–.

322. Progress report 1967. Nuclear chemistry. 1968. 30 p. Sw. cr. 10:–.

323. Noise in the measurement of light with photomultipliers. By F. Robben. 1968. 74 p. Sw. cr. 10:–.

324. Theoretical investigation of an electrogasdynamic generator. By S. Palmgren. 1968. 36 p. Sw. cr. 10:–.

325. Some comparisons of measured and predicted primary radiation levels in the Ågesta power plant. By E. Aalto, R Sandlin and Å. Krell. 1968. 44 p. Sw. cr. 10:–.

326. An investigation of an irradiated fuel pin by measurement of the production of fast neutrons in a thermal column and by pile oscillation technique. By Veine Gustavsson. 1968. 24 p. Sw. cr. 10:–.

327. Phytoplankton from Tvären, a bay of the Baltic, 1961–1963. By Torbjörn Willén. 1968. 76 p. Sw. 10:–.

328. Electronic contributions to the phonon damping in metals. By Rune Jonson. 1968. 38 p. Sw. cr. 10:–.

329. Calculation of resonance interaction effects using a rational approximation to the symmetric resonance line shape function. By H. Häggblom. 1968. 48 p. Sw. cr. 10:–.

330. Studies of the effect of heavy water in the fast reactor FR0. By L. I. Tirén, R. Håkansson and B. Karmhag. 1968. 26 p. Sw. cr. 10:–.

331. A comparison of theoretical and experimental values of the activation Doppler effect in some fast reactor spectra. By H. Häggblom and L. I. Tirén. 1968. 28 p. Sw. cr. 10:–.

332. Aspects of low temperature irradiation in neutron activation analysis. By D. Brune. 1968. 12 p. Sw. cr. 10:–.

333. Application of a betatron in photonuclear activation analysis. By D. Brune, S. Mattsson and K. Lidén. 1968. 13 p. Sw. cr. 10:–.

334. Computation of resonance-screened cross section by the Dorix-Speng system. By H. Häggblom. 1968. 34 p. Sw. cr. 10:–.

335. Solution of large systems of linear equations in the presence of errors. A constructive criticism of the least squares method. By K. Nygaard. 1968. 28 p. Sw. cr. 10:–.

336. Calculation of void volume fraction in the subcooled and quality boiling regions. By S. Z. Rouhani and E. Axelsson. 1968. 26 p. Sw. cr. 10:–.

337. Neutron elastic scattering cross sections of iron and zinc in the energy region 2.5 to 8.1 MeV. By B. Holmqvist, S. G. Johansson, A. Kiss, G. Lodin and T. Wiedling. 1968. 30 p. Sw. cr. 10:–.

338. Calibration experiments with a DISA hot-wire anemometer. By B. Kjellström and S. Hedberg. 1968. 112 p. Sw. cr. 10:–.

339. Silicon diode dosimeter for fast neutrons. By L. Svansson, P. Swedberg, C-O. Widell and M. Wik. 1968. 42 p. Sw. cr. 10:–.

340. Phase diagrams of some sodium and potassium salts in light and heavy water. By K. E. Holmberg. 1968 48 p. Sw. cr. 10:–.

341. Nonlinear dynamic model of power plants with single-phase coolant reactors. By H. Vollmer. 1968. 26 p. Sw. cr. 10:–.

List of published AES-reports (In Swedish)

1. Analysis be means of gamma spectrometry. By D. Brune. 1961. 10 p. Sw. cr. 6:–.
2. Irradiation changes and neutron atmosphere in reactor pressure vessels-some points of view. By M. Grounes. 1962. 33 p. Sw. cr. 6:–.
3. Study of the elongation limit in mild steel. By G. Östberg and R. Attermo. 1963. 17 p. Sw. cr. 6:–.
4. Technical purchasing in the reactor field. By Erik Jonson. 1963. 64 p. Sw. cr. 8:–.
5. Ågesta nuclear power station. Summary of technical data, descriptions, etc. for the reactor. By B. Lilliehöök. 1964. 336 p. Sw. cr. 15:–.
6. Atom Day 1965. Summary of lectures and discussions. By S. Sandström. 1966. 321 p. Sw. cr. 15:–.
7. Building materials containing radium considered from the radiation protection point of view. By Stig O. W. Bergström and Tor Wahlberg. 1967. 26 p. Sw. cr. 10:–.

Additional copies available from the library of AB Atomenergi, Fack, S-611 01 Nyköping, Sweden.

EOS-tryckerierna, Stockholm 1968