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Investigation on Natural Convection Decay Heat Removal for the EFR
Status of the Program

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Abstract

The European R+D Program on decay heat removal by natural convection for the European Fast Reactor (EFR) covers the calculational methods and the model experiments performed for code validation. The studies concentrate on important physical effects of the cooling modes within the primary system and the direct reactor cooling circuits and include reactor experiments.

Introduction

In the European Fast Reactor (EFR) which is a common project of France, the United Kingdom and Germany the decay heat is rejected from the primary sodium via a safety graded Direct Reactor Cooling (DRC) System (1) in the case of failure of the normal steam plant (Fig. 1).

There are two Direct Reactor Cooling Systems (DRC 1 and 2) of three loops each. All loops extract heat from the hot pool of the primary sodium by immersed sodium/sodium heat exchangers (DHX) and reject the heat to the environment by sodium/air heat exchangers (AHX) arranged some 34 m above the DHXs.
All 6 loops are rated for 15 MW under nominal conditions (primary sodium temperature at 530°C, ambient air at +35 °C).

Only 30 MW of the total heat removal capacity is sufficient to cope with category-4 temperature limits. The DRC systems comprise an initial redundancy of 6 x 50% in total which increases to 6 x 100% beyond 100 h after shutdown because of the decreasing decay heat production.

DRC 1 is exclusively relying on natural convection heat transfer, i.e. natural circulation on the loop side and natural draught on the air side.

DRC 2 is normally operated in forced flow conditions, i.e. each loop is equipped with a flow supporting EM pump and with two fans in parallel on the air side. These active loops also have a high passive heat removal potential in case pump and fans are off, it amounts to about 2/3 that of the active flow mode.

Each DRC loop is equipped with
- one plugging meter unit
- one sodium discharge line, branching off the cold leg of the DRC loop pipework
- one freezing device in the discharge line for normal sodium discharge
- one shut-off disk device in the discharge line parallel to the freezing device for fast sodium discharge.

The six DRC loops are segregated/separated and functionally independent of each other. They are provided with strictly loop specific I&C equipment for DRC loop operation and freezing protection. The segregation/separation protects against adverse consequences from external and internal failures by means of barriers or distance.

Objectives and Program

To prove the feasibility of the passive decay heat removal it has to be shown that all thermal hydraulic phenomena are well understood and all processes can be described adequately.

To fulfill these requirements an extensive experimental and theoretical R+D program is carried out to support this DRC system which covers the following topics:
- thermal hydraulics of the primary system: i.e. reactor tank including the main components with different scales
- thermal hydraulics of the complete DHR circuits and components, i.e. reactor tank including the piping system and sodium/air heat exchanger with different scale
- code development and validation.

Experiments

A. Thermal hydraulics in the primary system.

Mainly three different models have been set up to study global and local effects:

RAMONA, Fig. 2, is a 1:20 scale 3-dimensional water model in SNR 2 geometry. It is equipped with active components (4 pumps, 8 straight tube-type IHX´s and 4 DHX´s). The core (max. power 30 kW) consists of 8 annular flow channels formed by 9 heater rings. The rings are individually heatable to allow power gradients across the core. About 250 thermocouples are mounted in the components and the plena. RAMONA is very flexible in design, measuring techniques and operation. Up to now about 100 experiments were performed both under steady state conditions and the transition range from forced to natural circulation with varying design geomtries (e.g. DHX, ACS) and operating parameters (core heating, primary/secondary pump coastdown, pony motor simulation, DHX standby operation and malfunctions etc) (2).

NEPTUN, Fig. 3, is the 1:5 scaled 3D water model in SNR 2 geometry equipped with active core and DHX´s . The core (max. power 1600 kW) is modeled by about 340 19-rod bundles individually heatable in 6 groups. The 4 DHX´s are built as straight tube-type heat exchangers. About 1200 thermocouples are installed in flow sections of interest. As NEPTUN is equipped with rod bundles assembled in wrapper tubes, a very detailed simulation of the core geometry is realized, and studies of the thermohydraulic interactions between core and hot plenum including the interwrapper flow phenomena are possible. This is a unique feature of the facility. In the test facility the core mass flow is controlled by flow meters. Velocities are measured by LDA-technique. The tests performed up to now concentrate mainly on the longterm behavior of the overall systems thermalhydraulics (2).

GODOM2, Fig. 4 , is a 90° water model of SPX 2 hot pool. Some tests have been performed to study the interaction of the core and DHX flows in DHR situation with primary natural convection. The DHX flow were simulated by an injection of cold fluid at the location of the DHX. It was shown that the cold flow can penetrate deeply under the ACS and interact with the outer fuel elements

B. Thermalhydraulics of the DHR Circuits and Components

Several scaled model experiments using water and sodium have been set up to study global and local effects:

KIWA-Facility

KIWA is a 1:10 scale water/air model in EFR geometry of the complete DRC chain including primary and intermediate circuits as well as the AHX with the air stack. The reactor vessel is a 2d model (1/2 slab).

After completing of the DHX calibration, the instrumentation is being upgraded for the thermal calibration of the air/water heat exchanger (AHX mock up). Fig. 5 shows the air stack with 13 instrumentation planes which can optionally be equipped with up to 200 thermocouples, the upper two-blade louver, the drum-type air/water heat exchanger and the multi-blade louvers at the air intake. The stack can be run under forced convection (see the blower at the left intake) to vary the air mass flow for calibration purposes.

An initial operation under natural circulation conditions has demonstrated that the heat exchanger is able to reject the 10 kW power it was designed for (3).

ILONA Facility

The ILONA experiment models the complete heat sink in a power scale 1:3 (Fig.6, 7). So the power rejection capability is 5 MW at nominal operating conditions compared to 15 MW of the original AHX of EFR. This reduction of the nominal power is achieved by reducing the global heat transfer area of the heat exchanger bundle. So the temperature fields, the flow distribution and the pressure drop in the ILONA AHX are nearly identical to those in the AHX of EFR (4).

The main objectives of this large ILONA experiment are:

- Investigation of the thermal hydraulics of the complete DRC heat sink (AHX, stack and dampers) under steady state, natural convection and transient operating conditions
- influence of the meterological boundary conditions (e.g. wind) on the operation of the heat sink
- test of the heat sink components (AHX, stack and dampers) under original temperature and flow conditions.
- sodium freezing procedures inside the AHX.

For two test phases important results are shown in the next Figures:

Fig. 8 shows for steady state operating conditions, (constant sodium flow rate of 21,5 kg/s and constant AHX inlet temperature of 495°C) the removed power as a function of the opening of the dampers. If the inlet dampers are only opened at one side a maximum of 4.2 MW can be removed. If, however, the inlet dampers are opened on two sides according to the EFR reference case, a maximum of 4.9 MW thermal power can be removed. The calculated nominal design power of 5 MW for the ILONA heat exchanger is almost reached. If, in addition, the weather protection grids at the inlet windows are removed, the maximum heat removal values increase to 4.6 MW and 5.1 MW, respectively.

In a next test phase transient tests with forced convection in the sodium loop were

performed to study the transient behavior of the AHX system after demand. The transient starts from a usual standby operation mode as it is defined for the EFR. As an example results for a nominal DRC demand after LOSSP (loss of service station power) from 100% reactor operation is presented. The transient starts by opening the outlet damper to 100% within 400s. During the opening of the outlet damper the AHX tubes will be cooled down rapidly resulting in an increasing sodium flow rate in the natural convection reactor system. This has to be simulated in the ILONA loop by means of the EM pump.
The behavior of the sodium temperatures at the outlet of the AHX tubes as a function of transient time is presented in Fig. 9. It can be seen that the temperature drop in the AHX tubes immediately starts with the opening of the outlet damper. The underswing results from the delayed increase of the sodium flow rate stopping the sodium outlet temperature drop. It is an indication for the good modelling of the ILONA system. Six tube outlet temperatures are plotted, two of each bundle cylinder. They represent the tubes with the maximum and minimum outlet temperature of each cylinder during the initial standby phase. During the plotted transient time period the order of the six temperatures remained stable without significant changes in the single tube flow distribution. Additionally it can be derived that the maximum temperature difference between the hottest and coldest tube outlet temperatures did not exceed the limit of about 60 K found in the steady state tests.

On the basis of the existing test series the following can be concluded:
During the extensive experiments no problems occurred running the specified EFR standby, full power and transient operating conditions on ILONA scale. The nominal heat capacity of 5 MW could be removed although the stack of the ILONA AHX is lower than the EFR one. The shapes of the temperature are very similar to those of the precalculated curves. Even the underswing, typical of the behavior of the sodium loop of this system, can be seen.The sodium/air heat exchanger functions perfectly under all service conditions, and the freely expanding design of the helical tube bundle proved to be of particular advantage.
Further investigations will be carried out to examine the system behavior at natural convection on the sodium side too and to get detailed informations for code validation.

C. Code Development and Validation

The experimental effort described above is used to develop and validate one- and multidimensional computer codes that will be ultimately applied to predict the temperature and flow distribution within the EFR primary vessel, the individual components and the complete DRC system. The following computer codes are applied in the EFR community:

DYANA/ATTICA (1-2 dim.)
TRIO 3-dim.
ASTEC 3-dim.
FLUTAN 3-dim.

These codes have been validated by

A) in-pile test and related water test
B) benchmark exercise on the basis of RAMONA experiments.

In case A a transition test from forced to natural circulation have been compared for a PHENIX-COLTEMP in pile experiment with comparable RAMONA out of pile experiments. Fig. 10 shows the vertical temperature distributions at different time intervals after the primary pump stop together with the comparable RAMONA experiments. Both tests were simulated by the 2d code ATTICA. In addition results of the RAMONA simulation with the 3d code FLUTAN are indicated. The graph shows that the computed and experimental results do not differ remarkably.

Concerning case B a benchmark problem had been defined on the basis of a RAMONA experiment. This experiment simulated the transition from steady state (40% power) in forced circulation to natural circulation with decay heat removal via the dip coolers (DHX). The results of this experiment had to be precalculated with the following codes:

DYANA/ATTICA Code (Siemens/KWU) (5)

The validation of the RAMONA test showed good agreement with respect to axial temperature gradients, but the calculated temperature levels were higher compared to the measured axial profiles (Fig. 11, 12) This discrepancy can be explained by heat losses and by axial heat transfer effects in the upper core which are not modeled in the code.
The achieved agreement on mean deviations is about 10% within the limits of 2d DYANA/ATTICA. Stronger deviations for positions in the lower hot pool - the "corps mort" region - are caused by 3d effects of the dip cooler (DHX) operation.

TRIO Code (CEA) (6)

Activities to model the 90 degree section of RAMONA with 23.000 cells were conducted, and the steady state before scram calculation was carried out as a preliminary step. Transient calculations are under progress and have been conducted under the first hour.

ASTEC Code (AEA) (7)

The potential of the ASTEC code was demonstrated satisfactorily by the modelization of RAMONA with 38.000 nodes and a calculation over a time interval of 1800 s after scram. Figs. 13, 14 show that following the pump rundown transient the core inlet and outlet temperatures, and hence the core flowrate, recover faster than the experimental data although the final values show reasonable agreement. One possible explanation would be the discrepancy in the core thermal capacity. However, the temperatures are in good agreement during the pump rundown transient which suggests that this is not the case. Another possibility is that the response time of the thermocouples measuring these temperatures is large due to their close proximity to the large mass of core material. A possible explanation of the discrepancy between the experimental and computed core flow rate is the fact that the accuracy of the flowmeters in the stagnation region is only ± 50%.

FLUTAN Code (KfK) (8)

Calculated results for a real time after scram of 1 h were discussed. The 90 degree RAMONA section had been modelled by 12.000 cells. The results show good agreement with the experiments (Fig. 15). As the maximum core temperatures were reached after 1 h the calculation was stopped and completed by a steady state calculation representing the natural circulation operational status 20 h after scram.

Conclusion

In pile tests - water out of pile tests

The comparison of computed and experimental results is satisfactory, i.e.
- qualitatively: good
- quantitatively: temperature deviations 10 - 15%.

RAMONA benchmark

The simulation of the benchmark experiment has provided a successful demonstration of the potential of 3d and 2d modeling. Qualitatively good results were obtained. Quantitative results are partly good depending on the modeling of the codes. CPU/real time is very high for 3d-computations.

In general:

The consistent thermal hydraulic approach of the DHR through natural circulation by multidimensional codes has been validated on a series of in-pile and out-of-

pile tests. The ongoing programme will provide the necessary extension of the validation basis given by the large scale NEPTUN tests as well as KIWA tests.

References:

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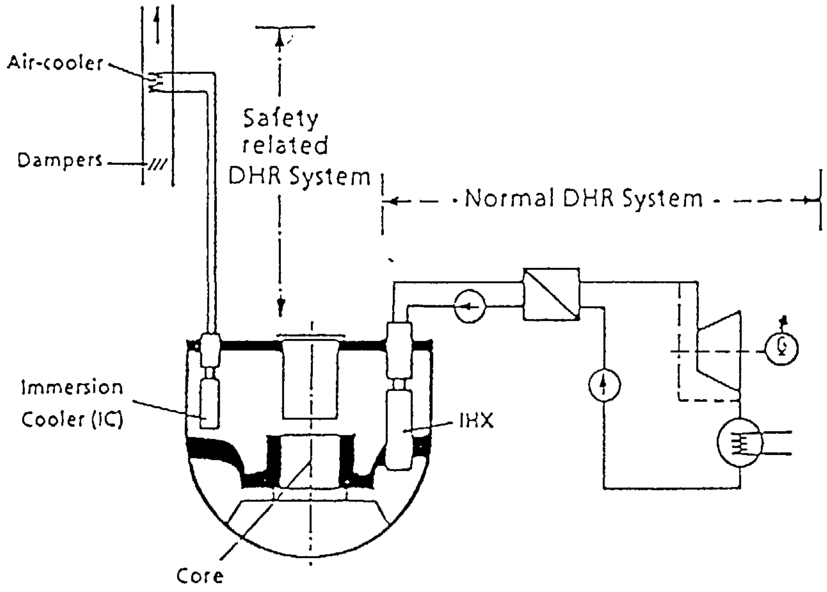


Fig. 1: DHR-Normal/Safety Related Systems

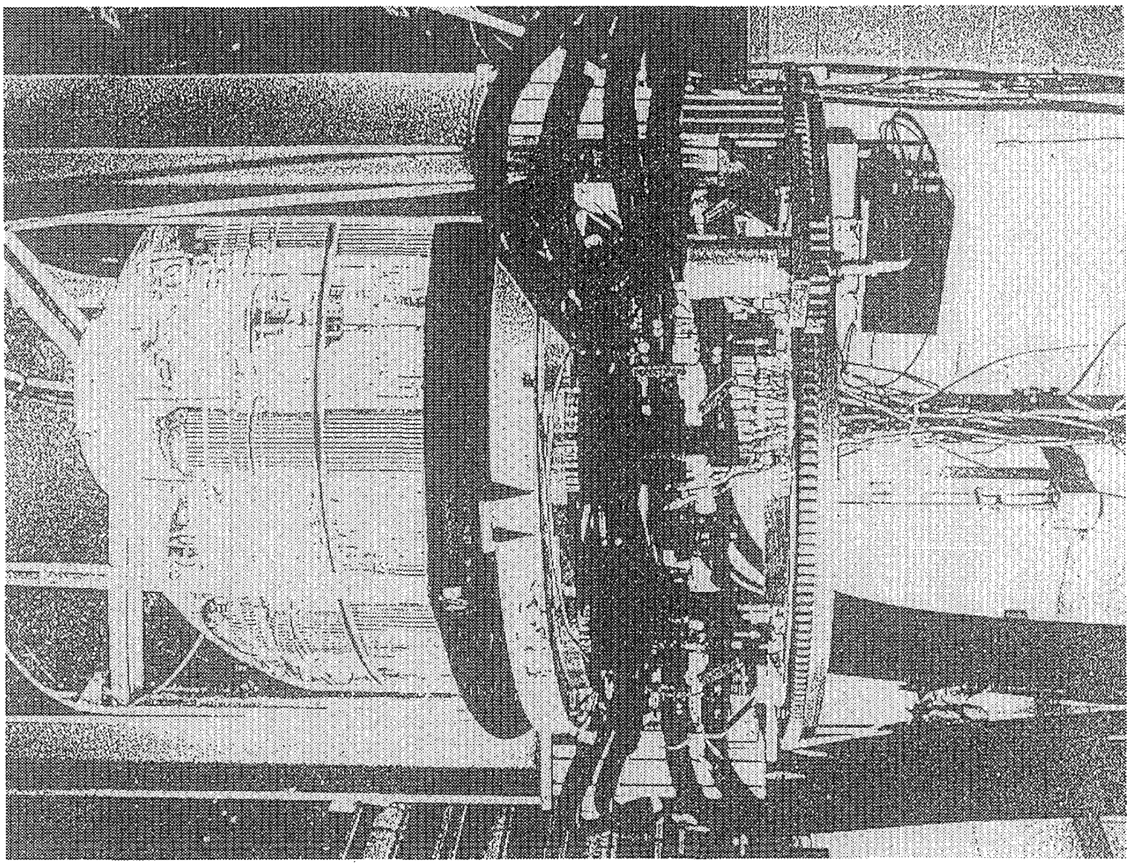


Fig. 2 DHR-Testfacility RAMONA

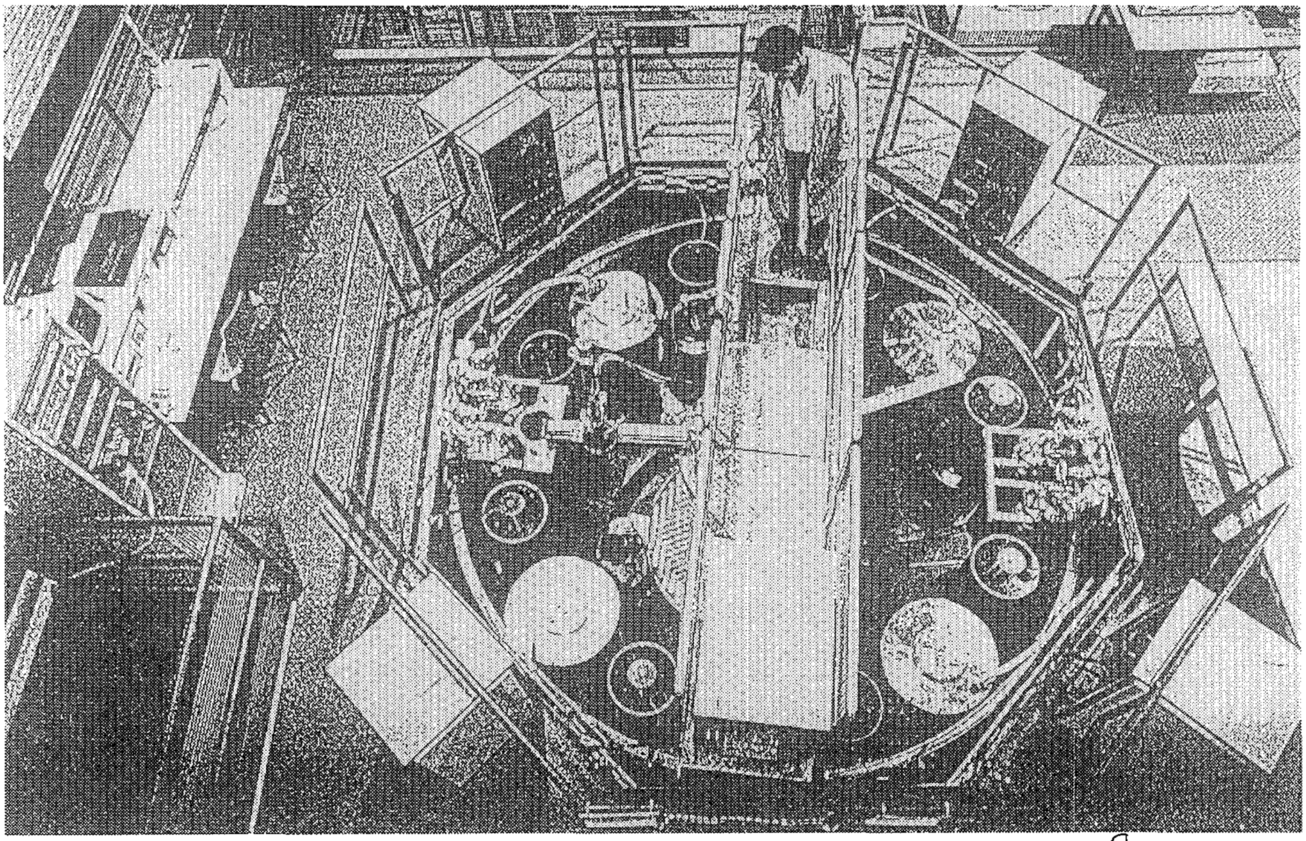
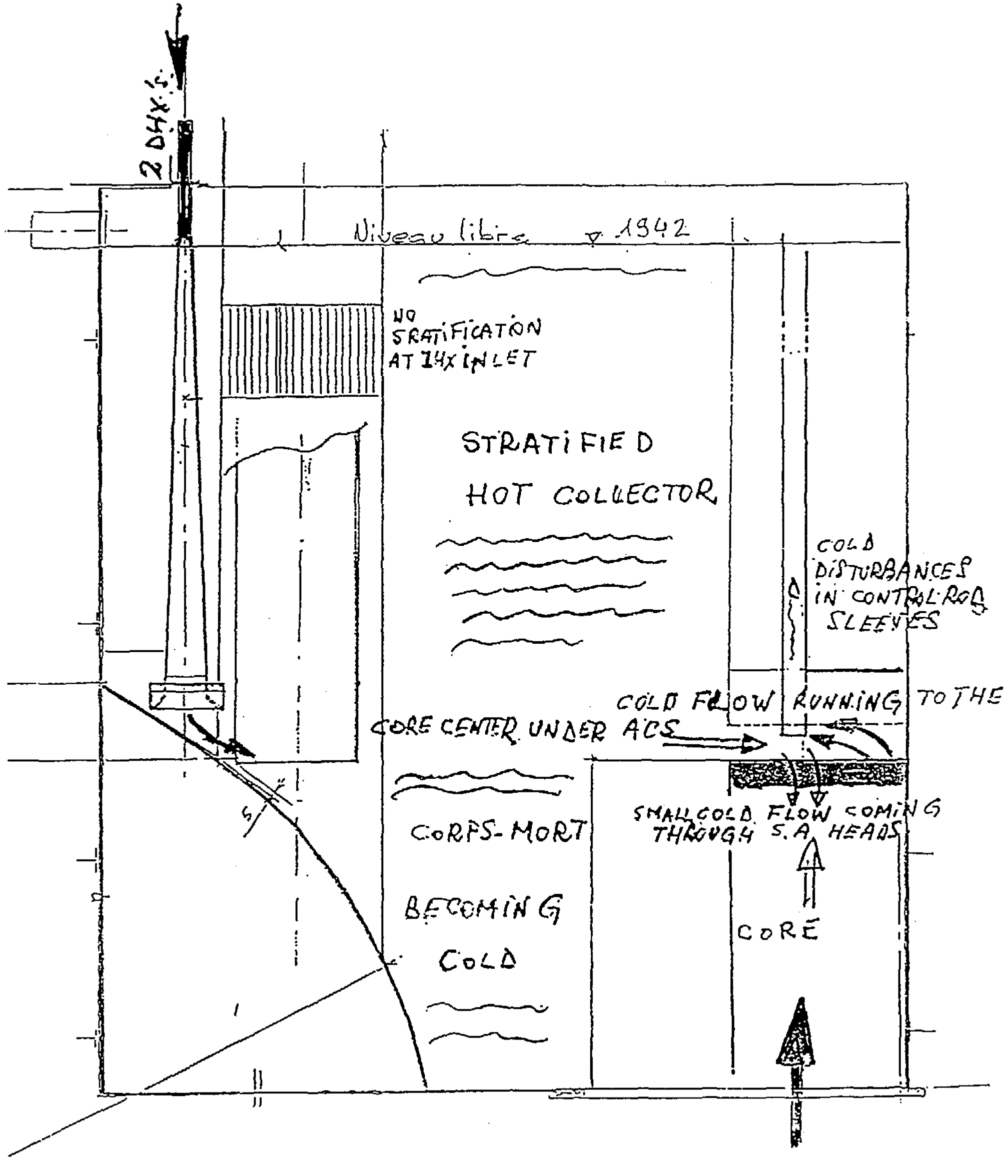


Fig. 3 DHR-Testfacility NEPTUN

Fig. 4 GODOM 2 / DHX



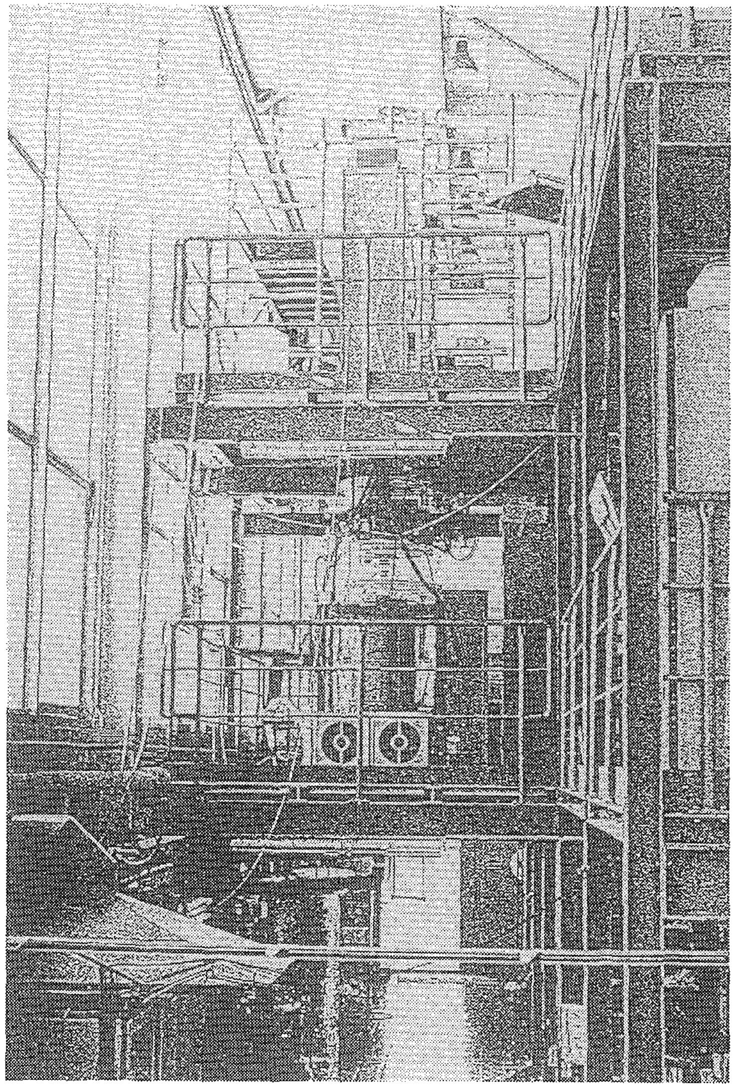
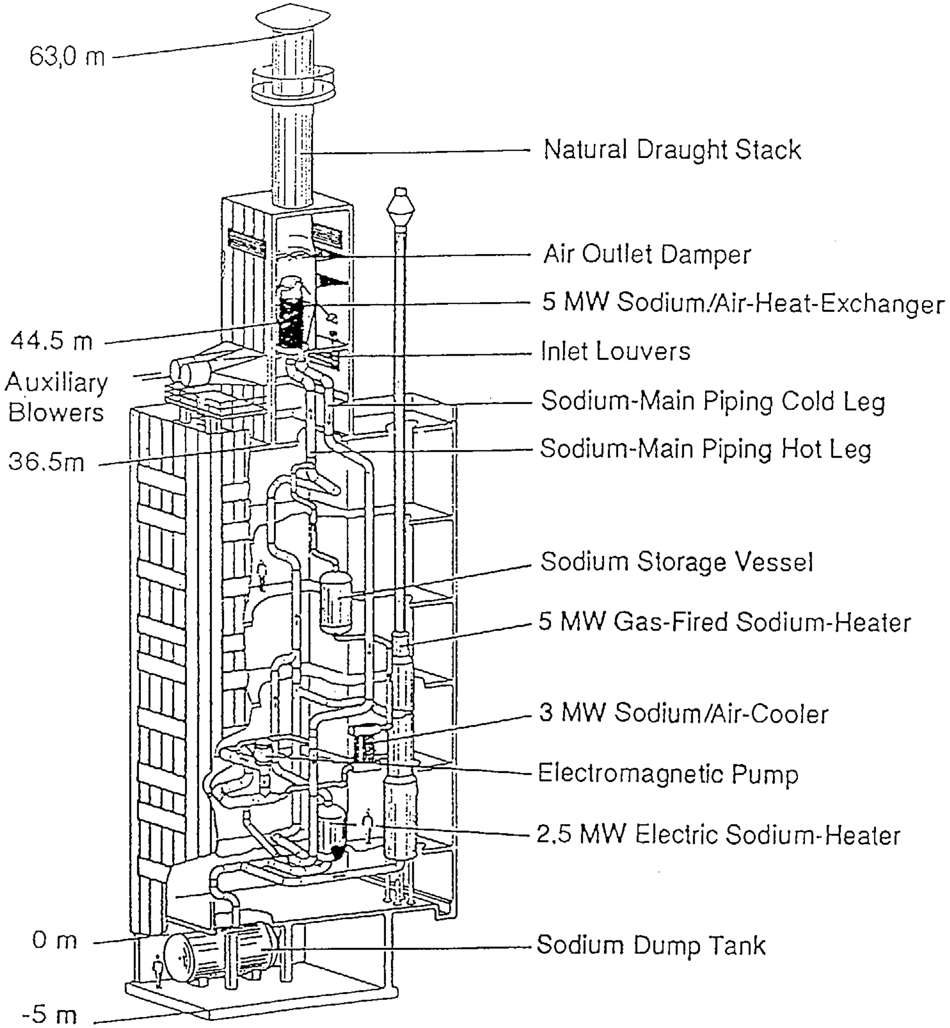
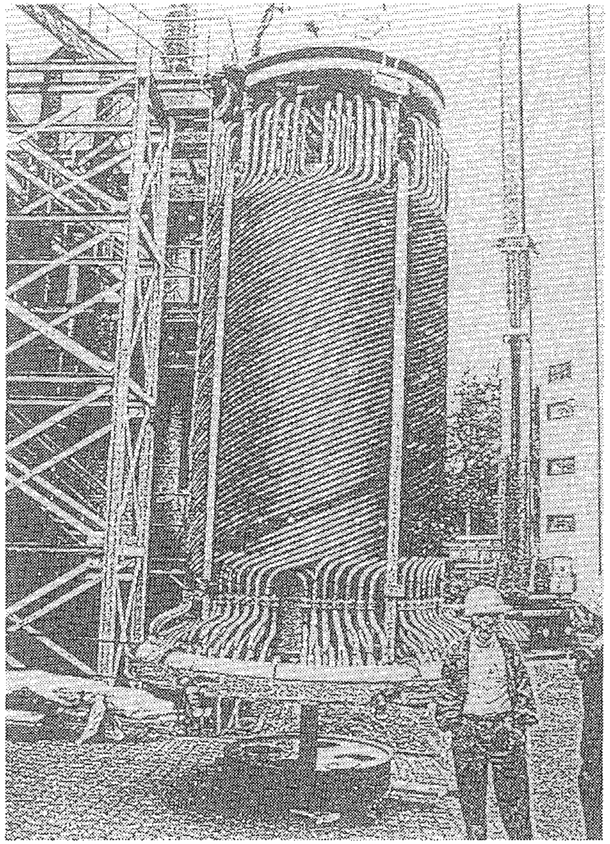


Fig. 5 DHR-Testfacility KIWA



ILONA : DHR Test Facility Fig. 6



ILONA : Sodium / Air Heat Exchanger Fig. 7

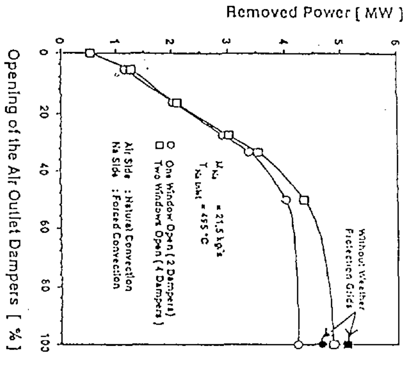


Fig. 8 ILONA: Removed Power

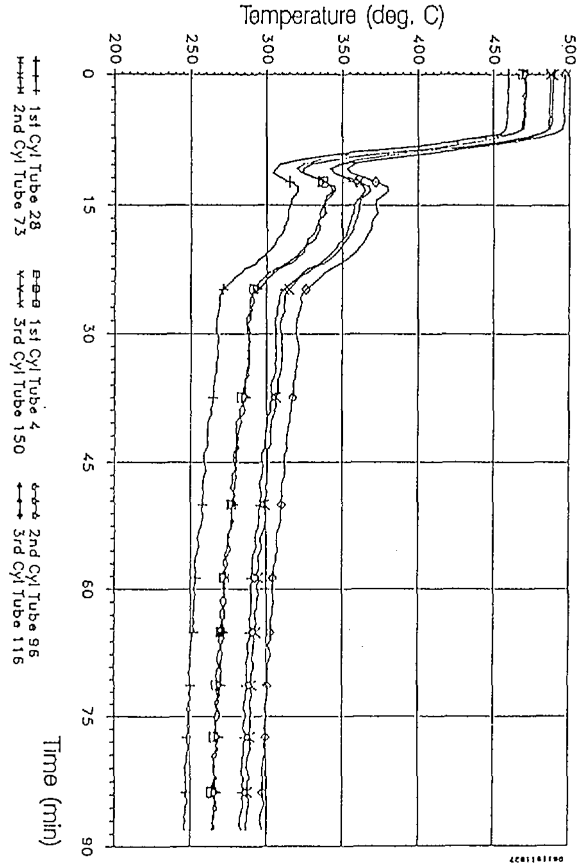


Fig. 9 Sodium Temperature Transients at the Outlet of the 1st, 2nd and 3rd Cylinder, 2 tubes each TEST: TZ1.0LAV8

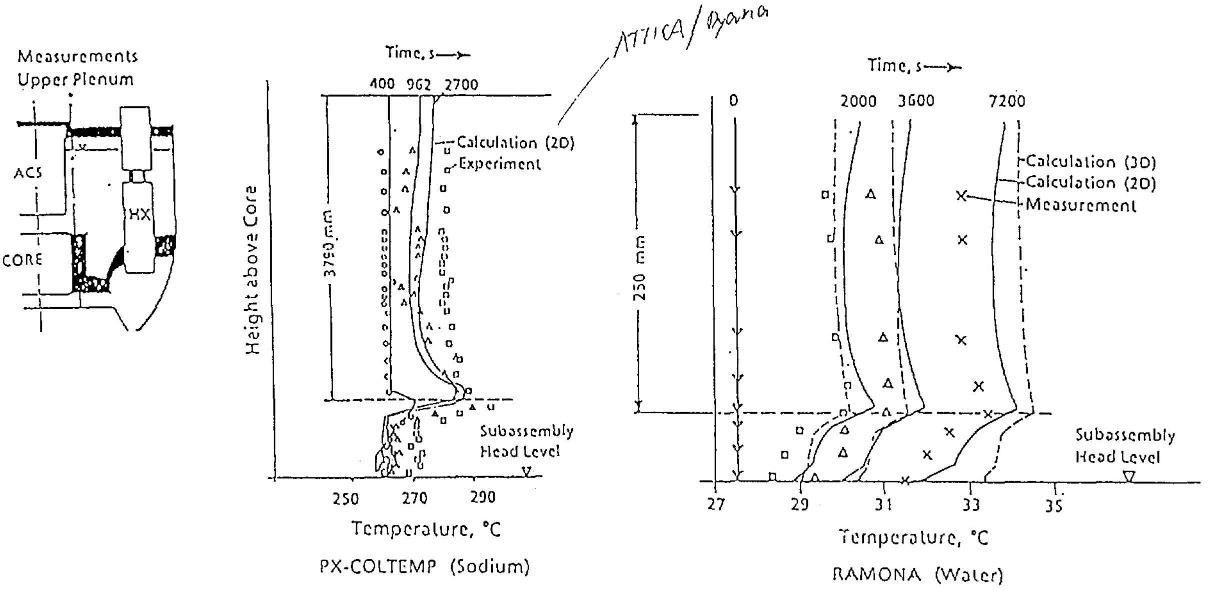


Fig. 10 Vertical Temperature Distribution in PX-COLTEMP 4 and RAMONA Hot Plenum after Sudden Pump Stops

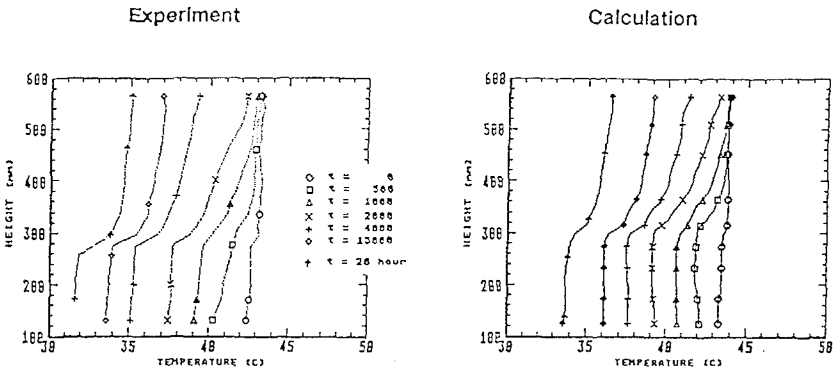


Fig. 11 RAMONA–Benchmark

Hot Plenum Vertical Temperature Distributions

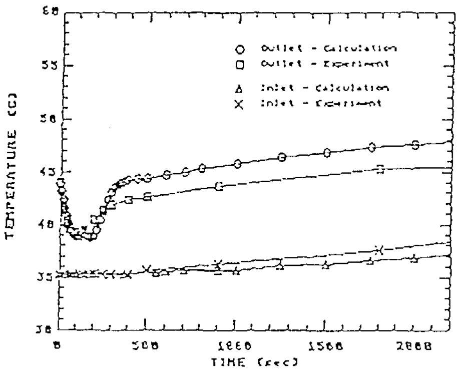


Fig. 12: RAMONA Core Temperature
DYANA / ATTICA versus Experiment

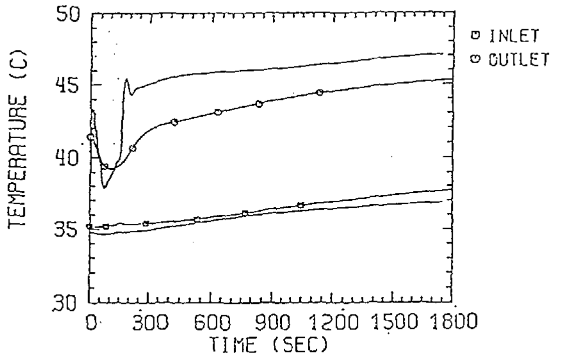


Fig. 13 CORE INLET AND OUTLET TEMPERATURES
(BENCHMARK-CASE1) (0-1800 SEC)

ASTECK

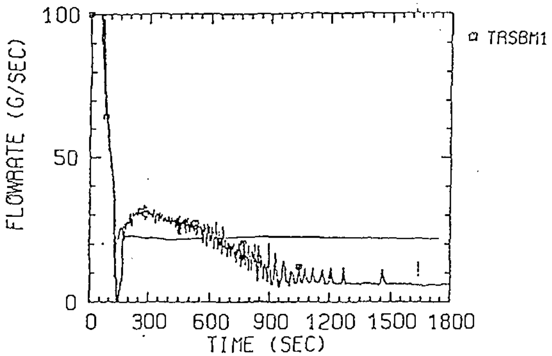
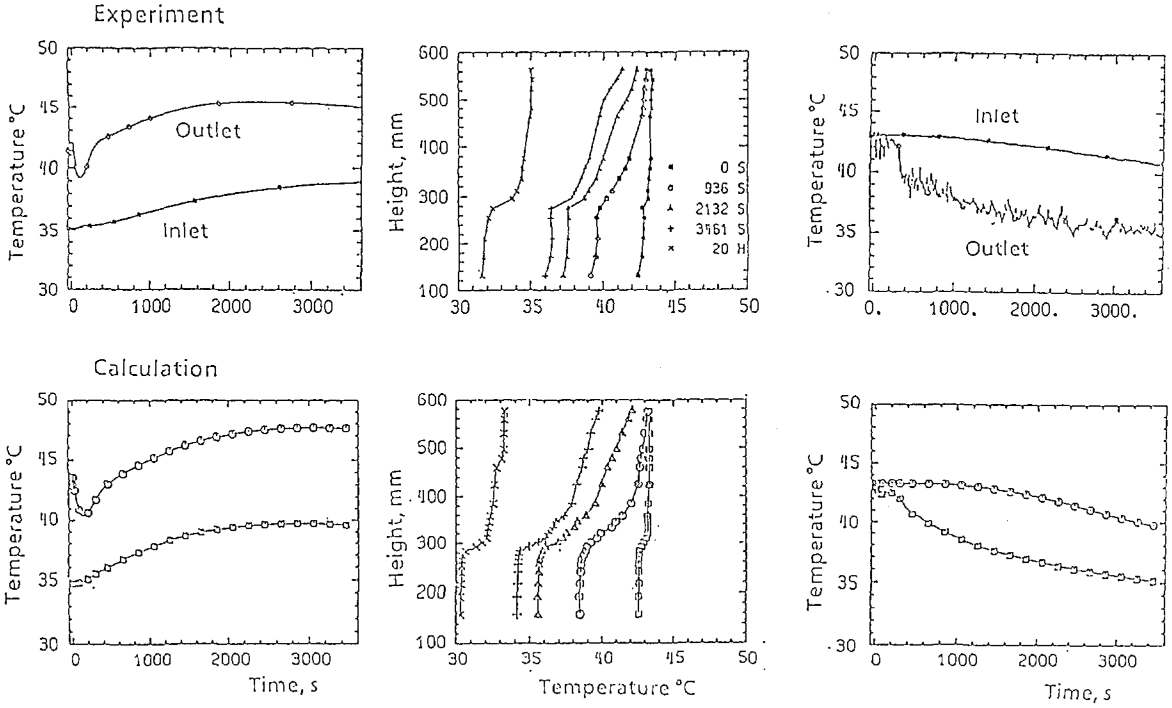


Fig. 14 CORE FLOW RATE (0-1800 SEC)
(BENCHMARK-CASE1, FLOWMETER)



Core Inlet and
Outlet Temperatures

Hot Plenum Vertical
Temperature Distributions

Immersion Cooler Inlet
and Outlet Temperatures

Fig. 15: Comparison of Experimental and Computed Results RAMONA Transient Benchmark (FLUTAN)