ASPECTS OF WATER AND AIR INGRESS ACCIDENTS IN HTRs

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1. Introduction

Accidents resulting in an ingress of water or air into the primary circuit of a HTR are considered significant from a safety engineering point of view because there is the danger of several fission product barriers being affected simultaneously. Air-oxygen and water react chemically with hot graphite, corroding the fuel elements and producing burnable gases whose release into the containment may lead to explosive gas mixtures. Furthermore, steam and the reaction products formed during water ingress will cause a pressure build-up in the primary circuit. Whether and to what extent these processes result in a release of radioactivity will depend on the actual accident sequence.

2. Water Ingress

2.1 Design Basis

In the first phase of an accident involving the ingress of water into the primary circuit the most important effect is the build-up of pressure. It is determined primarily by the total mass of water and by the rate at which the primary circuit is cooled down. The means of controlling these accidents are therefore directed towards both the localisation and shut-off of possible sources of water ingress within a short time as well as the shut-down of the reactor and the rapid cooling of the primary circuit in order to maintain the pressure build-up within narrow limits. Thereby it is achieved that the effects of the design basis accidents involving water ingress are confined to the primary circuit.

The shut-down of the reactor and the rapid cooling of the primary circuit can also be an efficient method to confine the effects of water ingress accidents to the primary circuit in cases when the localisation and shut-off of the source is not successful. For this the THTR 300 gives an example. The after-heat also under accident conditions must be removed from the primary circuit by the steam generators. Therefore the possibility that a defective steam generator operates during after-heat removal cannot, in principle, be excluded. However even in this case a pressure relief valve is not necessary for the limitation of the primary circuit pressure. The reasons for this are the extraordinarily high capacity of the emergency cooling system and the particularly favourable design parameters (see section 2.5).

2.2 Emergency Cooling Systems /1/

The THTR 300 is fitted with two emergency cooling systems, which are independent from each other. Both systems are shown schematically in Fig. 1. The removal of heat from the primary circuit is carried out by the main loops, of which three are designated to each emergency cooling system. Two loops for each system half are preselected for emergency cooling. The two non-selected loops are shut-down following the initiation of emergency cooling. The selection is automatically changed when moisture is detected in a preselected loop. However an automatic switch from a selected loop to a non-preselected and already shut-down loop is not possible during emergency cooling operation.

Following the start of emergency cooling the normal secondary-circuit is automatically divided between the two emergency cooling systems. The feed of steam generators used for emergency cooling is taken over by the emergency feed pumps of both emergency cooling systems. Before that the pressure in the steam generators is reduced by steam relief valves. Within about 90 s after initiation of emergency cooling the systems have reached their full cooling capacity.

As long as the steam generators are producing steam the secondary circuit remains open (left hand side of Fig. 1). In this situation water and steam are separated in the steam separator. The water returns to the emergency water tanks via heat exchangers, while the steam is released to the atmosphere after cooling the reheaters. As soon as steam production ceases the secondary circuit is closed (right hand side in Fig. 1). The reheaters are then no longer cooled.

Emergency cooling is introduced by either a moisture or a pressure signal. Both criteria lead to an emergency cooling mode, known as EC 5, which provides an extremely rapid cool-down of the primary circuit. The gas mass-flow in each loop is estabilished in this condition at about 27 % of the nominal flow rate in normal operation. In the case when only one loop is operating in one system half the heat removal capacity of this loop is automatically doubled by the increase of the feed water and the gas flow rates.

2.3 Probability of Emergency Cooling with one Defective Steam Generator

The probability of emergency cooling with one defective steam generator is extremely small as a systematic accident analysis has shown. As an example the accident topology is shown in Fig. 2 for multiple tube failure in one of the steam generators preselected for emergency cooling. The number of ruptured tubes is assumed to be so large, that the entire emergency feed water flow to this steam generator enters the primary circuit if this steam generator is used for after-heat removal. Due to the increase of the gas outlet temperature caused by the superheated steam the defective steam generator would be shut-down as a result of over-temperature trip. If the temperature instrumentation fails, within 13 s after the beginning of the accident the moisture detection system in the defective loop will react and shut-down the steam generator. Simultaneously the reactor is shut-down and emergency cooling 5 is introduced in which only intact steam generators are operating.

If the moisture detection system in the defective loop has failed, the shut-down of the reactor and the introduction of emergency cooling will occur somewhat later due to the increased pressure in the primary circuit. In this case the moisture detection system remains active, so that after introduction of emergency cooling an intact steam generator might be shut-down by this system. The probability that this intact steam generator belongs to the same system half as the defective is 1 : 2. In both cases emergency cooling is operating with two intact and one defective steam generator. However in one case the defective steam generator is double fed, in the other case single fed. If the moisture detection system also fails in the intact loops, emergency cooling operation takes place with three intact and one defective steam generator. The same condition occurs if the pressure instrumentation of the primary circuit has failed but instead of that emergency cooling is introduced by activation of the moisture detection system in one intact loop. The values shown in the figure are the assessed frequencies for each sequence. The values can only be used as indications because the frequency of the simultaneous failure of several steam generator tubes is not known. Therefore, on the basis of the failure probability of one tube an upper limit of 10^{-5} per steam generator and year was assumed. It is expected that this limit is already too high for a single fed steam generator and much too large for the case of a double fed defective unit, because twice the number of tubes must fail in the latter case to allow the full feed-water flow to enter the primary circuit.

2.4 Temperature- and Pressure-Time-Behaviour in Emergency Cooling with one defective steam generator.

Because of the expected higher occurrance probability and the greater relevance for similar accidents, which are initiated by a single tube failure in one steam generator and which have an occurance probability four orders of magnitude higher both sequences with a single fed defective emergency steam generator were chosen for detailed transient analysis. In this case the continuous water ingress rate during emergency cooling is 12,5 kg/s. The calculation starts at that time when the circulators have reached their full speed. At this time already 2,7 t of steam have entered the primary circuit.

One important physical parameter controlling the pressure transient in the primary circuit is the gas temperature in the cold-gas plenum, because more than 90 % of the gas inventory of the primary circuit is contained in this plenum. Fig. 3 shows the time dependence of the cold-gas temperature together with the gas-outlet temperature of the defective and the intact loops. In the beginning all temperatures fall very rapidly as a result of the very effective cooling, but run through a minimum and later increase again. The increase of gas-outlet temperature both in the defective and in the intact steam generators is a result of the rapid increase of the steam content in the coolant, which causes an increase of the thermal capacity of the coolant. The consequence is an accelerated cooling of the core. In the intact steam generators this leads to an excess of thermal power, which cannot be removed by the steam generators. Therefore the gas-outlet temperature increases with increasing steam content. In addition, already after 200 s condensation takes place, which increases the excess of thermal power.

For the defective steam generator the effect of the rapid increase of the steam content in the coolant automatically causes a rise of the steam content at the gas-outlet of the steam generator, because part of the thermal power must be stored in evaporating feed water. In saturation conditions of the coolant, which is already reached after 150 s, this is only possible if a simultaneous increase of the gas-outlet temperature of the defective steam generator occurs. A decrease of the gas-outlet temperature of the defective steam generator occurs, when the time dependent reduction of the evaporation rate, which depends on the thermal power, is greater than the time dependent increase of the steam content in the cold-gas-plenum. This will occur after about 1300 s. At this time, the condensation rate in the cold-gas plenum has reached such a high value, that the steam content increases only very slowly.

The gas temperature in the cold-gas plenum falls until the start of condensation and then increases again with the gas-outlet temperature of the intact and the defective loops. The calculated temperature behaviour is based on the assumption, that the water fed into the cold-gas plenum is spontaneously evaporated as long as saturation has not been reached. This is a conservative assumption with regard to the pressure build-up in the primary circuit.

Fig. 4 shows the time dependent behaviour of the primary circuit pressure and the condensation rate in the cold-gas-plenum. In spite of the continuing operation of the defective steam generator a pressure of 48 bar is not exceeded. The maximum lies only a little above proof-pressure and is far below the value which is accepted for such an improbable accident. It is reached after 1750 s. At this time, the condensation rate in the cold-gas-plenum exceeds the feed-water flow rate of the defective steam generator, so that the steam content in the primary circuit is slowly reduced. Up to this time 23,5 t of water have entered the primary circuit of which 14,8 t are in the form of steam while 8,7 t have been condensed.

2.5 Conclusions

The analysis has shown, that in case of favourable design characteristics even very severe water ingress accidents, in which an identification and shut-off of the water source is not successful, can be coped with without opening the primary circuit for limiting the pressure build-up. In this respect, the particularly favourable design characteristics of the THTR, which are related to this, are as follows:

- the large cold-gas plenum, which contains more than 90 % of the coolant inventory of the primary circuit,
- the low cold-gas temperature of 523 K (250° C), which is the boiling temperature of water at a pressure of 40 bar,
- the low core temperature during normal operation,
- the large cooling capacity of the after-heat removal systems (emergency cooling systems) and
- the large difference between operation pressure and failure pressure of the primary circuit.

The large volume of the cold-gas plenum is capable of storing a considerable amount of steam. The low operation temperature of the cold-gas plenum prevents, that condensed water, which comes into contact with the plenum structure, is vapourised by boiling so long as the primary circuit pressure is above 40 bar. The large cooling capacity of the after-heat removal systems provides for a rapid cooling of the core and the cold-gas plenum, so that early condensation take place and only negligible amounts of reaction products are formed.

3. Air Ingress

3.1 Air Ingress Rates

Significant quantities of air can only enter the primary circuit of an HTR, if there is a large opening between the primary circuit and the containment. In the case of a completely integrated primary circuit in the PCRV (Prestressed

Concrete Pressure Vessel) the air ingress rate depends primarily on the size and the position of the opening as well as on the thermodynamic conditions in the primary circuit and in the containment. The largest ingress rates occur, when the opening is in the top head of the PCRV. In this case a natural convection flow between the primary circuit and the containment can be established/2/.

The rate of the natural convection flow was calculated for various depressurization accidents by a computer code developed for this objective. The investigation was based on an annular gap, because the openings in the top head of the PCRV are fitted with doubly secured plugs and only a failure of the seals is postulated. It was assumed, that the flow cross section is equivalent to the clearance between the plug and the liner. The effect of flow-restrictors was taken into account. However it was neglected, that the plug because of its weight will reseat after depressurization of the primary circuit, acting like a safety-valve.

Natural convection in an annular gap can only take place, when the pressure balance shown in the vector diagram of Fig. 5 is fulfilled. In the case of the ingress stream the following must hold: static pressure in the containment plus the pressure of the weight of the gas column minus the pressure loss equals the primary circuit pressure. For the case of the outlet stream the weight of the gas column and the pressure loss act in the same direction, so that the addition of both values to the static pressure in the containment gives the pressure of the primary circuit. Both mass flow rates, which are coupled by the primary circuit and by the containment, take up the value by which the described pressure balance is fulfilled. It is difficult to say how the total cross section is divided between inlet and outlet flow. However, it can be shown that both mass flows reach a maximum for a certain relationship between the relative cross sections. This maximum depends on the conditions in the primary circuit and in the containment and is automatically used by the computer code.

The time dependent mass-flow through the opening is shown in Fig. 6 for the case of a leak cross-section of 0,5 m^2, an equilibrium pressure of 2 bar and with the after-heat removal system in operation. The results are based on the time dependent behaviour of the temperature of the primary circuit typical for HTRs under these accident conditions. In the initial phase the ingress rate is much larger than the outlet flow rate in spite of the increasing temperature in the primary circuit. This is due to the fact that the lighter gas in the primary circuit is displaced by the heavier gas in the containment. This exchange effect is shown by the dotted curve, which gives the helium fraction in the primary circuit as a function of time. Also in the later phase the inflow exceeds the outflow, which is caused by the decreasing temperature of the primary circuit. The average ingress rate over 6 h is only about 0,5 % of the gas flow rate in the primary circuit. In the same period about 650 kg O_2 enter the circuit. The ingress rate is reduced from an initial value of 190 kg/h to 75 kg/h. At this time, the oxygen content in the containment atmosphere has fallen by 4,5 %.

In the case in which the after-heat removal system has failed, approximately the same mass flow rates in the leak were calculated. Therefore it can be concluded, that the gas exchange between the primary circuit and the containment by natural convection in a top head leak is relatively insensitive to the specific accident sequence. The calculated air ingress rates lie within an order of magnitude, in which circumstances the graphite burn-off of the core is not critical. The quantities of burnable gases which are formed present no danger to the containment in the case when the after-heat removal system is operating and present no immediate danger to the containment in the case when the after-heat removal system has failed.

3.2 Graphite Burn-Off in the Case of Large Air Ingress Rates

Large air ingress rates, which are substantially greater than the values given above, are only conceivable for the current integrated designs of HTR-concepts in conjunction with extremely improbable depressurization accidents. Because these accidents are so unlikely they have no influence on the engineered safeguards. In spite of this, parameter-studies have been carried out with relatively large air ingress rates for the purpose of understanding the behaviour of HTR-pebble bed systems with massive air ingress /3/. In this study the newly developed graphite corrosion computer code REACT/THERMIX was used for the first time. This code has been developed specifically for pebble bed reactors.

The PNP 500 reactor was chosen. It was postulated that the reactor is shut-down at the beginning of the depressurization accident and that the after-heat removal systems start 5 min later. The gas temperature at the entrance of the cold-gas-plenum was taken to be 300° C. The gas flow rate through the core and the gas exchange rate between primary circuit and containment were varied. The latter was taken to be a fixed percentage of the flow rate through the core. The gas which leaves the primary circuit was assumed to mix spontaneously with the containment atmosphere.

The axial temperature profile in the center line of the core is shown in Fig. 7 for various times after the start of the accident. The gas flow through the core was taken in this case to be 6 % of the gas flow during normal operation and the volume exchange rate was taken to be 40 % of the gas flow rate. This case was chosen in order to demonstrate the effects of corrosion on the temperature profile.When the after-heat removal systems start operation the maximum temperature was 1030° C approximately. The maximum lies 480 cm below the core top. After 15 min this maximum has been shifted to a depth of about 170 cm caused by the heat of reaction of carbon combustion in the upper core region. After 30 min the highest temperature of about 1300° C is reached. From then on the maximum temperature moves in the flow direction through the core, which means that the reactor is cooled down.

The total graphite burn-off as a function of time is shown diagramatically in Fig. 8 for a constant volume exchange rate of 20 % and various flow rates through the core. The reduction of the total burn-off with increased flow rate through the core is caused by the more rapid cooling of the core which arrests the chemical reaction at an earlier time. In the case of low core flow rates and the assumed high volume exchange rates almost the total inventory of oxygen in the containment is consumed. The maximum burn-off of a fuel ball is less than 50 % of the fuel-free region.

The parameter-study carried out has shown that even in the case of an accident involving high air ingress rates the reactor core is safely cooled down and graphite burn-off of the fuel balls is limited to the fuel-free region. Massive fission product release as a result of corrosion is therefore not to be expected. The frequently feared "graphite fire" can even under these unfavourable accident conditions be excluded.

4. Summary

The results of the presented work can be summarized as follows:

- The favourable design features of the THTR limit the pressure build-up in the primary circuit to values below critical values in water ingress accidents even when the source of water is not identified and shut-off. A pressure reduction by safety valves is in this case not necessary so that the accident consequences remain confined in the primary circuit.
- The expected air ingress rates following a depressurization accident through an opening in the top head of the PCRV are extremely small in the case of complete integration of the primary circuit in the PCRV. The chemical processes in the primary circuit remain so limited that no danger for the fuel elements and the containment exists.
- The often feared"graphite fire" can be excluded even in the case when the circulators of the after-heat removal systems take in a high percentage of containment atmosphere. The core is cooled down safely.

The presented work has contributed towards improving the understanding of the processes taking place during water and air ingress accidents. Future work is aimed at reducing uncertainties and improving the modelling for a more realistic description of the processes involved in such accidents.

5. References

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/3/ R. Moormann, W. Katscher, K. Petersen, H.-K. Hinssen
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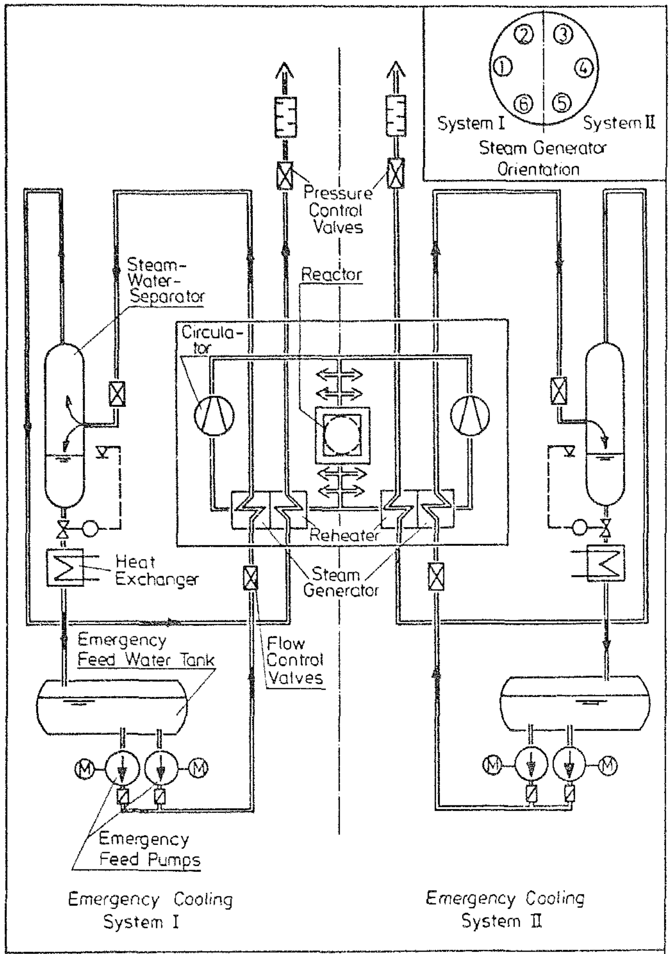
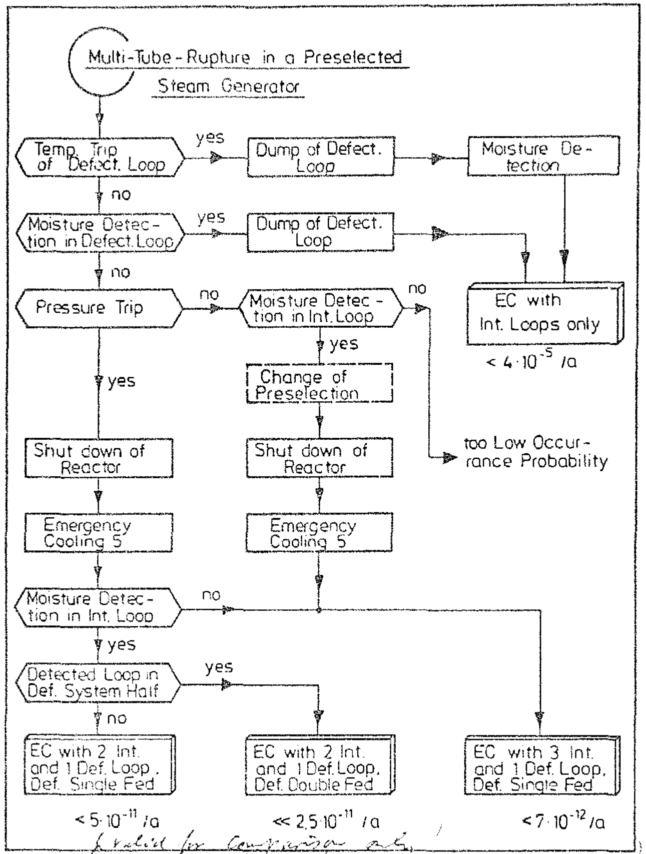


Figure 1: Emergency Cooling System of the THTR 300



(valid for comparison only
(don't know failure frequency for multiple tubes)

[ ] Changed only if detected intact loop was preselected for EC.
EC: Emergency Cooling

Figure 2: Topology of Water Ingress Accidents Initiated by Multi-Tube-Rupture in a Preselected Steam Generator

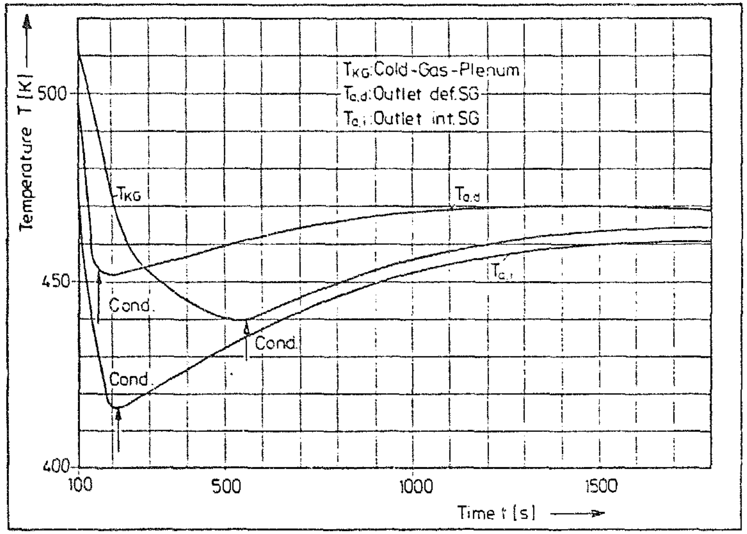


Figure 3: Time-Dependent Behaviour of Important Primary Coolant Temperatures of the THTR in the Case of a Single Fed Emergency Cooling Steam Generator.

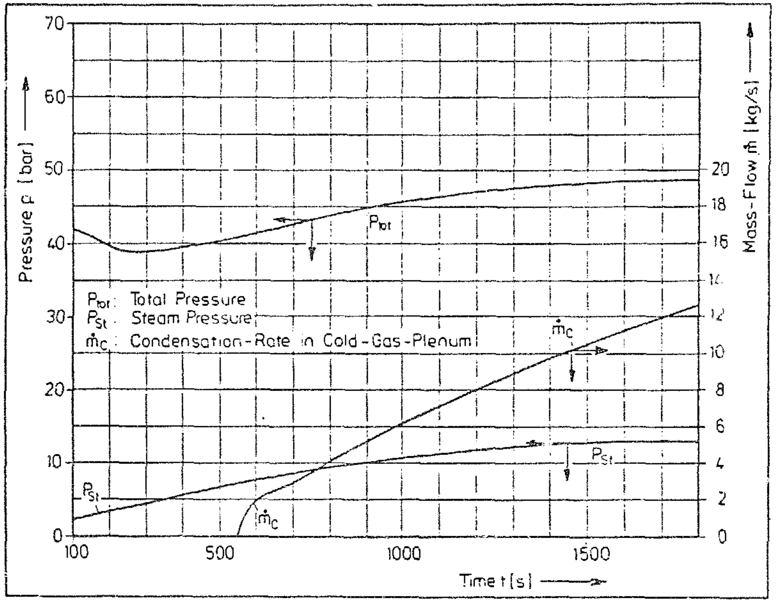
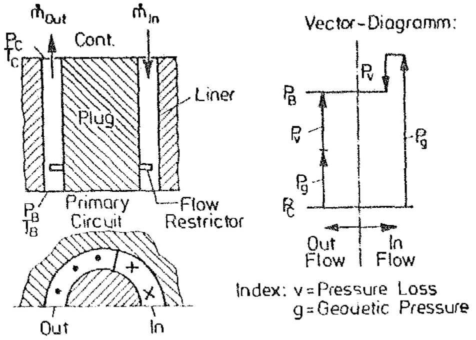
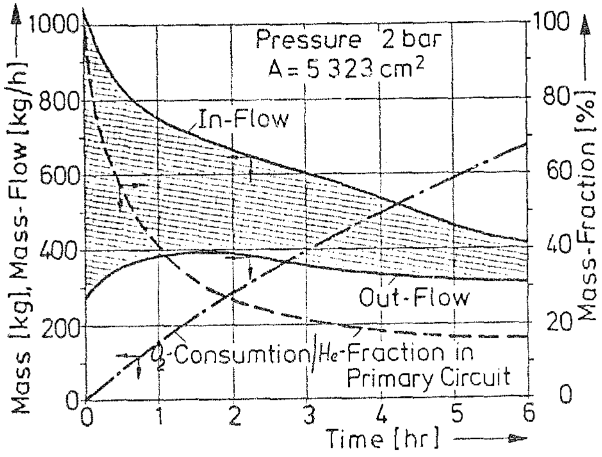


Figure 4: Time-Dependent Behaviour of the Total Pressure, the Steam Pressure and the Condensation Rate in the Cold-Gas-Plenum of the THTR in the Case of a Single Fed Emergency Cooling Steam Generator.



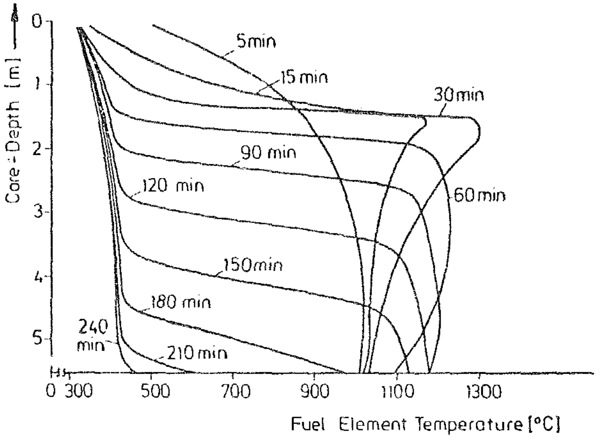
Model for the Calculation of the Natural Convection Flow in an Annular Gap

Figure: 5



Time-Dependent Behaviour of Various Parameters in the Case of a Depressurization Accident with Operating After-Heat Removal Systems

Figure: 6



Temperature Profile in the Core Center Line for Various Time-Steps, a Flow Rate of 6% and a Volume-Exchange Rate with the Containment of 40%.

Figure: 7

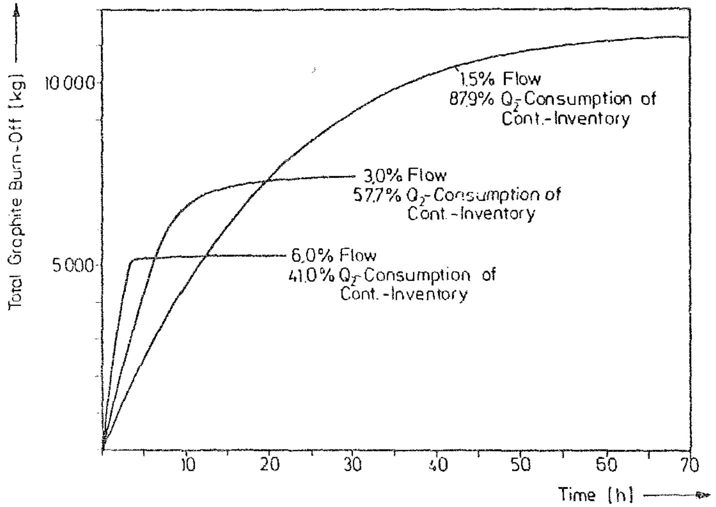


Figure: 8

Time-Dependent Graphite Burn-Off for a Constant Volume-Exchange Rate with the Containment of 20% and various Flow Rates.