A HYPOTHETICAL ACCIDENT OF A SODIUM COOLED FAST BREEDER REACTOR AS BASIS FOR THE DESIGN OF A PRISMATIC CONCRETE CONTAINMENT SYSTEM

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Appendix : Structural design of the containment system

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Abstract

For a prismatic concrete containment system of a LMFBR there are presented design criteria which have been derived by dynamic analysis. They essentially appear as pressure buildups within the inner and outer containment as well as transient temperature distributions in the concrete walls.

A nuclear excursion in the reactor tank partially or completely filled with sodium is regarded as the design basis. If a complete failure of the normal coolant loops and the emergency cooling system is assumed, the decay heat of the disassembled core and the heat stored in the sodium will be transported out of the reactor tank by sodium evaporation and be dissipated into the inner containment. Chemical reactions between the oxygen traces in the nitrogen atmosphere of the inner containment and sodium vapour or liquid sodium leakages add heat sources which finally result in the pressure load of the containment system and temperature gradients in the concrete walls.

The results of an appropriate dynamic computer model are reported and their consequences for the prismatic reference containment system of the sodium cooled fast breeder prototype reactor SNR-300 are discussed.

1. Introduction

The containment system for the SNR-300 (300 MWe sodium-cooled fast breeder reactor) is a structure bounded by rectangular walls (Fig. 1). It is defined as the safety enclosure system consisting of several shells for the protection of the plant environment against non-permissible radiation hazards. The rectangular structure meets the requirements of plants with 1000 - 2000 MWe.

The inner containment encloses zone 1. This is the area filled with nitrogen atmosphere (0.5 vol% oxygen content). It consists of the reactor cell, the reactor plug cell, 3 primary cells and the pressure relief room. The walls forming the boundaries of the inner containment serve as primary shielding and carry steel liners fastened onto the inner sides in order to increase the leak tightness of the system and protect the concrete against sodium sprays.

The outer containment is also a rectangular concrete structure and completely surrounds the inner containment. At the outside it also carries a leaktight steel liner at a definite distance from the concrete walls. The outer containment encloses all installations of the plant which contain radioactive materials and the associated rooms for their safe operation.

The nitrogen atmosphere (2 vol% oxygen) reduces the sodium fire hazards for the sections where sodium containing components are located.

If the radioactivity level within the outer containment is higher than specified for normal operating conditions, the fresh air supply line is closed immediately by check valves against the atmosphere of the environment. Radioactive gas leakages from the outer containment reach the ring gap between the concrete walls and the liner. They are pumped back inside the outer containment's concrete walls (principle of the reventing system). The liner acts as a safety enclosure therefore because it avoids radioactivity release into the environment.

No special safety requirements arise for the reactor building (zone 3) which surrounds the outer containment. It protects the plant against the influences of the weather.

The design basis for the containment system refers to the highly hypothetical situation in which a nuclear excursion has caused the failure of the normal and emergency cooling installations and the primary system is open to the inner containment.

The slow transient behaviour of the sodium evaporation-contrary to the situation in light water reactors - and the effectiveness of pressure relief reduce the pressure peak to such a low level that it can be accommodated by a rectangular structure.

The concern of this presentation is a first analytical approach to the processes of heat distribution, leakage behaviour and pressure buildup. In a further phase of investigations, the analytical and experimental analysis of the natural convection of the inner containment gas is planned. These results will allow the determination of the specific heat loads (φ_i) of the individual rooms of the inner containment. The φ_i are up to now roughly estimated.

2. Accident description

Starting point for the calculation of the temperature and pressure loads of the containment system by the method outlined below is a nuclear reactor excursion which is not limited by the safety system. Such accidents are extremly unlikely to occur and will normally be contained within the reactor tank. Nevertheless it will be additionally assumed here that all main and emergency coolant loops had failed due to the mechanical consequences of the nuclear excursion. Sodium vapour is produced by the decay heat of the disassembled core after the time for heating up sodium to its boiling temperature has elapsed. Then it distributes over the primary cells and the pressure relief room where the heat stored in the vapour is set free by recondensation and cooling down of sodium.

This process of heat transport depends on the decay heat production with time and on the sodium level left in the reactor tank due to the mechanical consequences of the preceding nuclear excursion.

Chemical reactions of liquid sodium and vapour with the oxygen (0.5 vol%) of the cells' atmosphere as well as hot sodium spills eventually present in the cells may represent additional heat sources.

The pressure rise in the cells is a consequence of the mechanisms mentioned above. Pressure relief to the pressure relief room is guaranteed by appropriate open connections between the different sections of the inner containment. Additional pressure reduction is caused by leakages to the outer containment where minor pressure is built up.

After the pressure rises the temperature increases in the concrete structure of the inner containment. The heat is transferred to the steel liners by free convection from the containment atmosphere and by radiation from sodium spills and further by radiation from the liners to the concrete walls where it is either stored or conducted through.

Besides reducing pressure, the pressure relief room is also a very effective heat sink because of its large amount of concrete masses and surfaces.

Its position is elevated with respect to the primary cells and its lower part is connected to the bottom section of the reactor cell by channels wide enough so that an integral convection over the different sections of the inner containment is favoured and an approximately uniform distribution of heat over the inner containment is achieved.

3. Computer model

In order to design adequately the containment system with respect to safety requirements it is necessary to know its temperature, pressure and leakage behaviour during the incident outlined in Chapter 2. To achieve this, a dynamic computer model consisting of a coupled system of ordinary differential and algebraic equations has been developed which is able to describe the pressure and temperature buildup in the atmosphere of the inner containment due to the following heat sources:

a.) The heat stored in the sodium which is set free by recondensation and cooling down of sodium in the containment atmosphere and at the walls. For a conservative estimate it is assumed that sodium vapour produced in the reactor tank is cooled down without time delay in the inner containment to the temperature there. This assumption directly couples the heat source with the decay heat production of the reactor.

b.) The heat from chemical reactions of liquid sodium and/or sodium vapour with the oxygen content of the nitrogen atmosphere where the dependence of the enthalpy of reaction on temperature and phase is taken into account.

The time dependence of temperatures and pressures in the containment atmosphere are determined by the generation rates of the heat sources, by the heat transfer to the concrete structures of the inner containment, by the heat conduction within the concrete walls and by the mass and enthalphy exchange between the different sections of the inner containment due to pressure relief.

The mechanisms of heat transfer are free convection of the containment atmosphere and radiation from liquid sodium to the steel liner of the inner containment and from there subsequently to the surface of the concrete walls.

For the description of the conduction and storage of heat in the concrete structure, the walls are subdivided into several zones which are coupled thermally by the energy balance. An average, time dependent temperature is associated with each zone. The computer model assumes uniform heat load to the walls of each room. The fraction of total heat set free in the different rooms is characterized by the parameters φ_i $(0 \leq \varphi_i \leq 1)$. The pressure and density dependent leakage from the inner containment builds up pressure in the outer containment.

The linkage between the various mechanisms can be best seen from the flow diagram given in Fig. 2.

An approximately uniform distribution of heat over the various rooms necessitates the establishment of a closed loop natural convection over the whole inner containment. A mathematical description which will be included into the presented dynamic model is being developed at the present time. Nevertheless criteria for the establishment and order of magnitude of this natural convection can be given now.

For the derivation of these criteria, the relations describing the pressures existing in free atmosphere at different heights above ground level have been used, together with basic equations for hydrodynamics and heat transport by convection. For the evaluation of the buoyancy, which serves as driving force for the natural convection, it is necessary to know the temperature destribution within the gas atmosphere along the closed path of that convection. If the integration of that temperature distribution along the closed convection path from the reactor cell to the primary cells, to the pressure relief room and through the convection channels back to the reactor cell yields a positive value it can be shown that the natural convection can always be established in the direction of integration. By that condition a stable natural convection from the heat source positioned at a low level is guaranteed to the heat sink at a higher level.

To determine the resulting buoyancy term as the driving function the temperature distribution along the closed convection path must be known. This distribution depends on the gas velocity - which is again a function of the buoyancy and the total friction losses along the convection path - and on the heat flux from the gas to the concrete walls.

The calculation of the natural convection starts with an assumption for the temperature distribution in the gas from which the effective buoyancy can be determined. With the buoyancy and the known friction coefficients the velocity of convection in the different rooms can be obtained. This velocity influences the heat flux to the walls. This represents a correction to the assumed temperature distribution by which one cycle of the iteration process is finished. The sum of the heat fluxes to all walls can be compared with the decay heat production at a certain time. This gives a measure for the efficiency of the natural convection in the underlying system. This efficiency can be fitted to preset requirements by an appropriate design, i.e. choosing friction coefficients and relative height positioning between the different rooms.

4. Results

The results obtained with the presented model and their consequences for design refer to the prismatic containment system enclosing the SNR-300. The pressure evaluations in the inner and outer containments are reproduced in Fig. 3. During the initial phase of the incident a peak of 0.3 bar overpressure is shown for the inner containment. The rapid pressure rise results from recondensation of sodium vapour mainly in the atmosphere of the cells and from the chemical reaction of the sodium vapour with the oxygen of that atmosphere.

The following pressure decay in the inner containment and the pressure buildup in the outer containment is strongly influenced by the rate of leakage from the inner to the outer containment.

Non-uniform distribution of heat over the inner containment scarcely affects the pressure-time behaviour.

The spatial temperature distribution in the concrete structures of the inner containment depends on the fraction φ_i of the decay heat production which goes through a certain concrete surface F_{Bi} ($F_B = \sum_i F_{Bi}$ = total concrete surface of the inner containment).

A normalized representation ψ_i (x, t_i) for walls of the inner containment which are heated from one side only or from both sides is shown in Fig. 4 and Fig. 5, where x is the distance to a point inside the concrete from the wall surface and t_i is the time after the incident has started. The real temperature rise in the concrete results if ψ_i is multiplied by a factor f_i ($f_i = \Delta T_o * \varphi_i * F_o/F_{Bi}$, with the normalization parameters T_o = 100 °C and $F_o = 10^4$ m^2). The area F_{Bi} is assumed to be uniformly heated.

Supposing that the heat is uniformly distributed over the surface of the inner containment ($F_{Bi} = F_B$ = 12600 m^2, $\varphi_i = \varphi = 1$, $f_i = f$ = 80 °C), the temperature rise at the wall surfaces would reach a maximum of 80 °C only 70 hours after the start of the accident.

The actual design has been based on a higher load of the reactor cell and the primary cells with the following detailed distributions:

Reactor cell: F_{B1} = 2200 m^2, φ_1 = 0.31, f_1 = 140 °C
3 primary cells: F_{B2} = 2600 m^2, φ_2 = 0.26, f_2 = 100 °C
pressure relief room: F_{B3} = 7800 m^2, φ_3 = 0.62, f_3 = 80 °C.
This means a safety factor of $\sum_1^3 \varphi_i = 1.19$.

The factors $f_{1,2,3}$ together with the curves in Figs. 4 and 5 show that the maximum temperature rise is lower than 140 °C, 100 °C, 80 °C in the walls of the reactor cell, the primary cells and the pressure relief room respectively.

The integrity of the inner containment can be guaranteed if a layer of heat proof concrete (serpentine concrete) is placed in front of the load carrying concrete walls. The thickness of the layer must be proportioned so that the temperature rise in the walls stays below permissible limits.

Fig. 6 shows the results concerning the integral natural convection within the system of rooms of the inner containment. They were obtained by an estimate assuming a stationary natural convection and verify the demand that a great deal of the decay heat of the reactor should be transported to the pressure relief room by natural convection and should be stored there.

Fig. 6 can be interpreted the following way. Assuming a total friction coefficient $\varphi = 4000$ for the inner containment and assuming a temperature difference of 150 °C between the gas in the primary cells and the concrete surface of the pressure relief room, the resulting stationary convection has a velocity of 0.15 m/sec. Under these conditions a heat rate of $4.3 \cdot 10^6$ kcal/h can be deposited in the pressure relief room corresponding to a decay heat production (decay heat of the reactor plus heat stored in the sodium) which is present 8 hours after the reactor has become subcritical at the end of the nuclear excursion.

The friction losses of the inner containment with respect to the gas velocity in the pressure relief room is approximately $(F_{DE}/F_{Min})^2$ (F_{DE} = cross section for gas convection in the pressure relief room, F_{Min} = smallest cross section for convection in the inner containment).

With $F_{DE} = 500\ m^2$ the value for F_{Min} must be $8\ m^2$ so that $4.3 \cdot 10^6$ kcal/h can be stored in the pressure relief room.

Similar diagram for the other rooms of the inner containment and for a wider range of temperature differences $T_1 - T_B$ as well as the higher gas temperatures in the first hours have justified the selection of the values φ_i mentioned above.

Appendix

Structural Design of the Containment System

1. Inner Containment

The usual containment structures comprise sections of shells because this type of construction offers the special advantage of compensating the external loads by normal reactions within the structures. As was shown for the inner containment of the SNR-300, the internal pressure load is small (0.3 bar maximum) even for the hypothetical accident outlined in Chapter 2 of this paper. The load carrying structure can be established, therefore, by the usual constructions with plates, discs and frames.

As a rule, the wall thickness for the concrete of the inner containment necessary for radiation shielding is large enough so that the requirements of statics are automatically fulfilled.

The stresses and strains due to local stationary or transient temperature gradients, i.e. temperature differences between the inner and outer containment, are the same for constructions using plates or shells.

In order to keep the stresses, temperatures and temperature gradients within the concrete below permissible limits, a layer of heat-proof concrete is placed in front of the load carrying concrete walls. This layer does not carry loads and can expand freely with respect to the load carrying structures. A special problem arises due to the different thermal expansions of the individual load carrying elements. They are separated by expansion-gaps therefore, so that the stresses due to different absolute thermal expansions are kept within allowable limits. The steel liner of the inner containment covers the expansion-gaps. The concrete elements are as large as possible to achieve a liner design which is as simple as possible.

Criteria for calculating dimensions

Two individual states with different design criteria are defined:

a.) Service state

This state includes the state during plant construction and all working conditions for the total lifetime of the reactor (own weights, dead and live loads, service temperatures and pressures etc.) with all resulting pressure and temperature loads.

Two criteria are relevant in order to guarantee serviceability:

- Permissible stresses:
  The calculated stresses must have sufficient safety margin with respect to the compressive or tensile yield strength of the considered material for all conditions of loading which are included in the service state.
- Permissible deformations:
  The calculated deformations must guarantee with sufficient safety margin an undisturbed operation of the plant.

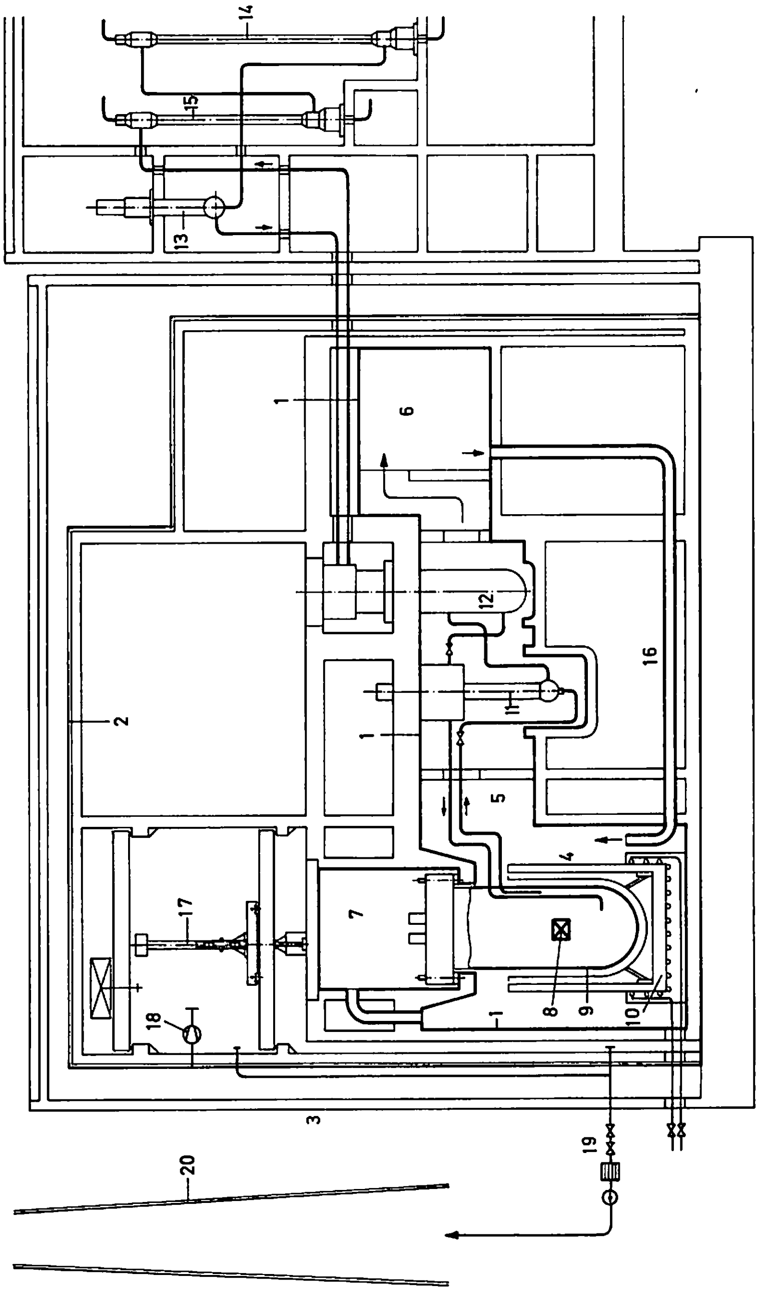
The two criteria can be fulfilled if the permissible stresses and deformations are used according to DIN 1045 E and DIN 4227 respectively (DIN = Deutsche Industrie-Norm) b.) Limit state

This state defines the loads due to the hypothetical accident after which the original reactor system cannot be operated further (see Chapt. 2). The behaviour of the load carrying structure remains reversible but the permissible compressive stresses in concrete and the permissible tensile stresses in steel are higher than in DIN 1045 E. According to DIN 1045 the maximum tensile stresses in steel may be as high as the yield strength and the maximum local compressive stresses in concrete may reach the characteristic cube strength.

In calculating the dimensions the time dependence of the pressure and temperature loads is taken into account.

2. Outer containment

The calculations of the dimensions for the concrete structure of the outer containment are performed according to the criteria for the service state defined for the inner containment. The dimensions of the liner for the outer containment and the associated stresses are evaluated according to the standards for safety vessels made of steel.



1 INNER CONTAINMENT
2 OUTER CONTAINMENT
3 REACTOR BUILDING
4 REACTOR CELL
5 PRIMARY CELLS
6 PRESSURE RELIEF ROOM
7 REACTOR PLUG CELL
8 REACTOR
9 REACTORTANK
10 CORECATCHER
11 PRIMARY PUMPS
12 IHX
13 SECONDARY PUMP
14 EVAPOURATOR
15 SUPERHEATER
16 GAS CONVECTION CHANNEL
17 FUEL HANDLING MACHINE
18 REVENTING SYSTEM
19 CONTAINMENT AIR SUPPLY
20 STACK

Fig. 1: Containment system SNR - 300

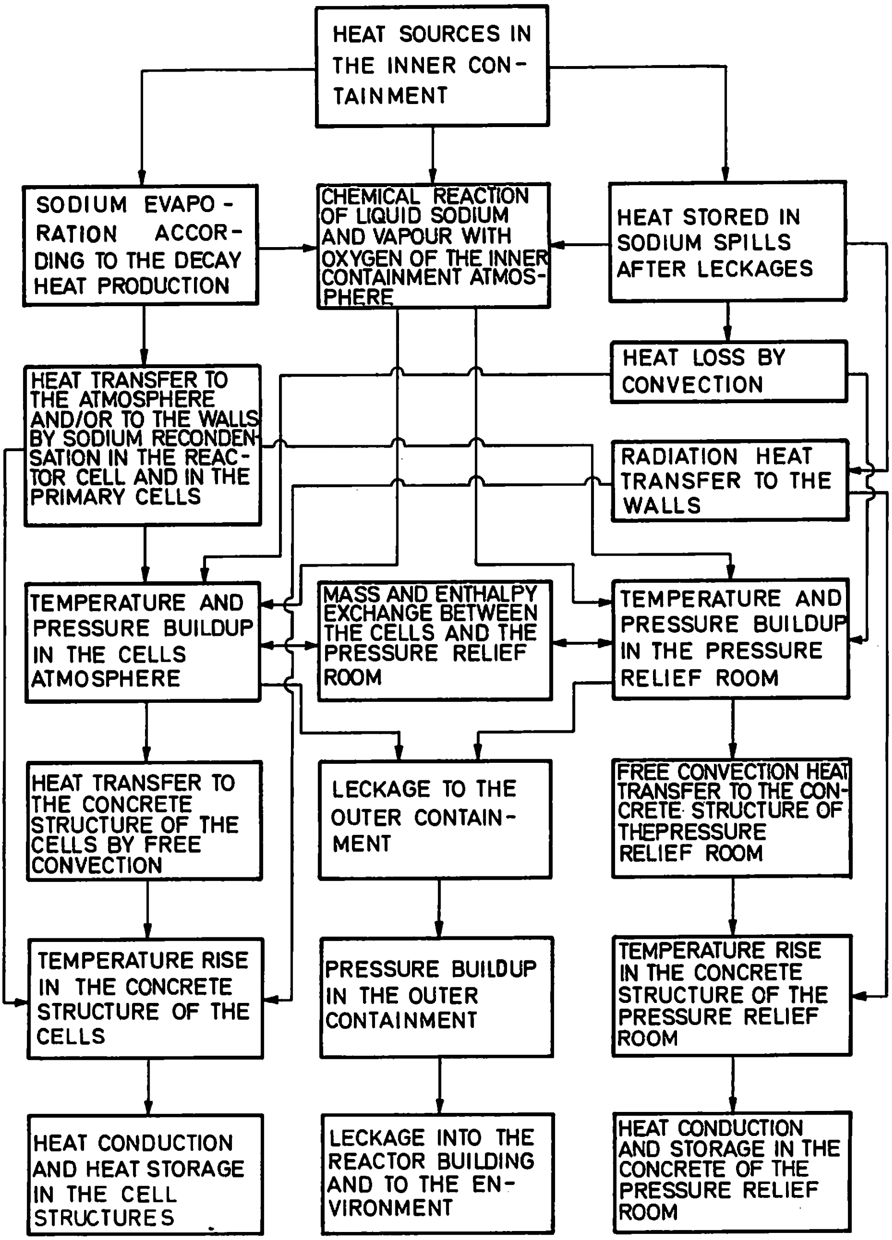


Fig. 2: Flow-diagram of the computer model

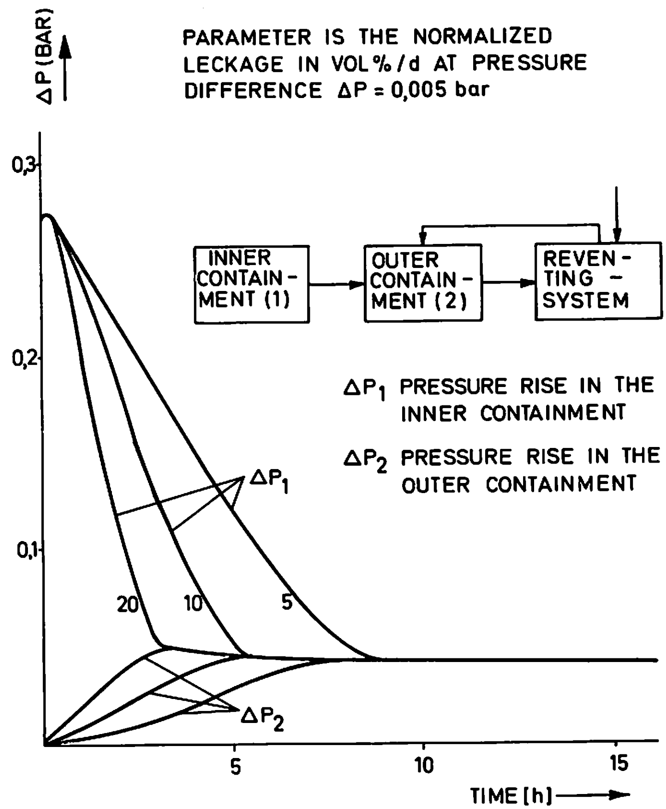


Fig. 3: Pressure-time functions in the containment system.

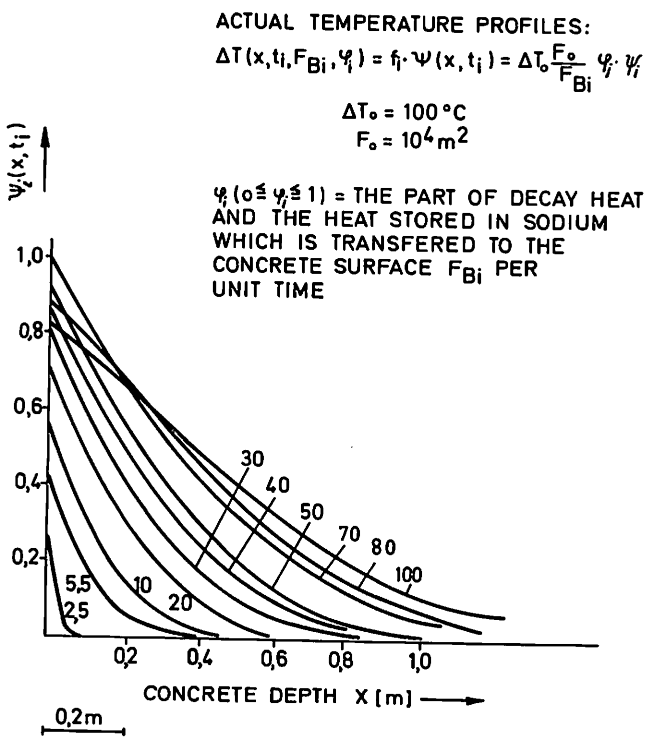


Fig. 4: Normalized local temperature profile ψ_i (x,t_i) in the concrete structure (walls heated from one side) (Parameter t_i = time after the start of the accident)

ACTUAL TEMPERATURE PROFILES:

$$\Delta T\,(x,\,t_i,\,F_{Bi},\,\varphi_i) = f_i \cdot \Psi_i(x,\,t_i) = \Delta T_o \frac{F_o}{F_{Bi}}\,\varphi_i \cdot \Psi_i$$

$$\Delta T_o = 100\ ^\circ C$$
$$F_o = 10^4\ m^2$$

$\varphi_i\,(o \leqq \varphi_i \leqq 1)$ = THE PART OF DECAY HEAT AND THE HEAT STORED IN SODIUM WHICH IS TRANSFERED TO THE CONCRETE SURFACE F_{Bi} PER UNIT TIME

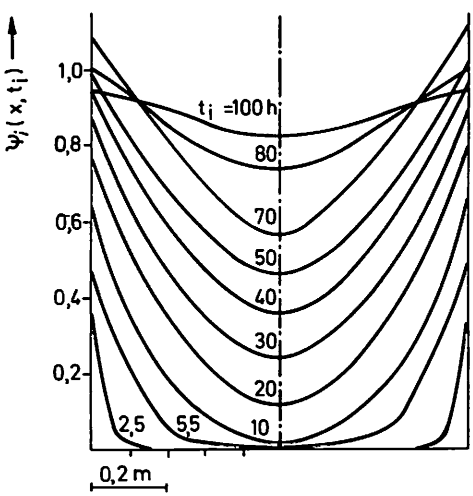


Fig. 5: Normalized local temperature profile $\Psi_i\ (x, t_i)$ in the concrete structure (walls heated from both sides) (Parameter t_i = time after the start of the accident)

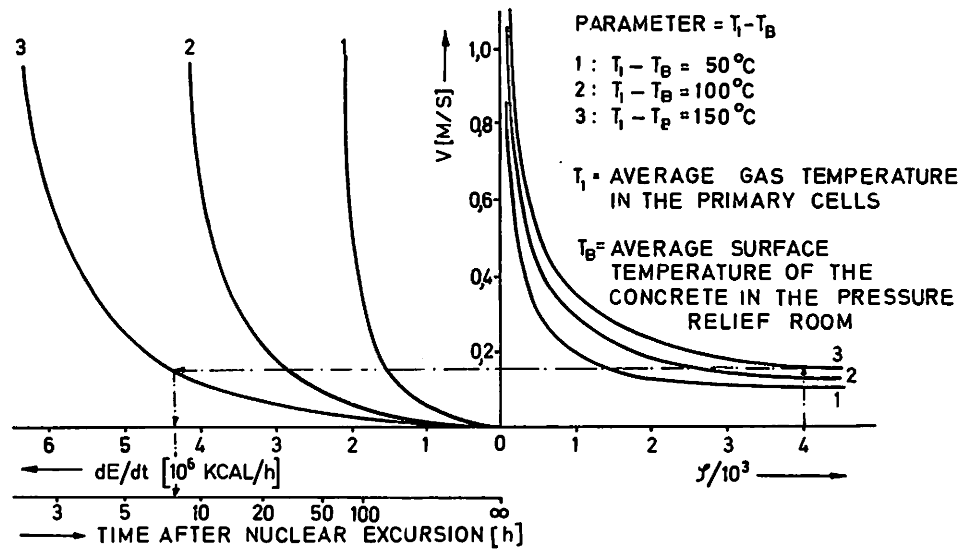


Fig. 6: Velocity (v) of the gas convection in the pressure relief room (PRR) as a function of the total friction coefficient of the inner containment and its correlation with the heat absorption rate in the PRR and the decay heat production of the reactor at a certain time after the nuclear excursion.

DISCUSSION

Q O. SCHAUB, Switzerland

Es wird angenommen, dass bei einem Unfall die anfallende Wärme durch Naturkonvektion einer Gasatmosphäre abgeführt wird. Sind Experimente zur Absicherung geplant ?

A M. HÜBEL, Germany

Das Primärsystem des SNR 300 ist so ausgelegt, dass es bezüglich seiner wichtigsten Funktionen auch nach einem Bethe-Tait-Störfall intakt bleibt. Seine Auslegungsbasis ist eine Gesamtenergiefreisetzung von 2000 - 3000 MWth. Von daher würde sich die Auslegung des Containmentsystems auf einen Störfallzustand erübrigen, bei dem die gesamte Nachwärme über das Containmentsystem abgeführt werden muss. Der Grund für die Ausrüstung des SNR 300 mit diesem aufwendigeren Containmentsystem ist vielmehr in dem Prototypcharakter dieser Anlage zu sehen: Der SNR 300 soll alle wesentlichen Informationen erbringen, die für den Bau einer Grossanlage erforderlich sind. Es lässt sich heute noch nicht absehen, wie sich das Problem der Beherrschung der Folgen eines Bethe-Tait-Unfalls bei einer Grossanlage stellen wird. Einmal sind die dazu erforderlichen sehr umfangreichen Detailstudien für eine Grossanlage noch nicht durchgeführt worden und zum zweiten sind die genehmigungstechnischen Voraussetzungen für eine klare Beurteilung dieses Sachverhaltes bei einer Grossanlage noch nicht abzusehen. Es war daher naheliegend, den Prototyp so zu konzipieren, dass die optimale Lösung dieser wichtigen Sicherheitsfrage für eine Grossanlage auf Systeme zurückgreifen kann, die bei einem Prototyp bereits erprobt worden sind. Unter Erprobung ist hier natürlich nicht die Beanspruchung der Sicherheitseinrichtungen bei einem Störfall zu verstehen, sondern vielmehr die Lösung aller planungstechnischen, bautechnischen, betriebstechnischen und vor allen Dingen der genehmigungstechnischen Probleme.
Primärsystem und Containmentsystem sind hinsichtlich der Beherrschung der mechanischen und thermischen Auswirkungen eines Bethe-Tait-Störfalles beim SNR 300 daher parallele Sicherheitseinrichtungen, denen im wesentlichen die gleiche Aufgabe zufällt Bei einer Grossanlage würde zumindest die Sicherheitsfunktion eines dieser Systeme nicht mehr benötigt werden.
In diesem Zusammenhang sollte auch gesehen werden, dass die Beherrschung der Störfallfolgen durch das Containmentsystem den sicherheitstechnischen Vorteil einer erhöhten Zuverlässigkeit besitzt, wenn erst einmal die grundsätzliche Funktion dieser Einrichtung sichergestellt ist. Im Gegensatz zum Primärsystem sind die Träger der Sicherheitsfunktionen, das sind im wesentlichen die Räume und die Wände des Containmentsystems, viel stärker von den Vorgängen am eigentlichen Störfallort entkoppelt. Ihre Funktion ist weit zuverlässiger als etwa die der Kühlsysteme innerhalb des Primärsystems. Die Möglichkeit einer Störfallbeherrschung durch das Containmentsystem ist umso eher gegeben, je weniger integriert das Primärsystem aufgebaut ist. Ein desintegrierter Aufbau führt zwangsläufig zu grösseren Räumen, in denen die Primäranlage aufgestellt ist, und die grösseren Betonoberflächen dieser Räume ermöglichen dann die Abführung der Nachwärme über die Wände. So gesehen bedeutet das Containmentsystem des SNR 300 die Ausschöpfung eines dem Loop- System inhärenten

sicherheitstechnischen Potentials.

Q O. SCHAUB, Switzerland

Sie nehmen an, dass das Primärsystem versagt und dass das Kühlmittel in das innere Containment verdampft. Bei den meisten Herstellern wird versucht, das Primärsystem bei einem Bethe-Tait-Störfall intakt zu halten. Wie verhält sich das Primärsystem des SNR 300 bei einem Bethe-Tait-Störfall und wie wird das Sicherheitspotential von Primärsystem und Containmentsystem gegeneinander abgegrenzt ?

A L. LANGE, Germanv

Grundsätzliche Versuche über das Zustandekommen und die Wirksamkeit der Naturkonvektion wurden im Auftrag der Fa. Interatom von der Fa. Krantz Lufttechnik durchgeführt. Die experimentellen Ergebnisse liegen mittlerweile vor und sind der Interpretation zugänglich.
An einem von der Fa. Krantz errichtetem Plexiglasmodell des inneren Containments im Massstab 1:10 wurden die Konvektionskriterien am prismatischen Containment eingehend untersucht. Dabei wurden die Wärmequellen durch elektrische Heizer simuliert, welche an verschiedenen Positionen sowohl in den Reaktor- als auch in den Primärzellen installiert waren. Gemessen wurden Strömungsgeschwindigkeiten der Luft und Temperaturen am Modell. Die gemessenen Ergebnisse zeigen, dass in jedem Falle ein Zustandekommen der Naturkonvektion erfolgt, unabhängig davon, an welchen Stellen das Gas erhitzt wurde, - oder auf den SNR übertragen, wo die Nachwärme entbunden wird -, und dass diese Konvektionsbedingung in jedem Falle so stark ist, dass durch sie die anfallende Wärme gleichmässig auf die Betonstrukturen übertragen wird. Mit den Versuchen wurde zunächst prinzipiell die Wirksamkeit der Naturkonvektion demonstriert, dies scheint uns wichtig, dass dem Nachweis im Genehmigungsverfahren Bedeutung zukommt. Theoretische Untersuchungen zur Übertragung der Versuchsergebnisse im Detail auf die Verhältnisse des SNR werden durchgeführt.