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Ed. by
B. Micheelsen and F. List

Risø National Laboratory, DK-4000 Roskilde, Denmark
February 1985

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DEPARTMENT OF ENERGY TECHNOLOGY
ANNUAL PROGRESS REPORT
1 January - 31 December 1984

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Abstract. The general development of the Department of Energy Technology at Risø during 1984 is presented, and the activities within the major subject fields are described in some detail. Lists of staff and publications are included.

INIS/EDB descriptors: ENVIRONMENTAL IMPACTS; FLUIDIZED-BED COMBUSTION; HEAT TRANSFER; POWER PRODUCTION; REACTOR PHYSICS; RESEARCH PROGRAMS; RESERVOIR ENGINEERING; RISOE NATIONAL LABORATORY.

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CONTENTS

1. DEVELOPMENT DURING 1984

1.1. The Department of Energy Technology

A major organizational change in the composition of the department was made in the beginning of the year, when the Section of Systems and Reliability Analysis was taken out of the department to form a risk analysis group, administratively closely connected to the Risø Energy System Analysis Group. The two groups were merged into a new Systems Analysis Department at Risø during the year. The Section of Systems and Reliability Analysis was earlier the Section of Reactor Engineering dealing with nuclear systems, nuclear criteria and rules, and reliability. The organizational change reflects a real change in subject fields, where the effort on nuclear technology is decreased, and the expertise is used on related technology.

The Thermo-hydraulics Section still worked with nuclear projects during the year, but the projects were parts of Nordic and international projects that are being terminated. The main effort of this section is now on combustion research, and projects on fluid bed combustion and flue gas measurements are being carried out, while new work on fundamental combustion research is being taken up.

The Reactor Physics Section maintains a substantial effort on nuclear reactor physics, but a diversification has been created and increased during the years also in this section. The work includes now sizeable efforts on simulators, for nuclear as well as non-nuclear plants, on models for environmental impacts of energy production systems, and on aerosol physics and chemistry.

The Reservoir Model Group maintained its efforts on oil-gas reservoir modelling during the year.

The Danish Reactor no. 1 is used for education and neutron radiography. This work was evaluated during the year with the purpose of reducing the free services offered and the resources involved.

1.2. Reactor Physics

During the past years the work of the Section of Reactor Physics has developed into new areas, the common background being the construction of computer programs to simulate physical and chemical processes.

In steady-state reactor physics a load-follow study for a BWR for the first fuel cycle using the core simulator COSMA has shown satisfactory results as to the quality of the reactor physics program system. In the study the probability of fuel failures in the first cycle was predicted. The predicted fuel failures did not agree completely with actual fuel failures but the calculations gave important information about the type of models which one has to use to predict fuel failures. Among the new developments in reactor physics methods the work on local pin power models and homogenization should be mentioned. The work has also resulted in new ideas for improvement of simple nodal theory methods.

A three-dimensional model for the research reactor DR-3 at Risø has been completed. The preliminary verification calculations have shown good results.

In process simulation the training simulator for the Barsebäck plant has been completed as originally planned. However, new modules will be developed, which will extend the area of operating conditions that can be simulated. Also a preliminary model for the turbine plant of a coal-fired power station has been completed.

The work in aerosol physics has for the main part been carried out in cooperation with the Danish utility company ELSAM and the Health Physics Department at Risø. The results have been a new version of the HAARM-S program which includes turbulent deposition of aerosols in a reactor containment, and a computer program CELEQ which predicts the chemical equilibrium speciation of elements present in the containment of a reactor during a large accident.

A program system to assess the environmental impacts from energy systems has been under development since 1982. The first phase of development is now completed. The program system contains modules for calculation of pollution dispersion via the atmosphere, deposition, chemistry of the upper soil layers, and a model for uptake in crops of different ions (nutrients, micronutrients, heavy metals). Pollutants may thus be followed from the source via the atmosphere to uptake in crops. Further work will concentrate on data collection and testing of the present program system before the models are extended and refined.

1.3. Heat Transfer and Combustion

Coal combustion and implementation of measurement techniques for important combustion parameters have been an increasing part of the work during the year.

The work within fluidized-bed combustion has been concentrated on circulating fluidized-bed combustion and experiments with sulphur dioxide removal from flue gas by adding limestone to the combustion process. Desulphurization processes have been studied by measurements performed in a 300-kW atmospheric bubbling fluidized-bed and in an electrically heated small-scale fluidized-bed.

During the year several commercial flue gas measurements have been performed at Danish power plants and in industry in Denmark and abroad.

At the end of the year 1984 the section had managed to establish equipment for measurement of important combustion parameters as temperature, pressure, flow and continuous flue gas analysis. Further, a powerful computer controlled data acquisition system has been established.

In the future equipment for measurements of basic combustion data as local velocity, temperature and gas composition will be established. As a start of this work a 3-D Doppler laser anemometer will be implemented for measurements of gas and particle velocities in flames from different types of combustion processes.

The work on nuclear two-phase flow has reached the final level of reporting during the year. There have been three fields of work: SÄK-3 and SÄK-5 are joint Nordic safety projects. SÄK-3 concerns computer modelling of small break loss-of-coolant accidents and SÄK-5 is a study of heat transfer during an accident situation. The third project was an experimental and theoretical study of rewetting and quench phenomena of electrically heated fuel rod simulators. This work was a part of the European Economic Community indirect action program.

A non-nuclear, two-phase flow project was an experimental and theoretical study of blowdown from a 2 m^3 pressure vessel. This work is in the final stage and will be finished in March 1985.

A new area of work, which naturally relies on know-how from nuclear two-phase flow, is the development of a computer model, MULTWO, for transient oil/gas two-phase flow in pipe lines. This work is initiated in cooperation with LICconsult Consulting Engineers Ltd. and Institute for Chemical Engineering of the Danish Technical University.

The temperature calibration laboratory has increased its number of calibrations during the year for both internal and external customers.

1.4 Reservoir Models

The Reservoir Group has continued the effort to increase the general knowledge in the reservoir-related fields, among other things through participation in a number of courses and meetings.

Further studies of the Danish North Sea fields have been performed with a three-dimensional black oil simulator.

A simple one-dimensional, compositional reservoir simulator was developed for Enhanced Oil Recovery screening purposes, while the development of a three-dimensional compositional simulator is well under way. In this connection a number of alternative mathematical and numerical methods have been investigated.

A model simulating burial history, temperature, and maturation of sedimentary basins has been developed for source rock studies.

The participation in the Danish project concerning heat storage in an aquifer has continued.

1.5 Danish Reactor No. 1

The reactor has been used mainly for training purposes and as a source for neutron radiography.

During the year approximately 40 students from various universities have carried out experiments at the reactor over periods varying from 2-8 days whilst 25 high school classes have carried out experiments at the reactor, each class for one day.

After a request from the management group an investigation has been carried out as to how the reactor can be operated more economically. As a result a paper entitled "The Future of DR-1" has been presented. The intention of the study was that the number of reactor courses are to be maintained whilst work with neutron radiography and image processing are to be reduced or transferred to another department.

The possibility of transferring neutron radiography work to the DR-3 reactor was considered. A neutron collimator has been installed outside the reactor shielding, but unfortunately the internal neutron scatterer is not homogeneous so only a minor improvement compared with DR-1 has been obtained in image quality so far.

2. ACTIVITIES OF THE DEPARTMENT

2.1. Core-simulator

The development of a system for calculating fuel failure probabilities based on information about the reactor design and operation began in 1979 at Risø. The system was named "COSMA" and it was composed of the following parts:

1) Microscopic multi-group cross-section generation.
   (Code: "CCC").

2) Fuel assembly calculation.
   (Code: "CDB").

3) Overall neutronic/hydraulic core calculation.
   (Code: "NOTAM").

4) Local pin power prediction.
   (Code: "LOCAL/MODULATION").

5) Calculations of fuel failure probabilities.
   (Code: "FRP").

The core-simulator system has now been tested against a full size BWR for the first fuel cycle. The following calculations were performed:

Based on calculated individual fuel pin power histories for the first cycle, and the design and material data, the fuel failure probability code FRP calculates the fuel state (distribution of temperatures, strain, stress, etc. in pellets and cladding) as a function of time, as well as the failure probabilities.

In order to generate the individual pin power histories that are to be used in the FRP-code the code LOCAL/MODULATION was developed. A short description is given below of the model in this code.

Let us first summarize the information available for the local pin power determination.

A. As a result of our fuel assembly calculations by CDB we know the power distribution in each assembly-type for discrete values of average void, local void and burn-up, assuming zero net current boundary conditions. (However, this assumption is invalid if we are considering assemblies placed in their natural environment in the core).

B. We know the average nodal powers, together with the average accumulated void and the local void at each burn-up step from the global coarse-mesh calculation (made by NOTAM).

The Modulation Method applied in this investigation is illustrated in Fig. 1.

The modulated pin powers are defined as:

$$p^{HET}(x,y) = p^{*HET}(x,y) \cdot p^{HOM}(x,y)$$

where

$p^{HET}(x,y)$ are the pin powers to be calculated

$p^{*HET}(x,y)$ are the predicted pin power distributions from the fuel assembly calculation (by CDB).

$p^{HOM}(x,y)$ are the global "homogeneous" pin power distributions inside the assembly normalized to unity.

The global "homogeneous" pin powers are calculated by assuming the average nodal powers to be in the centre points of the node. The "homogeneous" pin powers are then obtained from the node to be investigated and its eight nearest neighbours in the same horizontal plane by applying an interpolation procedure between these nine values.

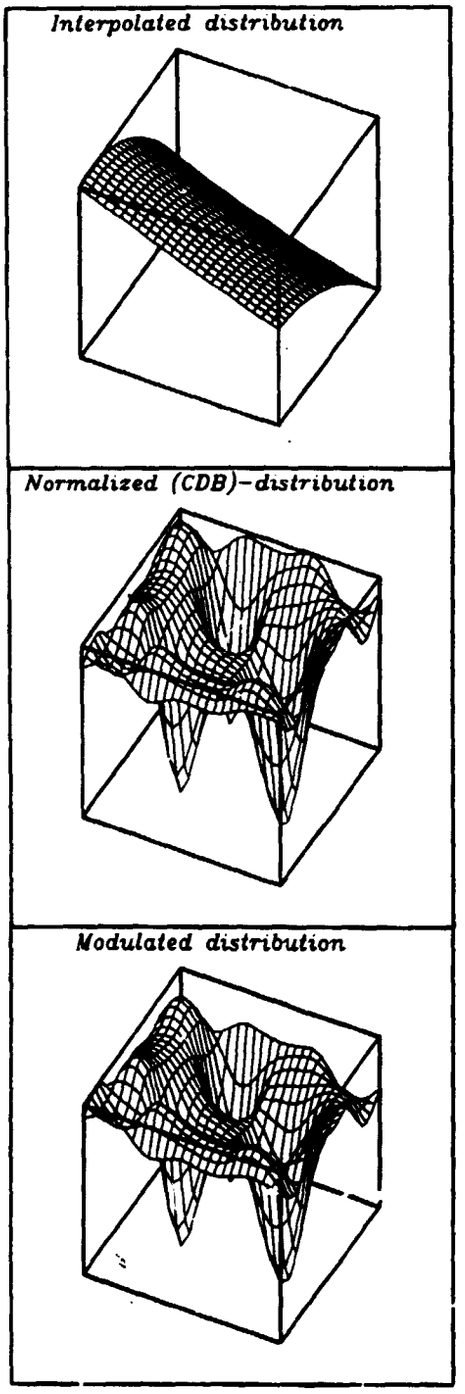
Results for the BWR test case

The 3-D calculation gave fairly good results (see Fig. 2) compared with measurements. The modulation method has been used to generate the pin powers for all the fuel pins in the reactor in 24 axial levels. The FRP-code has then been used for all the fuel pins. The number of failures predicted compared with measurements can be seen in Fig. 3, which gives a very condensed presentation of the results. A more detailed study of the results of the COSMA-system leads to the following conclusions:

1) The 3-D model should be reasonably accurate,

2) the fuel reliability prediction model must be used for each of the pins in the reactor, and

3) therefore, a good local pin power model should be used.



$p^{HOM}(x,y)$:

The interpolated "homogeneous" pin power distribution inside the assembly

$p^{+HET}(x,y)$:

The predicted heterogeneous pin powers applying the Normalization Method.

$p^{HET}(x,y) = p^{+HET}(x,y) \cdot p^{HOM}(x,y)$

The modulated pin powers.

Fig. 1. Illustration of the modulation scheme.

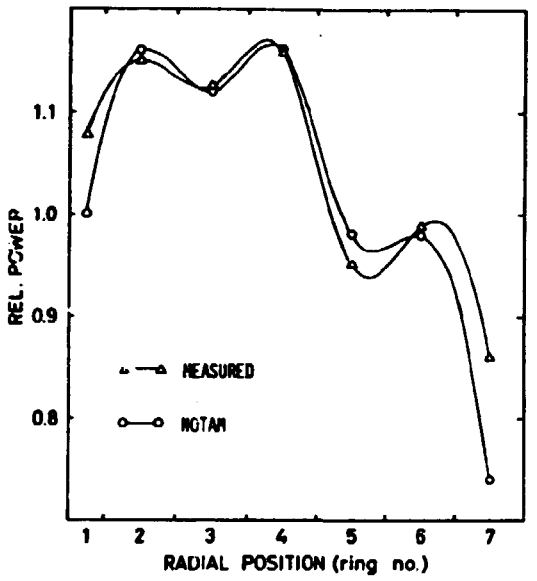


Fig. 2. Comparison of NOTAM and measured radial power distribution.

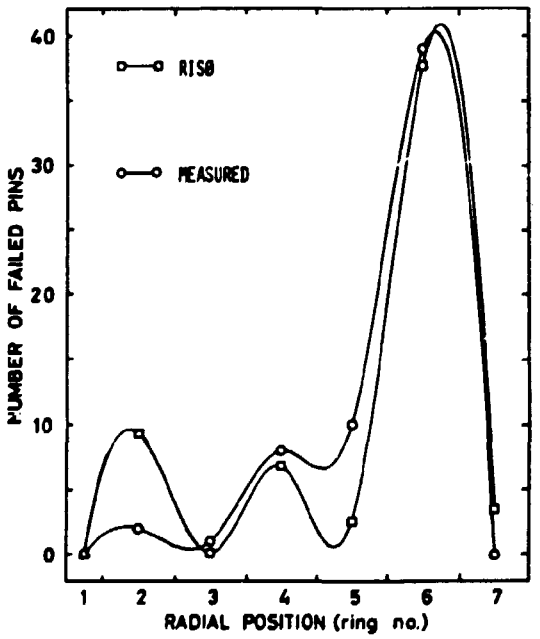


Fig. 3. The predicted and measured failures in seven radial rings.

2.2. A BWR Power Plant Simulator for Barsebäck

The Power Company Sydkraft AB in Malmö, together with the Technical University at Lund, and Risø have developed a simulator for a power plant unit at Barsebäck. The first phase of the work was finished and the simulator taken into use late in 1984.

The Barsebäck simulator is made as a tool for educating both operators and engineers with the emphasis on giving a better understanding of the dynamics of both the total plant and the separate units. The calculations of the simulator and the display of results are based upon a general purpose computer, a VAX 750, equipped with four multicolour display screens, and the operation of the simulator not in real time.

Transients caused by pertubations which rarely occur in the plant will be calculated and results stored on disk files. Later on one can easily set up curves on the colour screens and study the plant behaviour with help of flow diagrams for the plant. Four screens are available and each screen can display several variables. Examples of transients calculated at Risø's computer are shown in Figs. 4 and 5. The transients are calculated in advance as the computing time is about 5-10 times real time. Normally the operator may not intervene, but for special cases his function may be simulated as the integration process can be interrupted, parameters changed and the integration continued.

The simulator uses the SIMNON system developed at the Lund Technical University; it takes care of all administration, integration of equations, and logging and display functions. The process is modelled by 7 modules developed at Risø. The modules represent the reactor, the steam line, the turbine system with feedwater preheaters, three main control systems and a limit control system. As an example, the process diagram for the turbine system is shown in Fig. 6. The modules are developed for the normal power range but can be used down to the residual heat level by reactor scram and turbine trip.

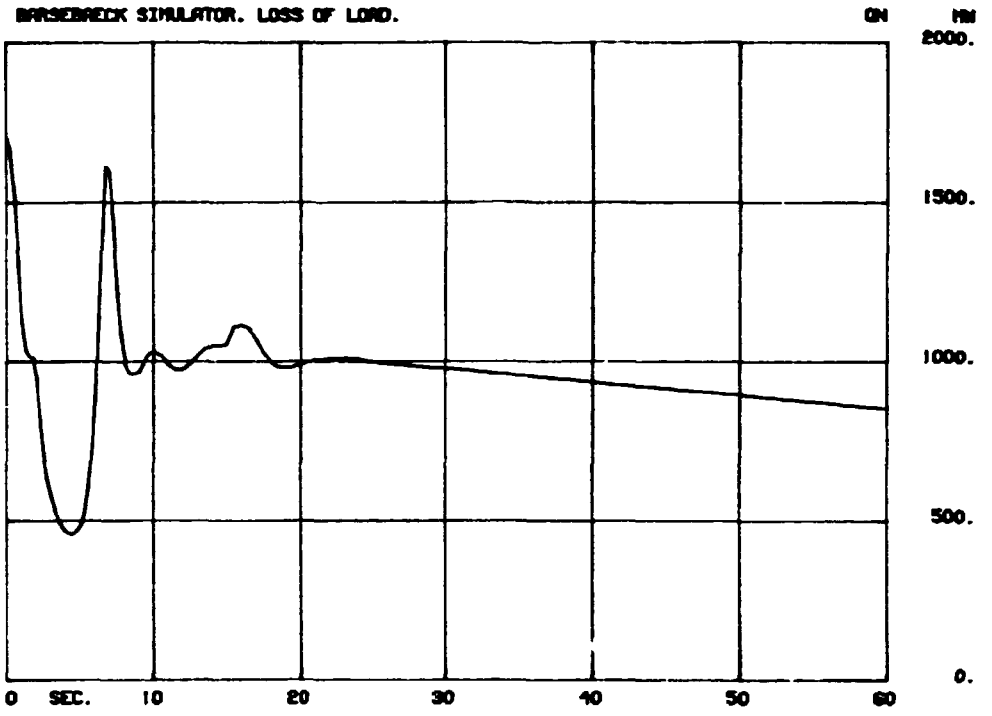


Fig. 4. Reactor power at loss af load.

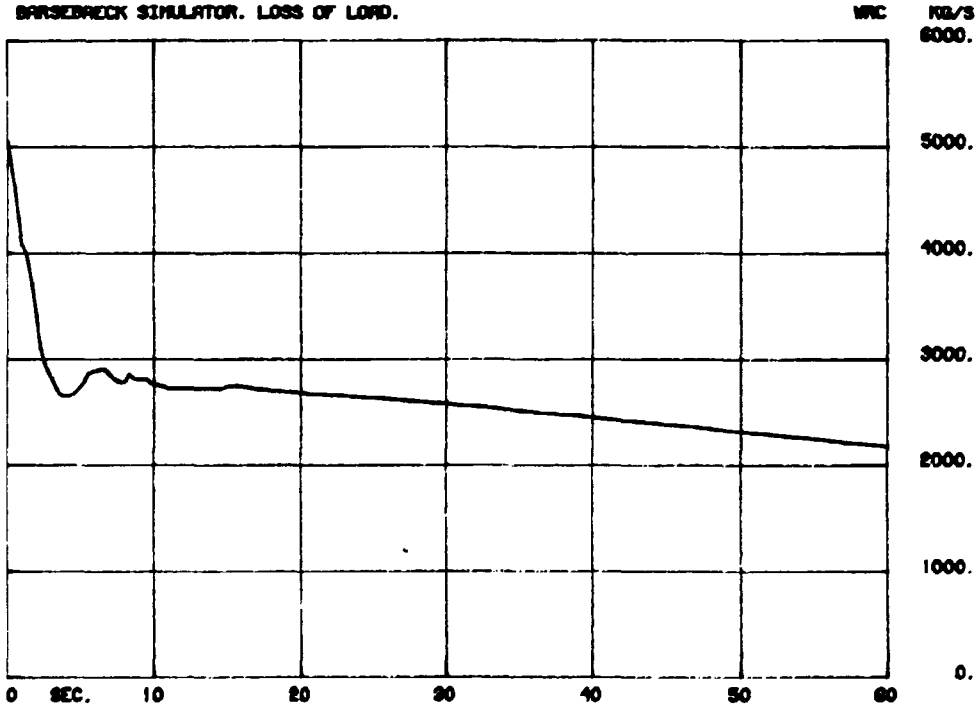


Fig. 5. Reactor coolant flow at loss of load.

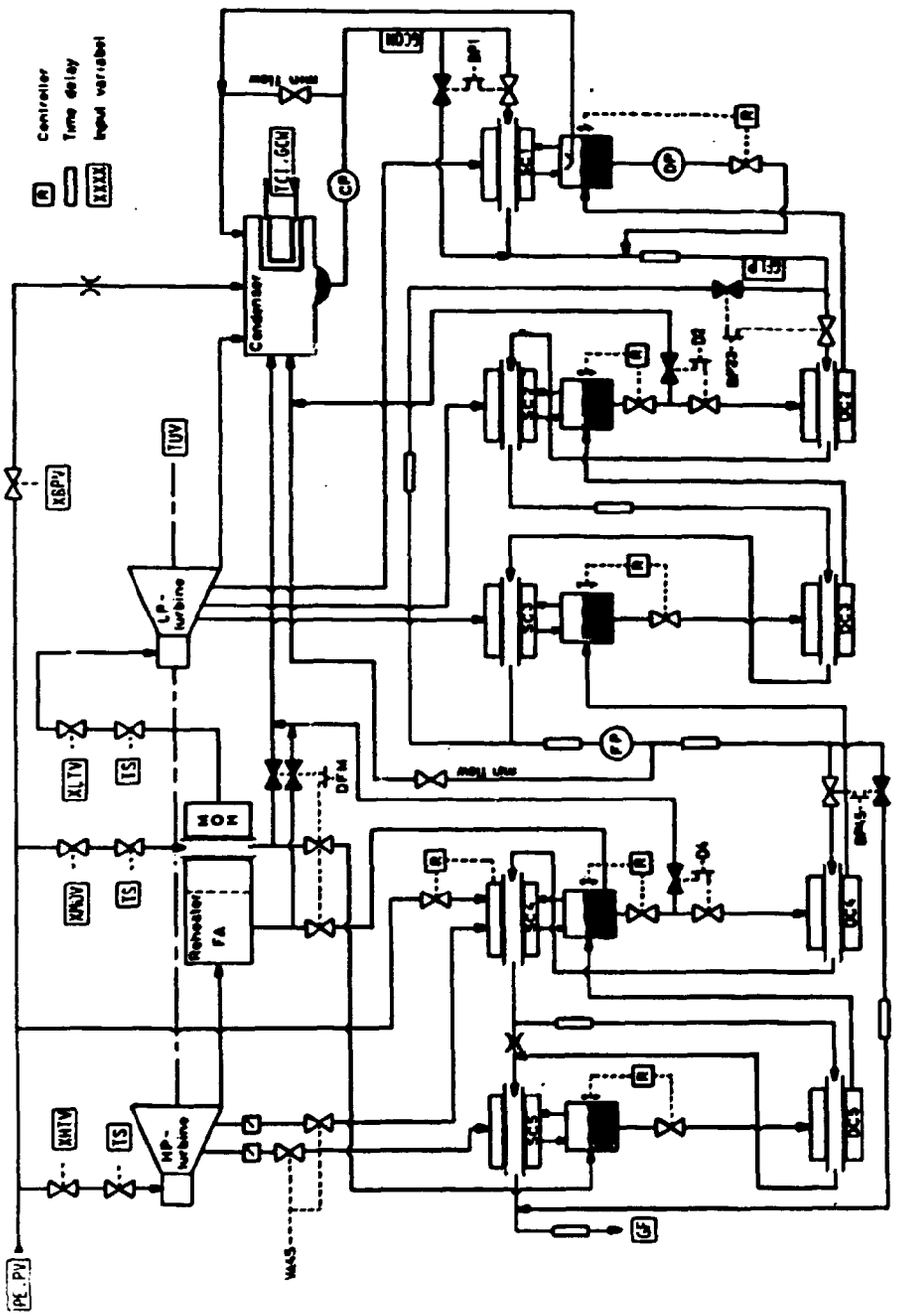


Fig. 6. Process diagram for the turbine system.

2.3. Three-dimensional Model of DR-3

The development of a 3-dimensional model of the Danish research reactor DR-3 has now been completed.

The model called DR-3/SIM calculates detailed flux distributions and burnup distributions. Also the flux in the different irradiation test facility tubes in the reflector is calculated.

Great attention has been devoted to the treatment of the "signal arm"-type coarse control rods in the reactor. It has resulted in a representation where the cross section of the control rods is added to that of the adjacent nodes. The cross sections of the control rods are given as second-order polynomials as functions of the angular position of the "signal arms".

Core-follow calculations of the actual operation of DR-3 are now being made routinely. Verification of the model by comparison with measured flux distributions is carried out together with the use of the model.

DR3/SIM has also been applied for studies of new fuel element designs as well as design of irradiation facilities in the reflector of the reactor.

The thermal flux at a horizontal plane in the center of the reactor is shown in Fig. 7. Figure 8 shows the thermal flux at the same plane but a different control arm angle. Figure 9 finally shows the corresponding average axial flux-distribution.

All three figures reflect the influence of the control arm positions upon the flux distribution.

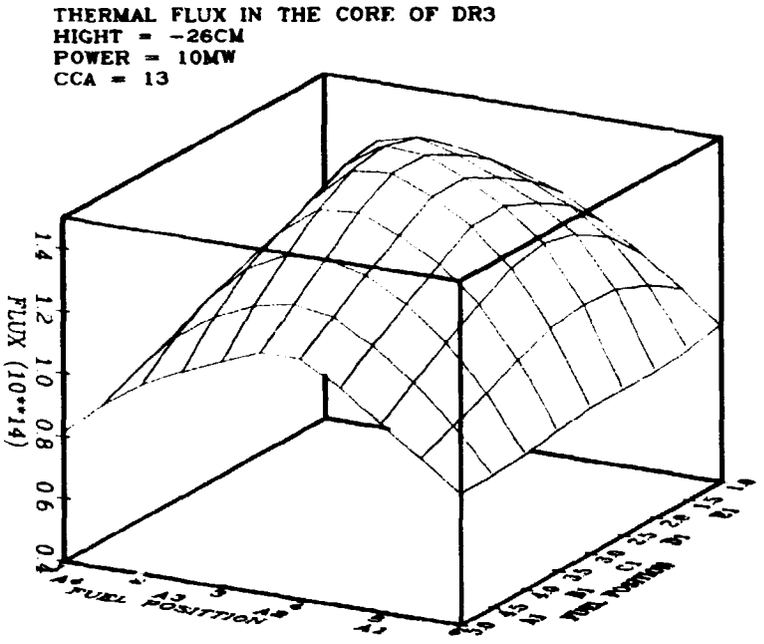


Fig. 7. Thermal flux in a horizontal plane in the center of DR-3 at a control arm angle of 13 degrees.

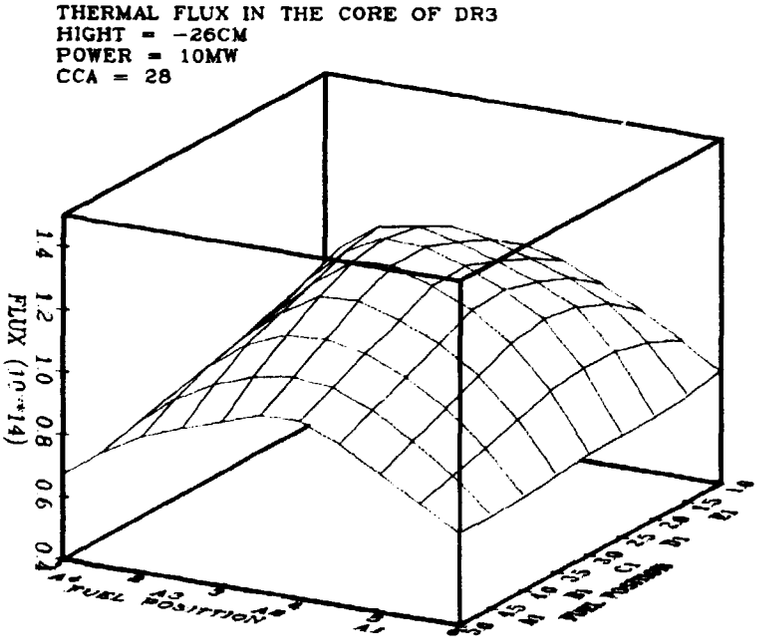


Fig. 8. Thermal flux in a horizontal plane in the center of DR-3 at a control arm angle of 28 degrees.

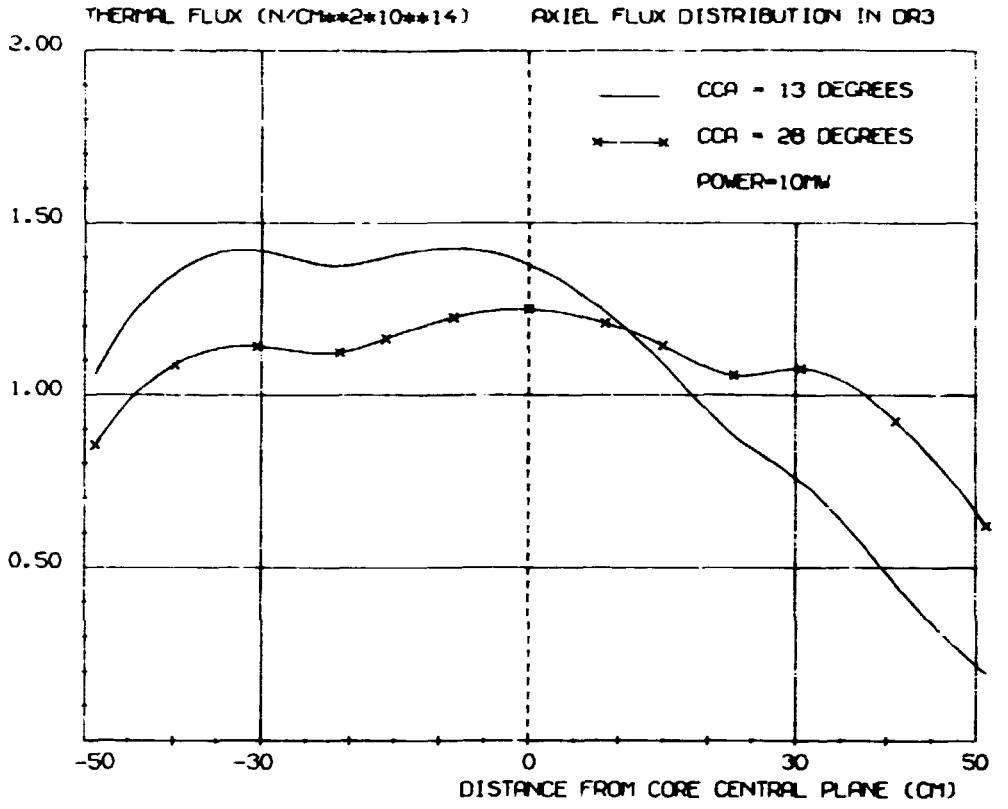


Fig. 9. Thermal flux in axial direction in DR-3 at control arm angles of 13 and 28 degrees.

2.4. Code for the Calculation of Chemical Equilibria

With the purpose of facilitating the description of the nature and amount of chemical species created during a LOCA resulting in fuel failure in a nuclear reactor, a computer code, CELEQ, has been developed. It performs a thermodynamic analysis on a specified system to determine the most stable species as a function of temperature, pressure and composition. The analysis gives a fairly detailed description of the system under the assumption that equilibrium is obtained. With the CELEQ code it is possible to perform a sequence of calculations both in time and in different compartments.

For each step the code will require information about temperature, pressure and the elemental abundances both of the fission products and of hydrogen, oxygen, and nitrogen. The user must also specify compounds of interest and the appropriate thermodynamic data. There will be an option for specifying whether the compound is a solid, liquid, or gas.
The central part of the CELEQ code is an equlibrium calculator developed by Smith (1982). The algorithm is based on a non-stoichiometric formulation of the chemical equilibrium problem and the conservation of the elemental abundances.

In its present version the code is able to handle systems of up to 100 chemical compounds composed of up to 15 elements in the temperature range 100 - 2500 K. So far the code has been tested and found to work on gaseous systems.

The development of CELEQ was a contract assignment from the utility group ELSAM.

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SMITH, W.R. and MISSEN, R.W. (1982). Chemical Reaction Equilibrium Analysis: Theory and Algorithms', J. Wiley & Sons.

2.5. Aerosol Physics

In collaboration with the Danish utility group ELSAM a project has been carried out with the purpose of introducing a model for turbulent deposition of aerosols in the code HAARM-S (Häggblom,1983). This code is an LWR version of the widely used LMFBR code, HAARM-3 (Gieseke, 1978). Turbulent deposition has not so far been regarded as an important mechanism for the removal of aerosols from containment atmospheres following a reactor melt-down. But we found it interesting to see if some of the differences between calculated and experimental results could be explained by mean of turbulent deposition.

The new mechanism is introduced in the code in a way much similar to the treatment of gravitational settling. The "removal rate", i.e. the rate of removal of aerosols from the atmosphere by turbulent deposition can be written as

$$R(x) = (R\varepsilon_T) \cdot f(G,A,P)$$

where x is the particle volume; f is a function of geometry of the container (G), the properties of the atmosphere (A), and the properties of the particles (P). The term ε_T is a measure for the dissipation of the turbulent energy. R is the characteristic eddy radius.

Calculations were performed with the modified code in order to compare the results with experimental results from the NSPP tests at Oak Ridge (Adams, 1979). As can be seen from Fig. 10 it is possible to obtain a good agreement with the measurement for the masses deposited on walls and floor, respectively. The results for $(R\varepsilon_T) = 0$, corresponding to a neglect of the turbulent diffusion, show a very large deviation from the measurements, and even by varying other parameters it is not possible to obtain agreement.

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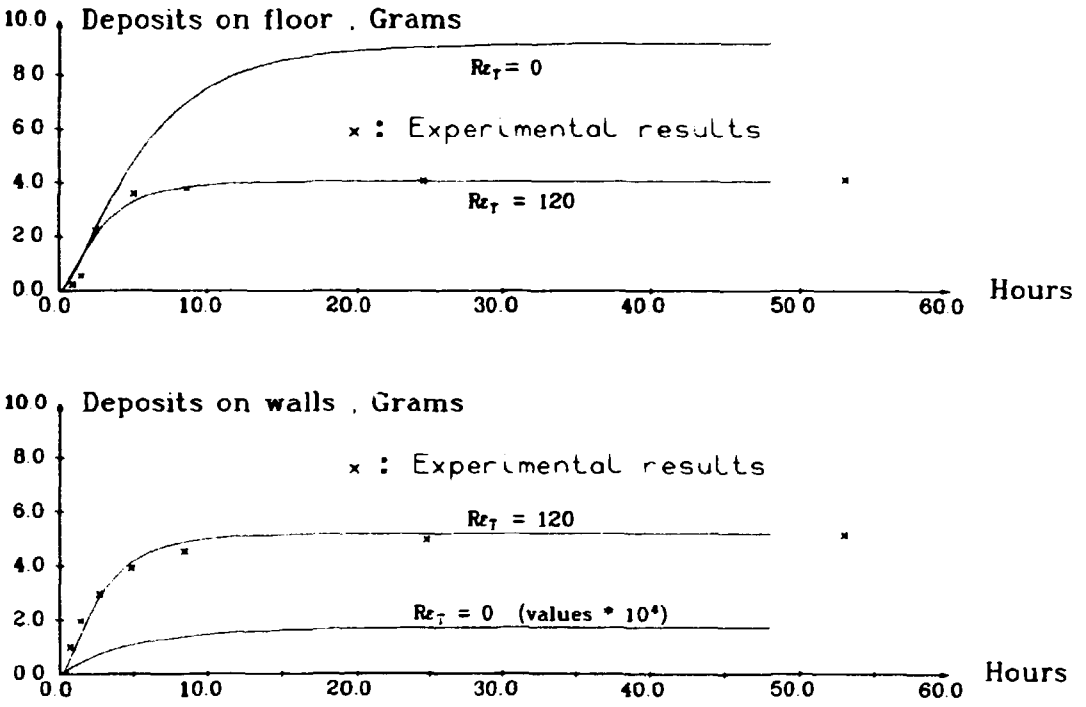

Fig. 10. Comparison of code predictions with experimental results

2.6. Model for the Environmental Impacts from Energy Production

The ECCES program system is designed to predict environmental impacts from a given energy production scenario in a given geographical area.

Presently ECCES can follow transport and transformation of selected airborne pollutants (Cd, SO_2, NO_x) from sources via dispersion in the atmosphere and deposition on the ground to uptake in selected crops. Thus ECCES system contains submodels for dispersion and deposition, soil chemistry, and uptake of ions in crops.

The model for atmospheric dispersion is based on a plume model (a modification of the Gauss model). Dispersion and deposition

are calculated for average meteorological conditions, that is, for atmospheric stability, wind direction and precipitation average values for longer periods (typically one year) are used. Deposition of a specific pollutant is characterized by a deposition velocity.

The soil-chemistry model describes the changes of pH and the concentrations of ions in different soil systems. This part of the model describes the interaction of rainfall, chemistry, and other inputs, with the soil chemistry processes. Equilibrium between ions in solution and adsorbed ions is the principal assumption of the model. The model works with anion adsorption of SO_4^{--} described as a pH-dependent Langmuir equation. The cation-exchange capacity is described as a permanent (CECP) and variable (CECV) exchange capacity. CECP is related to the electrical charges on clay particles and is largely dependent on the clay content. CECV is related to the hydrated oxides of aluminium, iron and magnese and organic substances; CECV is described as a function of pH.

Crops growing on a soil will influence the soil chemistry by uptake of water, nutrients, micronutrients and trace metals. The crop model included in the ECCES system has been set up to calculate the chemical effects on the soil upon which the plant grows and the amount of trace elements taken up by the plant. The uptake of nutrients and trace elements via the root system is assumed to be proportional to the uptake of water multiplied by concentration of the ions in the soil water. The proportionality constant may be different for different crops and different ions. When ions are taken out of the soil system by plants, electroneutrality is obtained by adding or subtracting H^+.

Examples of calculations from the ECCES-model is shown in the folowing figures:

Fig. 11 shows the pH-development in an artificial 4 layer test soil without crops, in a period of 20 years. The pH in rain was 4.9 and the start concentration in the soil water was 7.0. The

depth of the 4 soil layers was 20, 30, 50 and 100 cm with a permanent and variable exchange capacity at 10 and 1 meqV/100 g. The figure shows a characteristic decline in pH during the simulated years with a faster decline in the upper soil layer.

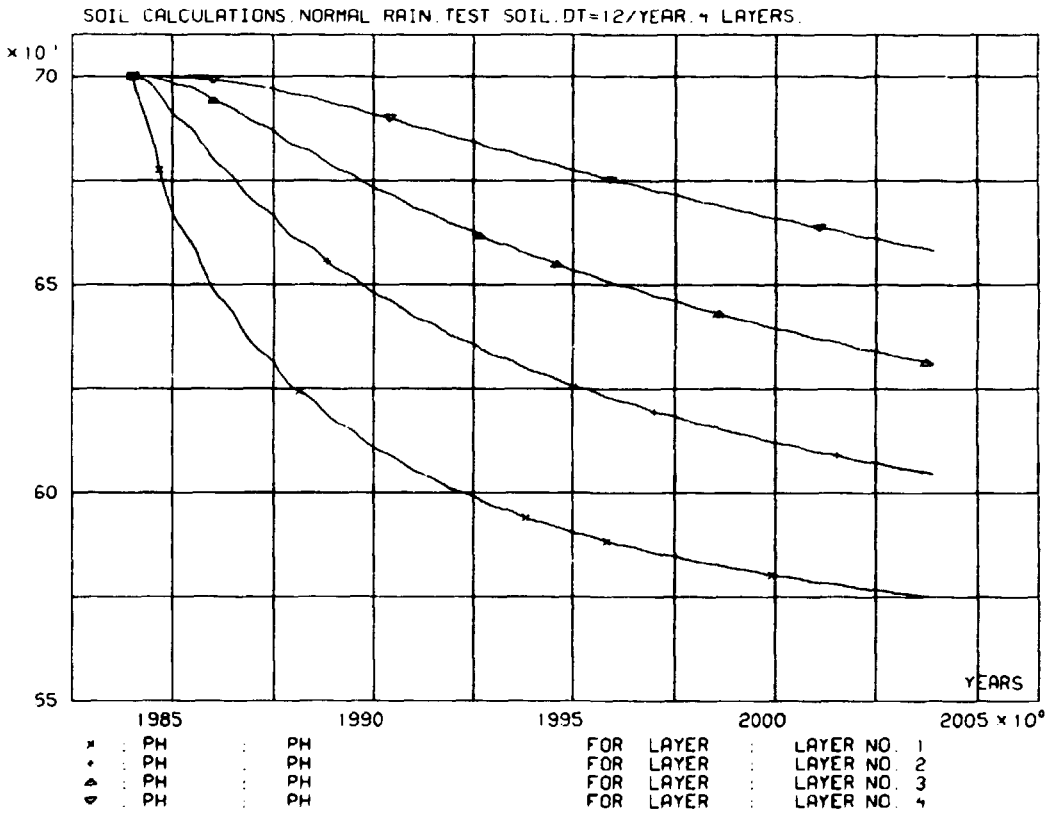

Fig. 11. PH-development in an artificial soil system.

Figure 12 is an artificial example that shows the pH in the soil water and the uptake of Cd in barley from a clay soil exposed to rain with a Cd concentration of $1.3 \cdot 10^{-9}$ Mol/l for a period of 30 years. Two cases have been run. One with a rather acid rain (pH = 4) and one in which the rain is in equilibrium with CO_2 in the atmosphere (pH = 5.6). To start the calculation a Cd^{++} concentration of $7.5 \cdot 10^{-9}$ Mol/l and pH of 7 were assumed in the soil water. It is seen that the low pH gives a higher uptake of Cd^{++}.

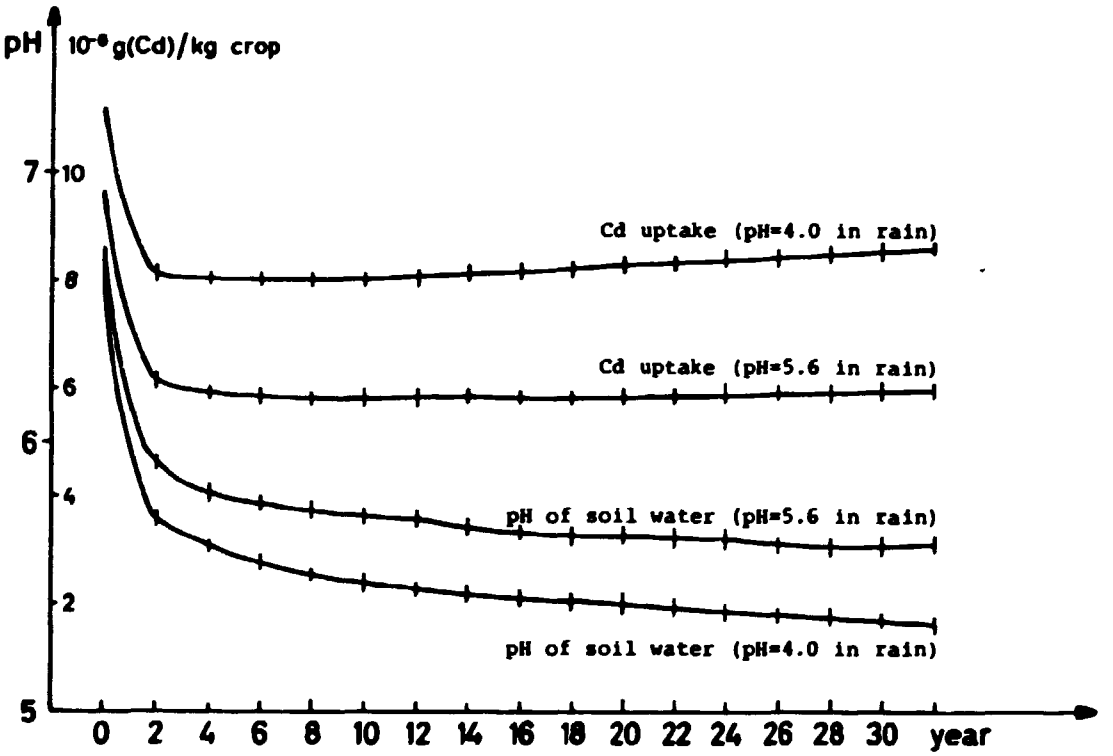

Fig. 12. PH in soil water and Cd concentration in crops for a period of 30 years (see text).

2.7. SÄK-3, Assessment of Codes for Small Break LOCA's.

The SÄK-3 project aims at recommending one or more computer codes for an analysis of Small Break LOCA's (of the Three Mile Island type).
The project, which runs over the period primo 1981 - medio 1985, is performed in cooperation with the Nordic institutes: Technical Research Centre of Finland, Studsvik Energiteknik AB, Sweden, and Institute for Energy Technology, Norway.
It is partly funded by the Nordic Liaison Committee for Atomic Energy (NKA).

The SÄK-3 project consists of theoretical and practical studies of a number of promising LOCA analysis computer codes: the two American systems codes TRAC-PF1 and RELAP5 and the Finnish small break code SMABRE. The practical study consists of comparative calculations of 5 LOCA experiments:

1. LOFT L3-6 2.5% cold leg break, PWR, pumps running
2. LOFT L3-5 2.5% cold leg break, PWR, pumps stopped
3. LOBI SD-SL-03 0.4% cold leg break, PWR, LOBI mod. 1
4. FIX-II-3031 48.0% recirculation line break, BWR
5. LOBI ISP-18 1.0% cold leg break, PWR, LOBI mod.2

In 1984 the calculations of the LOBI SD-SL-03 and the FIX-II experiment were carried out, analyzed and reported, (the LOFT calculations were completed earlier in the project). Furthermore, preparations for the "blind calculations" of the LOBI ISP18 experiment to be done in 1985 were made. Some representative results of the LOBI SD-SL-03 calculations are shown in Fig. 13 and 14.

Finally, a draft final report for the SÄK-3 project, excluding the ISP18-calculations, were prepared.
The findings obtained so far in the SÄK-3 project, as expressed in the draft final report, are that the codes studied are able to predict the over-all system behaviour (system pressure and temperature) rather well. For small break LOCA's the SMABRE

code, although much more simplified and faster than the two large systems codes, performs nearly as well as these.

However, in cases where extensive phase separation occurs, as with stopped main calculation pumps, all of the codes fail to predict the steam/water distribution in the system properly. It seems that in order to remove this defect, so that the codes can be used for reliable small break LOCA analysis, adequate models for stratified flow have to be implemented into the codes.

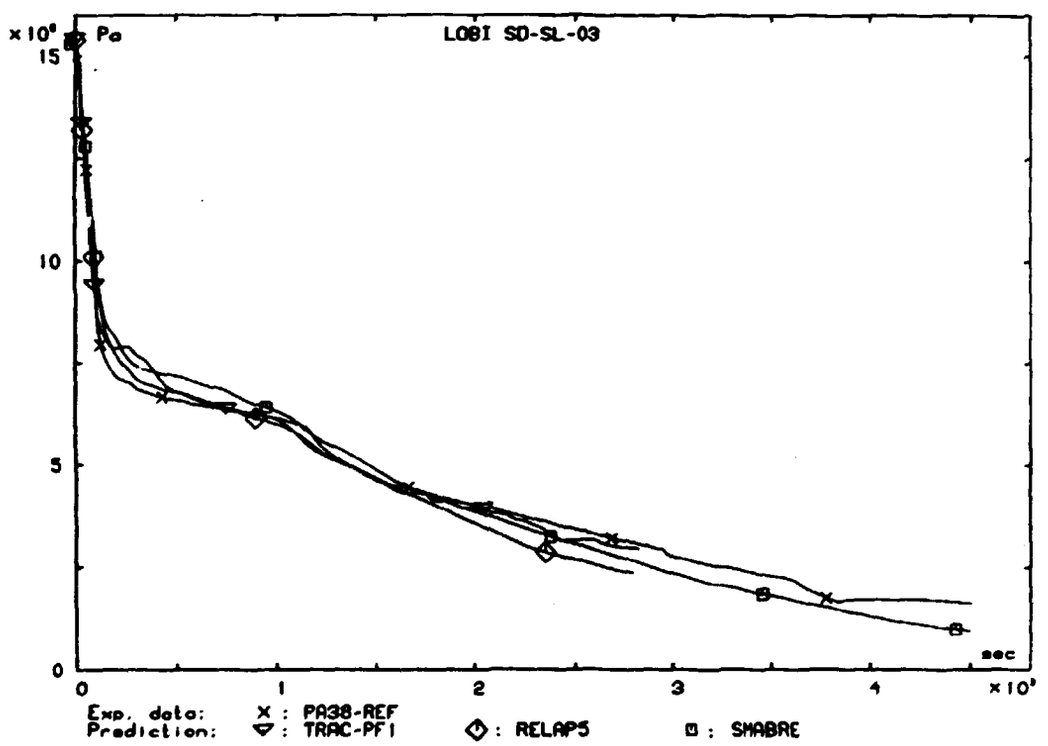

Fig. 13. Comparison of calculated and measured values of upper plenum pressure. The agreement is satisfactory.

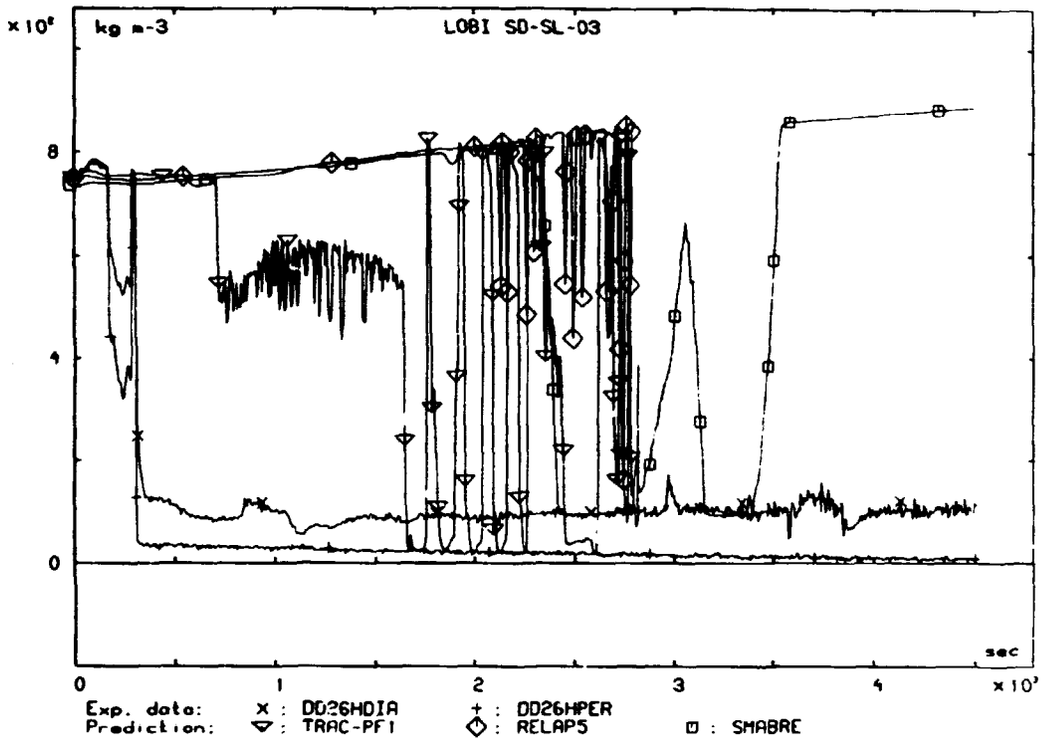

Fig. 14. Comparison of calculated and measured values of mixture fluid density in broken loop cold leg ar reactor inlet. The computer codes can not predict the liquid content correctly.

2.8. SÄK-5, Heat Transfer Correlations

Like SÄK-3, the SÄK-5 project is a Nordic reactor safety project under the auspices of the NKA. The objective of SÄK-5 is to provide a set of reliable heat transfer correlations, i.e. to contribute to the determination of the true wall temperature history of the fuel rod during a postulated accident.

Because of difficulties in making an assessment of different critical heat flux (CHF) correlations using the large thermohydraulic system program like TRAC and RELAP5, a separate examination of this issue has been made. The assessment has been performed as a separate part of the SÄK-5 project and was conducted at the Royal Institute of Technology in Stockholm. The

assessment was limited to four different CHF-correlations and was based on six full scale steady-state rod bundle experiments. The correlations included in the assessment were: Barnett, Becker, Biasi and CISE-4. The Biasi and CISE-4 correlations were originally developed for round tubes and the performance in rod bundle geometries could therefore be questionable. However, as they are utilized in several of the commonly used transient computer programs e.g. TRAC(PF1) and RELAP5(MOD1) it was decided to include also those correlations in the assessment.

The conclusions from this examination is important, as the results clearly indicate that Biasi and CISE-4 correlations do not predict the CHF conditions in large full-scale rod bundles. The correlations yield non-conservative results and their use in computer programmes like TRAC and RELAP should be avoided. The Barnett correlation is valid only at 7 MPa pressure, so the Becker rod bundle CHF correlation is recommended within the following parameter ranges:

Pressure	3.0 - 9.0 MPa
Mass flux	400 - 3000 kg/m^3 sec
Heat flux	0.5 - 3.0 MW/m^2

2.9. Study of Rewetting and Quench Phenomena

An experimental programme was performed with the purpose of investigating the behaviour of electrically heated fuel pin simulators during reflooding (from bottom) with special emphasis given to the pin composition. The experiment has included and CISE-4. The Biasi and CISE-4 correlations were originally developed for round tubes and the performance in rod bundle directly heated pins, conventionally indirectly heated pins, and advanced indirectly heated pins containing uranium dioxide as filler material. The three types of simulators are shown in Fig. 15 together with a real fuel rod.

The fuel pin simulators were tested under the same conditions in the same test rig in an annular geometry with only one pin at a time.

The test parameters were:

Initial pin temperature:	600, 700 and 800 °C
Coolant inlet temperature:	20 - 95 °C
Coolant inlet velocity:	1 - 10 cm/s
System pressure:	1 - 10 bar
Heated length:	4 m

Figure 16 shows the test rig mounted in the pressure vessel to be used at tests at elevated pressure. A typical experimental result is shown in Fig. 17. Here the quench front positions and collapsed liquid level have been plotted versus time. The experimental programme was started early in 1981 and was completed in the autumn 1984. The experimental results have been succesfully compared with calculations using the NORCOOL-II computer code.

NORCOOL-II is a best estimate, transient, thermohydraulic computer code with 3-fluid, 1-D hydraulics and 2-D representation of "Heat Components" (i.e. pipe walls, fuel rods etc.). The 3-fluid hydraulics allows for mechanical and thermal non= equilibrium between the three fluids (1): liquid film or continous liquid, (2) droplets, and (3) gas. The three fluids are represented by separate volume fractions, temperatures, velocities and a pressure common to all three fluids. Each of these fluids is described by separate continuity, momentum- and energy equations.

The 4-m long annulus was divided in 13 calculational cells with max. cell length 0.5 m for the hydraulic calculation. For heat conduction calculations in rod and shroud etc. fine mesh nodes down to 1 mm were used.

An example of the agreement between calculated and experimental results are shown in Figs. 18 and 19, a low-power, low-flooding rate, 1 bar experiment with the advanced rod. As seen the agreement in the progression of the quench front is fine while the calculated results show some overprediction of the wall cooling by steam with droplets above the quench front.

The entire set of calculations shows that NORCOOL-II predicts the effects of increased rod power, increased flooding rate and elevated pressure qualitatively, and mostly also quantitatively, correct for both rod types. However, discrepancies in comparison with the experimental results are seen due to inadequate modelling of flow regime effects and gap heat transfer and due to the lack of a rod-to-shroud radiation model.

However, because quenching of simple and advanced fuel rod simulators behave qualitatively in the same way it is believed that by means of a computer model like NORCOOL-II, experience regarding quenching gained from simple fuel simulators may be transferred to real power reactor fuel rods.

The programme was a part of the Commission of the European Communities "Indirect Action Programme on the Safety of Thermal Water Reactors".

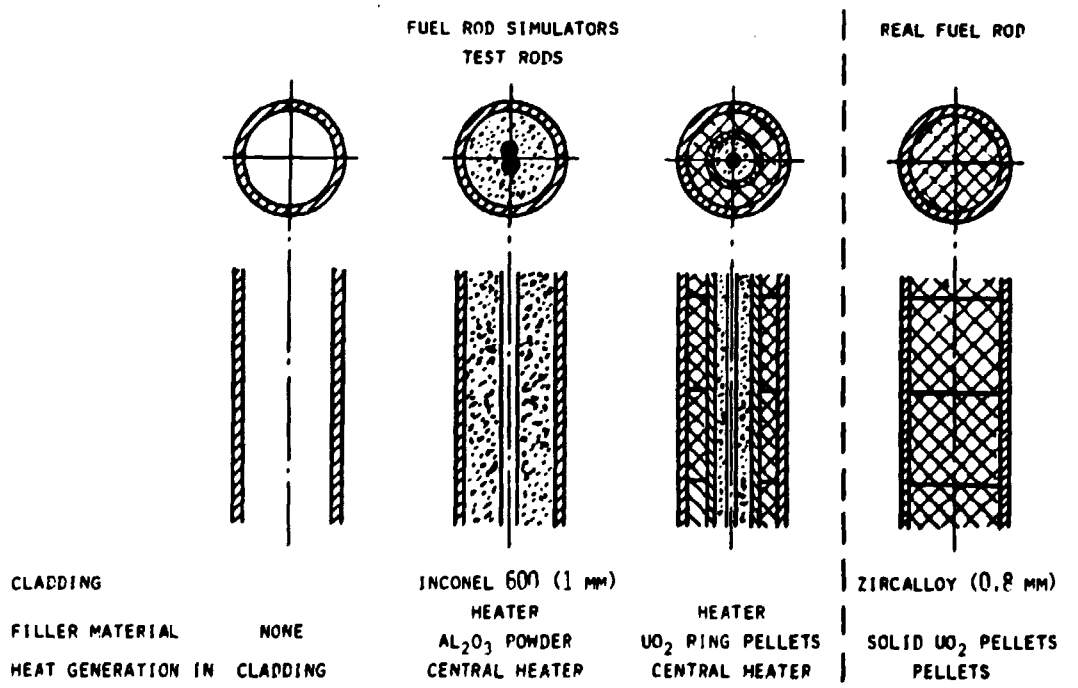

Fig. 15. Comparison between fuel rod simulators and real fuel rod.

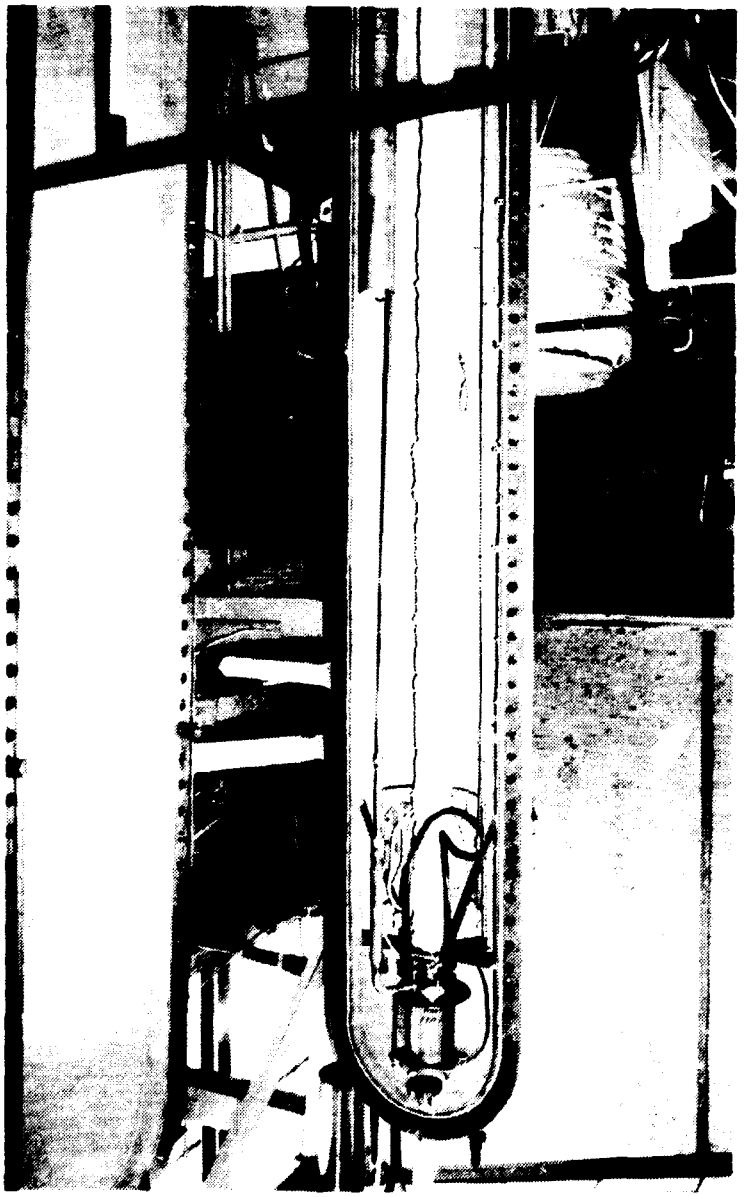

Fig. 16. Test rig in pressure vessel

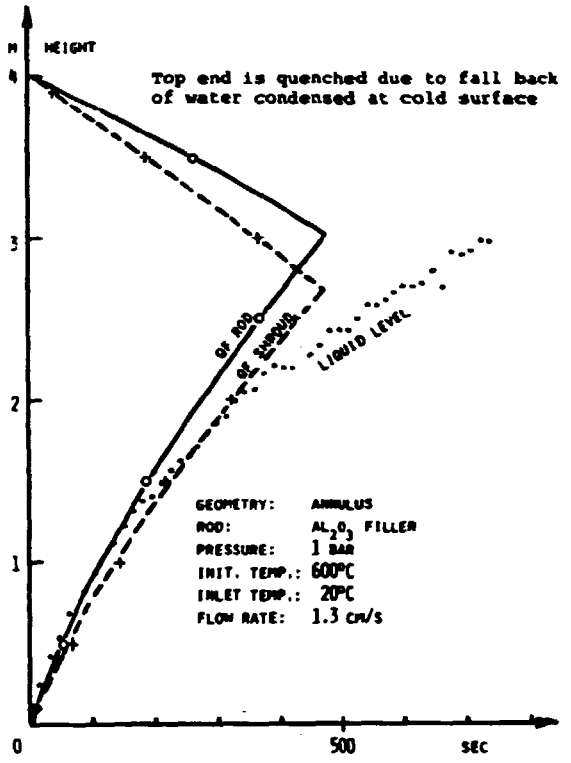

Fig. 17. Collapsed liquid level and quench fronts experimental results.

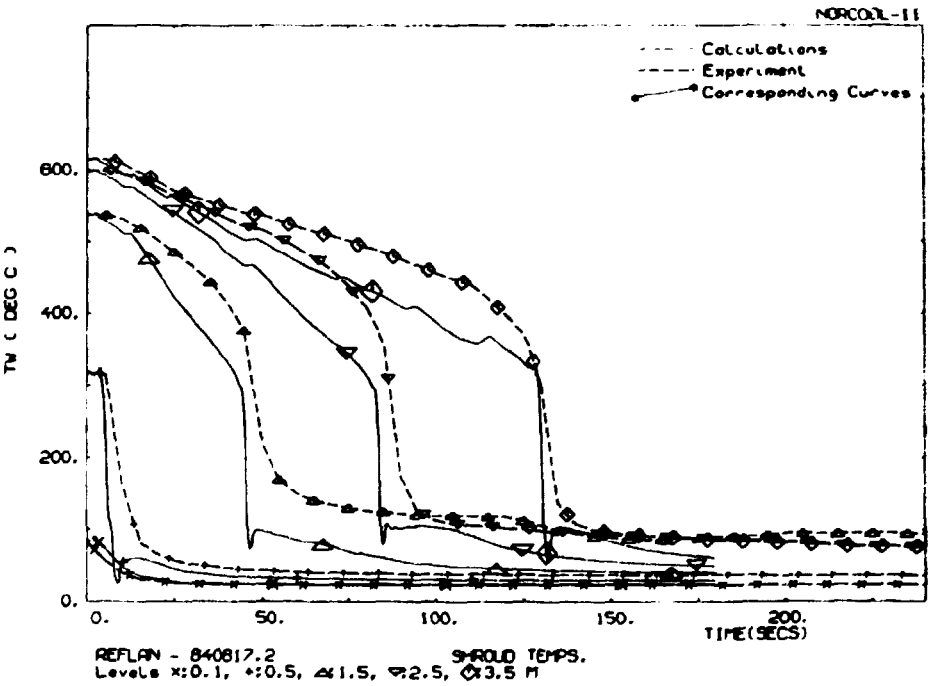

Fig. 18. Surface temperatures versus time.

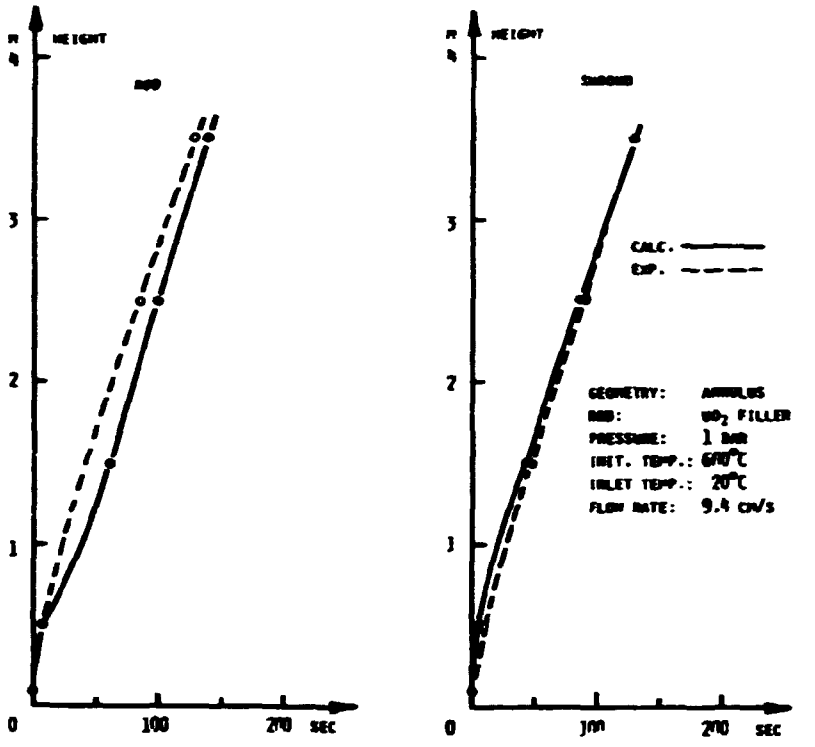

Fig. 19. Quench front positions versus time.

2.10. Blowdown from High-pressure Systems

A theoretical and experimental investigation of blowdown from a pressure vessel is being carried out. The experimental work is limited to blowdowns of initially saturated water. Pipes of different diameters and lengths have been connected to the vessel, and the initial pressure in the vessel has been varied between 4 and 10 bar. The measured parameters are mass flow rate, thrust force, average void fraction in the pipe, pressure and temperature. The experimental results are compared with results obtained by the computer-code NORA. Besides specific models estimating slip ratio, two-phase friction pressure drop and critical flow are tested against experimental results. The investigation will be finished in March 1985.

2.11. The Temperature Calibration Laboratory

The Temperature Calibration Laboratory was authorized in 1978 by the Danish National Testing Board to carry out certified calibrations of temperature sensors in the -150°C to 1100°C range according to the International Practical Temperature Scale IPTS-68. The standard thermometers in the Laboratory are traceable to the National Physical Laboratory, England.

The number of calibrations for external customers has increased steadily during the years. In 1984 The Laboratory has performed 148 jobs for external customers and 9 for other Risø departments. In all 505 thermometers ranging from liquid-in-glass models to advanced digital types and 16 thermostats have been calibrated during the year. The calibrations have been made in the temperature region from -100°C to 1100°C which covers the main part of the range authorized.

2.12. Coal Combustion in Circulating Fluidized Bed

The development of a circulating fluidized-bed boiler for industrial purposes, district heating, and power plants seems promising. The main reason for this is the possibility of achieving a high combustion efficiency accompanied by a large reduction of SO_2 and NO_x, which probably will meet the enviromental demands of the future.

The ongoing work is a part of a contract with the Ministry of Energy and it is performed as a co-work with a Danish boiler manufacturer. The main effort was to create Danish know-how in this field.

In 1984 work has been done in the following fields:

1. State of the art reports describing existing circulating fluidized-bed systems have been made.

2. A simple theoretical model of a circulating reactor was formulated.

3. A cold running test facility using different types of particles has been designed and constructed.
   The reason for this is the need of experimental data in the area of particle/gas flow in circulating systems.

As shown in Fig. 20, a power plant using a circulating fluidized bed consists of the following components:

- Coal and limestone feeding systems
- Reactor with primary cyclone for recycling of material to the reactor
- Heat exchanger in the reactor
- Secondary bed with heat exchanger
- Convective boiler part placed as the last boiler component
- Electrostatic filter
- Ash-handling system

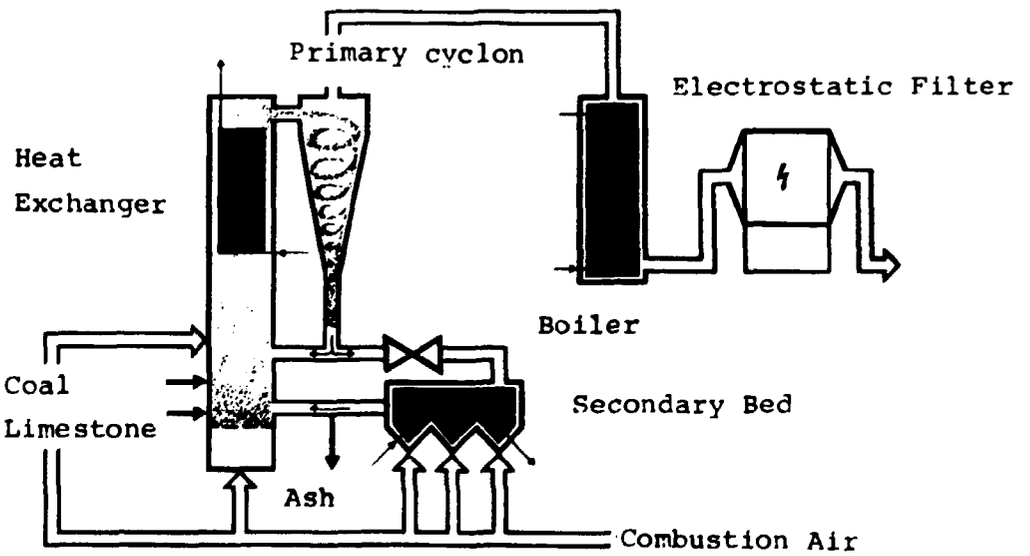

Fig. 20. Circulating fluidized bed.

The circulating bed in Fig. 20. is only an example and there are many other concepts.

As mentioned earlier SO_2 can be removed very effectively. This is done by adding small particles of limestone to the fluidized bed.

Fig. 21 shows how the reaction mechanism is working and how SO_2 is captured as $CaSO_4$.

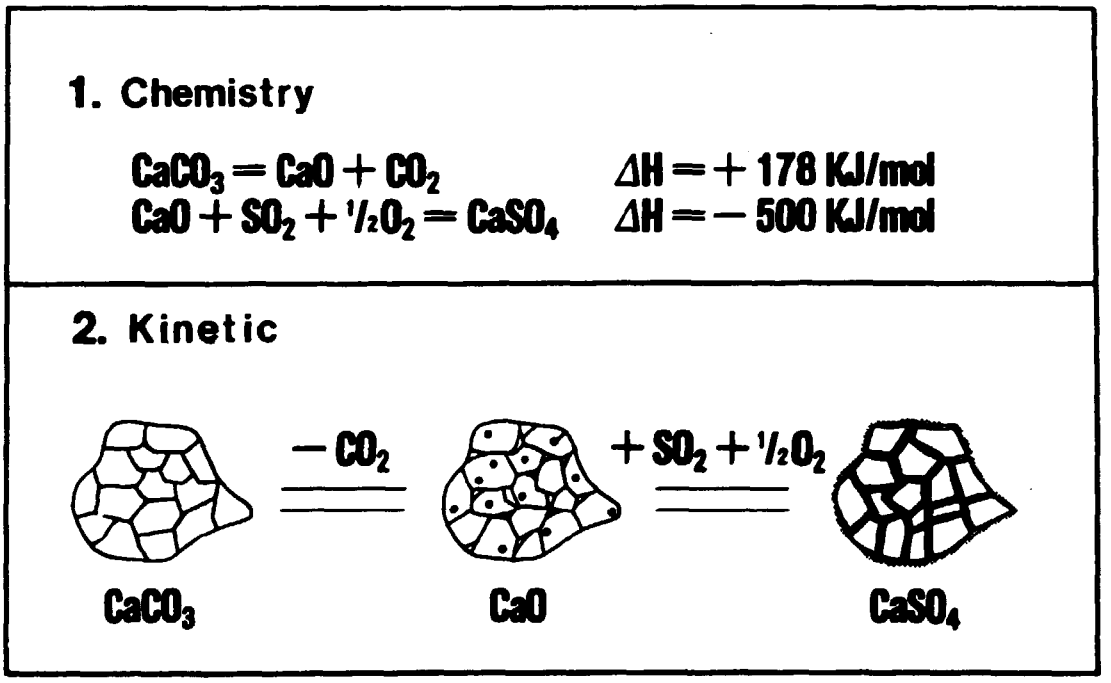

Fig. 21. Desulphurization in a circulating fluidized bed by adding limestone to the process.

2.13. Sulphur Dioxide Removal from Flue Gases

Sulphur dioxide can be removed from flue gases by adding limestone. In fluidized bed combustion the limestone can be supplied directly into the combustion zone simultaneously with the fuel.

A method to test the efficiency of different types of limestone to be used in fluidized beds has been developed.

A mini-fluidized bed to be used in the laboratory was constructed. The bed is very small. The content is about 200 g bed material. It is heated electrically and the tests are performed using an artificial flue gas made by mixing the pure gases: oxygen, nitrogen, carbon dioxide, and sulphur dioxide.

In the test facility 14 different commercially available qualities of limestone have been tested. The main part was of Danish origin, but for comparison also a couple from abroad have been tested.

A typical result from a sample test in the minibed is shown in Fig. 22. The sulphur dioxide content is plotted versus time.

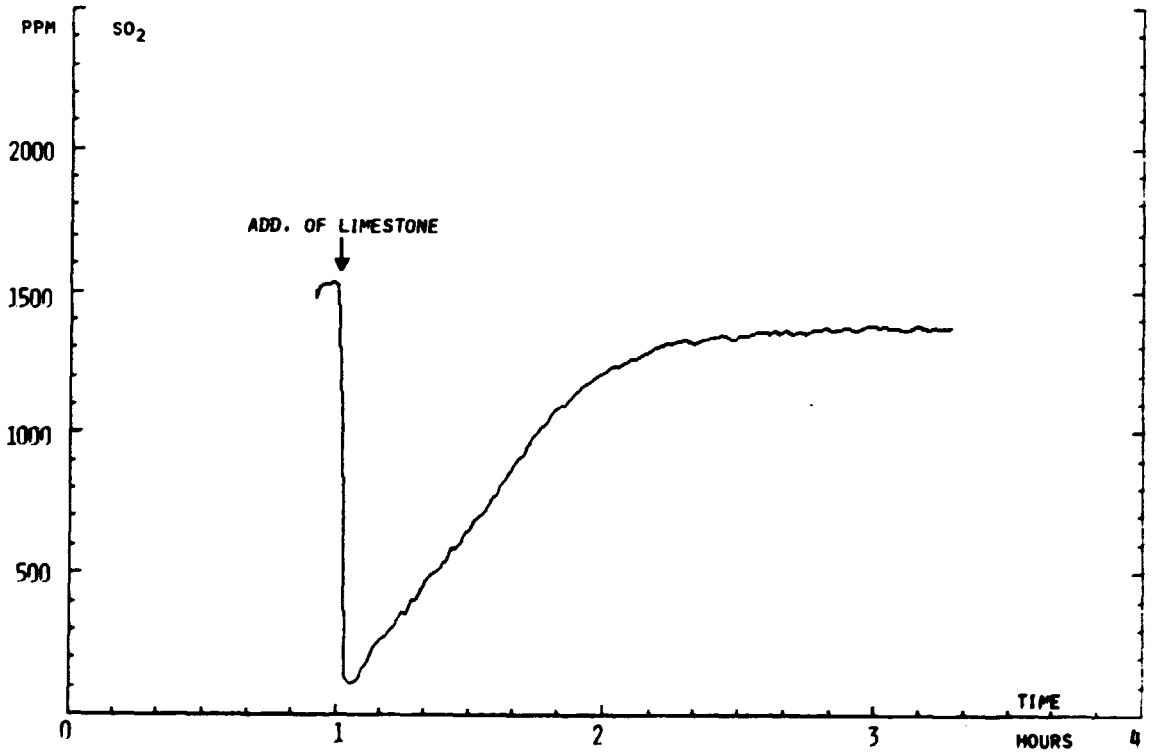

Fig. 22. Sulphur dioxide in flue gas versus time. Experimental results.

The four most promising types have been selected from the laboratory tests. These types have been tested in Risø's 300-kW atmospheric fluidized bed at real combustion conditions. Further tests are planned to take place at the Danish Boilerowners Associations test center in Vordingborg in a 1-MW fluidized bed.

Finally, the best type of limestone will be tested in full scale in a 12-MW bed in a district heating station.

2.14. Commercial Flue Gas Measurements

The Section of Heat Technology has made measurements of gases under commercial contracts both in Denmark and abroad in 1984. A trailer is rebuilt into a "rolling laboratory". It contains equipment for particulate measurements and for continuous measurements of the flue gas components CO_2, O_2, SO_2, NO_x and CO, as well as static and dynamic pressures and temperatures.

The datalogger system used for these field measurements is capable of sampling 40 transducers every 30 seconds for 10 hours; meanwhile, it makes calculations and stores all raw data on a disk for later computation, plotting, etc.

2.15. Oil and Gas Reservoir Models

The work on hydrocarbon reservoir modelling and simulation has been undertaken mainly because of its application to the Danish off-shore reservoirs.

The work has continued in a number of fields, partly in fulfilment of a number of contracts awarded by the Danish Ministry of Energy.

A black-oil simulator, BETA3A, has been further modified and tested. The simulator has been used for a single well study for the DAN-field reservoir, which is a North Sea chalk reser-

voir characterized by a very low permeability. This work has been carried out jointly by Risø and The Laboratory for Energetics at the Technical University of Denmark in collaboration with other laboratories of the University and with The Geological Survey of Denmark, the Danish Energy Agency, and Danish Oil and Gas Ltd.

Simulations for the GORM North Sea field, performed for the Danish Energy Agency, has been continued during 1984.

A 1-d simple compositional reservoir simulator has been developed for Enhanced Oil Recovery (EOR) screening studies. The development of a 3-d compositional simulator was started in 1984 in collaboration with The Laboratory for Energetics. A simple version is expected to be ready early in 1985. This version will be tested against simpler black-oil simulators. A fully compositional version is planned to be ready in 1986. In connection with this work a study of various mathematical and numerical methods has been performed.

In connection with the source rock project at the Danish Geological Survey, Risø has developed a computer model to simulate burial history, temperature, and maturation of sedimentary basins. The model includes compaction of sediments and heat conductivity as functions of compaction. The model has been tested against vitrinite reflectance measurements for two Danish wells with good results (Fig. 23).

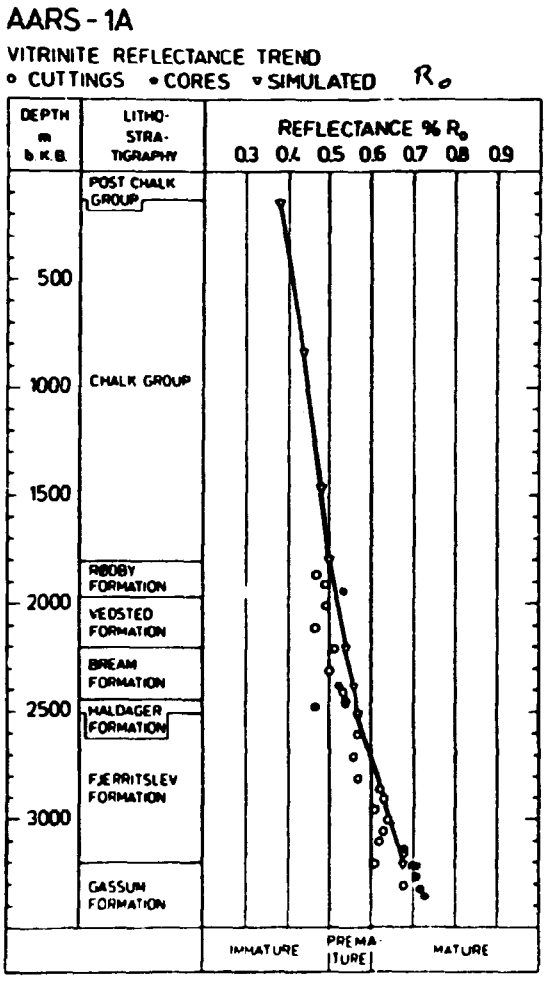

Fig. 23. Vitrinite reflectance trend

2.16. MULTWO: Compositional Computer Model for Transient Oil/Gas Two-phase Flow.

Oil/gas two-phase pipelines are of great technical and economic importance for offshore oil/gas fields, especially as connection lines between a central separation/pumping platform and a number of satellite fields sharing the platform. Computational tools in the form of computer models may help to solve the serious operational and safety problems associated with the use of two-phase pipelines.

Therefore, a development of a computer model, MULTWO, for oil/gas two-phase flow in pipelines has been iniated in cooperation with LICconsult Consulting Engineers Ltd. and the Institute for Chemical Engineering of the Technical University of Denmark. The 1984 work was partly funded by the Danish Ministry of Energy.

The model has been developed on basis of an existing water/steam two-phase code, NORCOOL-II. The version of MULTWO, resulting from the 1984 work, is a two-fluid model describing the oil/ gas flow in terms of time- and position-dependent compositions, volume fractions, velocities, pressure and temperature of the two phases (equal pressure and temperature for gas and oil). Compositional effects, unequal gas and oil velocities and heat transfer to the surroundings are fully considered by means of a full set of compositional mass flow equations, equations of motion for each of the oil and the gas phases and a single energy equation. Compositional phase equilibrium is also assumed but the evaporation/condensation submodel may be tuned to represent non-equilibrium.

The development of the current version of MULTWO has included development and implementation of a package for calculation of the composition dependent thermodynamic properties (density, enthalpy etc.) and transport properties (viscosity and thermal conductivity). The submodels for friction, heat transfer and flow pattern effects are only simple preliminary ones. However, a "catalogue" of such submodels to be implemented instead has been worked out, especially with regard to the modelling of severe slugging.

This catalogue contains new models developed within the project, for stratified, annular and slug flow, based on matching of logarithmic velocity profiles in the two phases. Lack of available experimental data has permitted test only of the new model for stratified flow which, however, compares very well with experimental results.

LICconsult has contributed especially with friction submodels for separated and slug flow while the Institute for Chemical Engineering has supplied know-how on modelling of compositional oil/gas thermodynamics and transport properties.

2.17. Risø Image-processing System

Risø Image-processing System (RIPS) is flexible in order to accommodate the different projects at Risø. The development of the system was initiated by the neutron radiography group at the DR 1 reactor, but it was claimed that the final system should be available for other groups. RIPS consists of five main blocks

1 A minicomputer
2 Computerboards for digitizing, image storage and image display
3 Software
4 Input medium
5 Output medium

At the moment the situation is as follows:
The minicomputer is a VAX-11/750 in the Electronics Department. The computerboards are 1 frame grabber (8 bit), 2 frame buffers (512 x 512 x 8 bit each) and a pipe-line-processor from Imaging Technology. The software for controlling the computerboards for basic image processing, image storage and image display is developed at Risø. It offers a comprehensive menu of commands and is easy to use with a help facility included. This software is currently improved according to experience with different tasks. All programing is in FORTRAN.

A general image-processing library called SPIDER with more than 400 subroutines in FORTRAN covering nearly all areas of image processing has just been included in RIPS. The input medium for images is a TV-camera, tape or disk. The output medium for images is a colour RGB-monitor, tape or disk. In 1984 we have used the system for image processing neutron radiographs. Programes for analysing microscopic images for features like

area, perimeter, compactness and counting have been developed for the Metallurgi and the Health Physics Department.

The advantage of RIPS is its low cost when based on an existing computer, and any computer from DIGITAL with the VMS operating system can be used to run the system. It means that RIPS can take advantage of new and improved computers. The display system needs only a colour RGB monitor. RIPS can be copied everywhere on an existing computer with the only expense of computerboards and a colour monitor.

The SPIDER program was developed by Mitsui, and the advantage of SPIDER is that it can run on any computer of reasonable size with a FORTRAN compiler, and that it covers nearly all aspects of image processing. SPIDER is written in FORTRAN with no input/output as a library of subroutines which need a main program. RIPS can be used as the main program for SPIDER, or the user can make his own.

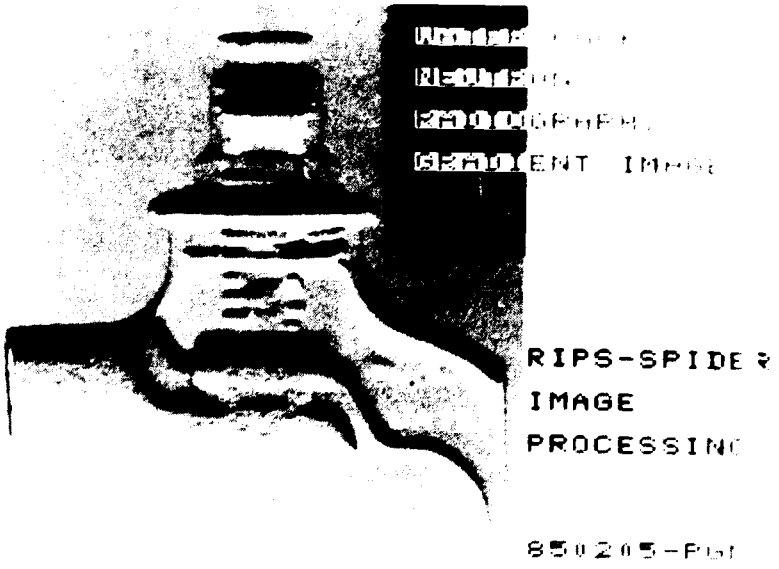

Fig. 24. Digitized image of neutron radiograph of a water cock.

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