AIR AND WATER INGRESS ACCIDENTS IN A HTR-MODUL OF SIDE-BY-SIDE CONCEPT

J. WOLTERS, G. BREITBACH, R. MOORMANN
Institut für Nukleare Sicherheitsforschung,
Kernforschungsanlage Jülich G.m.b.H.,
Juelich, Federal Republic of Germany

Abstract

Air Ingress

Since the possibility of a temperature induced release of fission products from the core has been eliminated by the design of the HTR-Modul, the question arose wether corrosion by air can result in a significant release of fission products.

The design basis depressurization accident is the fracture of a fuel element charge tube which are integrated in the reactor vessel and enter the pressure boundary at the bottom. For this design the gas exchange through the failed tube after depressurization was investigated. It was demonstrated by an experiment that the exchange rate is controlled by the temperature development in the primary circuit allone. As long as the temperature increases, thermal expansion of the gas prevents air from entering the circuit. Thus air is first sucked in when the temperature decreases after 100 h. But the total amount of air entering the circuit is so small, that corrosion can be neglected.

Massive air ingress is only possible by natural convection and requires three large leaks in the pressure boundary at suitable positions (chimney effect). Such an event is hardly imagenable, since the occurrance of one leak already eliminates the mechanism for the formation of additional leaks. Nevertheless this highly hypothetical event was considered in order to get knowledge about the behaviour of the system under these extreme conditions. The results show that the maximal degree of corrosion of fuel elements remains low for a long period of time, since the corrosion zone moves through the pebble bed core. A massive release of fission products is significantly delayed, thus plenty of time is available for counter measures.

Water Ingress

Water ingress accidents proved to be dominant for the risk of a HTR-Modul. This is due to the fact that fission products deposited on the surface of the primary circuit can be remobilized by re-

action with water and steam and can be released from the primary circuit via two release paths. One path leads via the relief valve and the ventilation system to the stack, the other via the steam generator leak and the dump line, if a dump line valve fails to close.

The first path would occur, if the pressure built up by steam and water gas causes an opening of the relief valve. Thus the pressure built up was investigated for a broad spectrum of boundary conditions taking into account the conversion of water into steam and the transformation of steam into water gas. The analysis has shown that the pressure increase by steam alone will not cause an opening of the relief valve. This is also true if the dump line fails to open although in the worst case 4 t of water therefrom 200 kg in the form of steam would enter the primary circuit. But less than 1000 kg of steam are produced due to the suppression of natural convection via the primary circuit. Thus the short term pressure increase is only double as high as in the design basis accident and not sufficient to open the primary circuit.

In any case the pressure relief valve will only open if the gas purification plant fails. The additional pressure increase necessary to reach the set point of the valve is caused by temperature expansion and water gas production. After having reached the set point, which takes several hours about one third of the remobilized activity mainly Cs-137 is released from the primary circuit. If the dump line fails to close the primary circuit will be depressurized and all the remobilized aktivity plus part of the radioactive substances released from the core by temperature increase (mainly Iodin) will be transported to the environment. This proved to be the worst case, although under conservative assumptions not more than 70 Ci Cs-137 (dominant nuclide) and 400 Ci I-131 escape from the primary circuit.

1. Introduction

By the limitation of the maximum core temperature to values below 1600 °C under all accident conditions the temperature-induced release of fission products from the core has been eliminated in an HTR MODUL /1/. Consequently the core heat-up accident loses its risk-dominating role. This means that the HTR-specific accidents 'depressurization' and 'water ingress' become significant from the risk point of view /2/. In conjunction with depressurization accidents the question arises whether air ingress can endanger fission product retention in the fuel elements. Graphite corrosion by air could be the only mechanism having the potential for the release of larger quantities of fission products from the core.

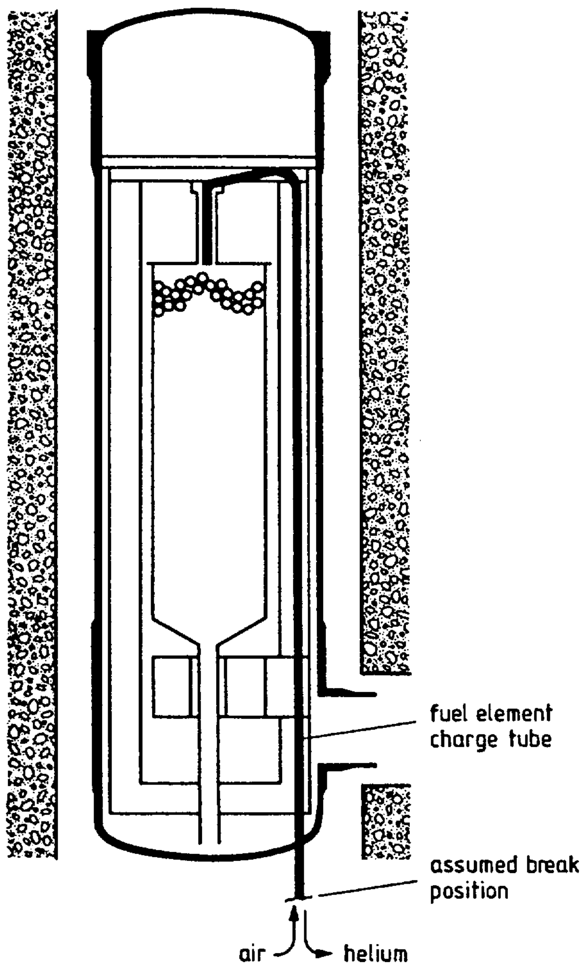
On the contrary, graphite corrosion by steam has no potential at all for a significant release of fission products from the core. But the water ingress accident can result in a remobilization of fission products deposited on the surface of the circuit, especially the steam generator, by reaction with water and steam and in a release of the remobilized fission products from the primary circuit. One reason could be the pressure build up in the circuit by steam and water gas. One is easily inclined to exaggerate the pressure build up in the primary circuit in conjunction with a water ingress accident because of the small volume of the primary circuit compared with that of an HTR of medium power size. Thus this aspect has been emphasized in this presentation.

2. Air Ingress

2.1 Design Basis Depressurization Accident

The design basis depressurization accident is the fracture of fuel element charge tube which is integrated in the reactor vessel and enters the pressure boundary at the bottom (Fig. 1). If this tube breaks off a depressurization occurs within about 15 min until pressure is balanced between the primary circuit and primary cell. In the course of this accident at first the remaning helium in the reactor heats up. Related to the gas exchange between primary circuit and cell, the behaviour of the average helium temperature in the whole primary circuit is important. During 95 h this average temperature increases from 210 °C to a maximum value of 290 °C. Then the primary circuit gas cools down and after 500 h an average temperature of 233 °C is reached. Because of temperature-induced expansion and contraction gas flows between primary circuit and cell through the failed tube. It was to be investigated, whether combined diffusion and convection effects in the tube result in a larger air ingress producing significant graphite corrosion.

Experiments were carried out for the investigation of the transport phenomena in the tube. In these experiments a large heliumfilled container was connected with the environment via a long vertical-



HTR-MODUL, Position of the Assumed Tube Break

Fig. 1:

ly installed 65 mm diameter tube /3/. Because of fluctuations of the container gas temperature and the atmospheric pressure, changes of the container gas state occurred producing gas motion through the tube, where convection and diffusion are superposed.

The air ingress in the container along the tube could be described very well by the following differential equation combining convection and diffusion

$$\frac{\partial c_{Lu}}{\partial t} = D_{He-Lu} \cdot \frac{\partial^2 c_{Lu}}{\partial x^2} - v \cdot \frac{\partial c_{Lu}}{\partial x} \qquad (1)$$

with

$C_{Lu} = C_{Lu}(x,t)$ = air concentration along the tube $\left[\frac{kmol}{m^3}\right]$

D_{He-Lu} = mass diffusivity helium-air $7 \cdot 10^{-5}$ $\left[\frac{m^2}{sec}\right]$

v = gas velocity in the tube produced by expansion and contraction of the container gas (see /3/) $\left[\frac{m}{sec}\right]$

Analysis of the experimental results and theoretical investigations has shown that transport phenomena along the tube - as described by the differential equation (1) - are very simple, if

$$D_{He-Lu}/L_{Rohr} \ll v.$$

Then diffusion effects can be neglected.

In the case of the design basis depressurization accident of the HTR-MODUL the inequality relation $D_{He-Lu}/L_{Rohr} \ll v$ is always fulfilled. By the thermal expansion of the primary circuit gas during the first 95 h convection velocities of 0.05 m/sec occur in the tube, during the contraction phase between 95 h and 500 h velocities in the range 0.01 m/sec are established. By taking into account this information the air ingress can be estimated very simply. For a fixed atmospheric pressure - its fluctuations can be neglected here - the change of the total number of moles of the primary circuit is influenced by the temperature change $\frac{dT}{dt}$ only. The following differential equation governs the time behaviour of the total number of moles N

$$\frac{dN}{dt} = - \frac{N}{T} \cdot \frac{dT}{dt}$$

By taking into account the time dependence of the average gas temperature the total number of moles of the primary circuit is then given by the curve of Fig. 2.

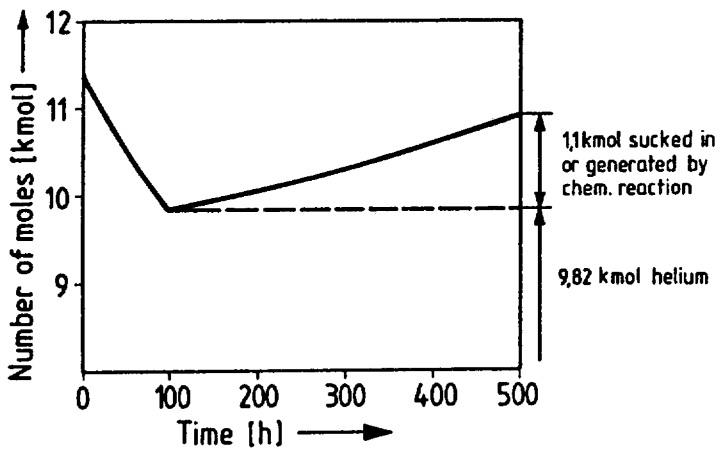


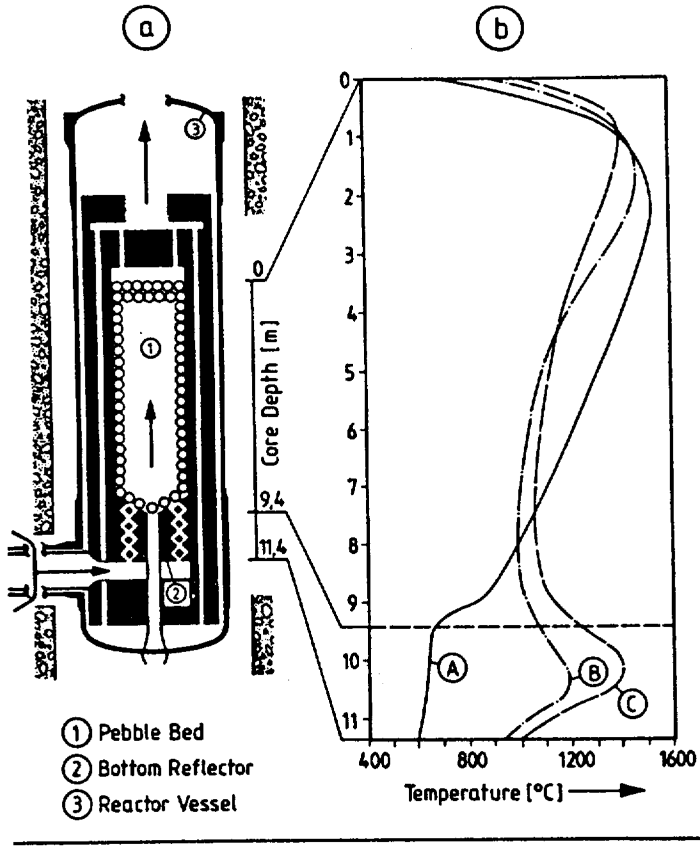
Fig. 2: Total Number of Moles in the Primary Circuit (0-500h)

After 95 h from originally 11.45 kmol helium, the primary circuit still contains 9.82 kmol He. No air can penetrate against the outflowing helium in this 95 h time interval. After this because of cooling down, gas is sucked from the cell into the primary circuit. After 500 h besides the remaining 9.82 kmol He, 1.1 kmol gas is found there, which is either sucked in or generated by chemical reactions with the reactor graphite.

By assuming conservatively that the gas sucked in consists of air only 0.73 kmol N_2 and 0.37 kmol CO are found in the primary circuit, if O_2 reacts completely to CO. A simple calculation shows that only 4-5 kg graphite (from more then 100 tonnes!) are converted by air ingress. So by averaging over 500 h the corrosion rate is less then 10 g/h.

2.2 Highly hypothetical depressurization accident

Since the blower is stopped in the case of a depressurization accident, no air can be drawn in by forced convection. Consequently massive air ingress into the core is only possible by natural convection. One possibility would be the so called chimney effect, which requires three large leaks in the primary circuit at suitable positions (Fig. 3). Such an event is hardly imagi-



a) Scheme of the HTR-MODUL with Flow Paths in the Case of a Chimney Draught Accident

b) Temperatures along the Central Axis of the Core after 20h in the Case of Massive Air Ingress Caused by a Chimney Draught of Different Intensity A:0.02kg/s, B:0.3kg/s, C:0.6kg/s

Fig. 3:

nable since two leaks must occur in the pressure boundary and the occurrence of one leak already eliminates the mechanism for the formation of another leak. Nevertheless this highly hypothetical event was considered to obtain knowledge about the behaviour of the HTR-MODUL under these extreme conditions.

The analysis of the corrosion process was carried out by the REACT/THERMIX code /4/ on the basis of three different air ingress rates, namely 0.02 kg/s, 0.5 kg/s and 0.6 kg/s. The upper value is to be expected if the pressure loss of the core alone controls the ingress rate. The other two values stand for a size of the entrance leak (Fig. 3) of 0.05 m^2 and $33 \cdot 10^{-4}$ m^2 (design basis depressurization accident) respectively. Pessimistically it was assumed that pure air at a temperature of 100 °C always enters the circuit and that the quantity of air is not limited by the volume of the primary cell. This requires an additional large orifice between cell and environment.

The diagram of Fig. 3 shows the temperatures along the central axis of the core 20 h after the initiation of the chimney draught. Due to the small chemical heat production with an air ingress rate of 0.02 kg/s (Curve A) the bottom reflector cools down by heat conduction within one day to such an extent that the C/O_2-reaction zone is shifted into the pebble bed. On the assumption of uniform corrosion attack about two days would elapse before a burn-off of the fuel-free zone of single fuel spheres is to be expected. At this time 0.2 % of the fuel spheres would show a burn-off of more than 90 % of the fuel-free zone. On this occasion it must be pointed out that an uncovering of coated particles does not automatically result in a fission product release from the particles. If the potential of oxygen in the oxidizing atmosphere is sufficiently high the SiC coating will be converted into SiO_2, which can inhibit a further corrosion attack.

With the large air ingress rates a small fixed C/O_2-reaction zone occurs in the bottom reflector, which results in a clear temperature peak in this component as can be seen from curves B and C of Fig. 3. This means that the air oxygen is completely consumed in the bottom reflector. At the prevailing graphite temperatures the corrosion is restricted to the surface so that the weakening of the core support structure is approximately directly proportional to the degree of corrosion. In the cases B and C the weakening of the reflector reaches crucial values after 32 h to 40 h so that parts of the bottom reflector are expected to fail in this time interval. This collapse affects the further development of the accident in an unknown way. Consequently it is less meaningful to extend the corrosion calculation for beyond this time.

Fuel sphere corrosion also occurs in the cases B and C due to the so called Boudouard reaction (C/CO_2). This endothermal reaction is not locally fixed under the prevailing accident conditions and takes place in a much broader zone than the C/O_2 reaction. The consequence is that despite the high ingress rates it takes 81 h in case B and 19 h in case C to remove the fuel-free zone of single fuel spheres. At this time 0.4 % of the fuel spheres in case B and 0.9 % in case C show a burn-off of more than 90 % of the fuel-free zone. The endothermal character of the Boudouard reaction contributes to the effect that the maximum fuel element temperatures are clearly lower (Fig. B) than in the case of an adiabatic core heat-up. The gas escaping from the reactor vessel consists mainly of CO and N_2. The concentration of CO_2 always remains low.

3. Water ingress

3.1 Event sequences

A water ingress into the primary circuit of the HTR-MODUL is detected by the moisture monitoring system. It causes different protective actions, namely: tripping of reactor and blower, closure of the blower valve, isolation of the steam generator on the secondary side and dumping of the steam generator to the pressure of the primary circuit from the feed water side. The operation of the purification plant is necessary to avoid an opening of the relief valve in the later phase of the accident.

In the case of a water ingress accident there are two paths via which remobilized fission products can be released from the primary circuit into the environment /2/. The one leads via the relief valve and the ventilation system of the reactor cell to the stack, if the pressure build up causes an opening of the valve. The other path leads via the steam generator leak and the dump line, if a dump line valve fails to close. This would result in a complete depressurization of the primary circuit with the consequence that a core heat-up at ambient pressure would take place.

3.2 Pressure build up

The pressure build up in the primary circuit was investigated for a broad spectrum of boundary conditions taking into account the conversion of water into steam and the transformation of steam into water gas. One important parameter proved to be the quantity of water and steam entering the primary circuit. It depends on the size and position of the steam generator leak. A leak at the feed water side (bottom) is the worst case as can be taken from the first two lines of Table 1. The given values are based on a double-ended fracture (2F) of one steam generator tube. This is the design basis leak size. From the risk point of view, leak sizes of up to 2 cm^2 (1F) are dominant because of their higher occurrence probability. This leak size in conjunction with dumping of the steam generator after 12 s causes an ingress quantity of 460 kg, mainly water which we suppose is very quickly converted into steam, thereby increasing the pressure from 60 bar to 62.3 bar. In order to reach the set-point of the relief valve at 69 bar additional pressure increase is necessary, which is caused by temperature expansion and water gas production, provided the gas purification plant fails.

Table 1:

Quantities of Water and Steam Entering the Primary Circuit in the Case of a Steam Generator Leak of Different Size and Position with Different Plant Reactions

Leak Size	Leak Position	SG-Dump	Quantities (kg)		
			Steam	Water	Total
2F	Super Heater	yes	75	135	210
2F	Economizer	yes	30	460	490
1F	Economizer	yes	~10	450	460
1F	Super Heater	no	985	65	1050
1F	Economizer	no	235	3875	4110

Detection Time inclusive Isolation : 12 s

In any case the pressure build up by steam alone is not sufficient to reach the set-point of the relief valve. This is also true if the steam generator is only isolated but not dumped although in the case of a leak at the bottom side the total inventory of the steam generator would enter the primary circuit. This is more than 4000 kg mainly liquid water as can be taken from the last line of Table 1. With respect to the pressure build up the decisive question is how much water entering the primary circuit is converted into steam. To answer that question one must know that the gas side of the steam generator is divided by support structures into eight practically closed vertical sections. Consequently the steam production is restricted to the volume of one section. For the calculation of the production rate it was assumed that instantaneous conversion of the water entering into steam takes place as long as parts of the structure in the volume exceed the saturation temperature. After that a complete saturation of the atmosphere in this volume by steam was postulated so that the steam production is controlled by the gas exchange between the volume and the surroundings.

The upper digram of Fig.4 shows the time-dependent ingress rate of water and steam and the vaporization rate of the entering water. For only a few seconds all the water is converted into steam by boiling. After that the vaporization rate drops down to a few kg per second so that the majority of the entering water remains in the liquid form and is collected in the bottom cap of the steam generator vessel. The vaporization from this pool is so low that the vaporization rate drops to nearly zero when the water ingress is finished.

The lower diagram of Fig. 4 shows the time-dependent development of the total pressure and the appropriate partial pressures in

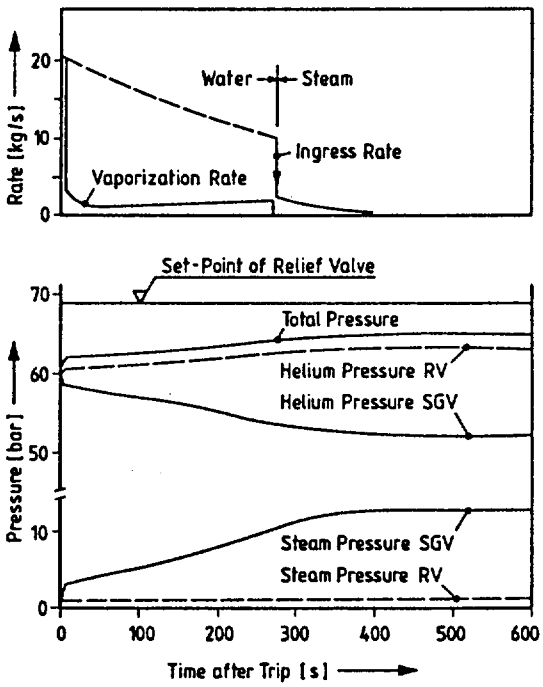


Fig. 4:

Conditions in Reactor (RV) and Steam Generator Vessel (SGV) of the HTR-MODUL in the Case of no Dump after a Steam Generator Leak of 2cm² (1F) at the Feed Water Entrance the reactor and steam generator vessel. The partial pressure of steam in the steam generator vessel, which has a strong influence on the vaporization rate, increases to about 13 bar, whereas that in the reactor vessel reaches less than 2 bar. The total pressure of 65 bar remains well below the set-point of the relief valve. This is also true if the ingress phase is extended due to a smaller leak or if the leak occurs at the top of the steam generator, but the total pressure is about 1 bar higher. Nevertheless the gas purification plant is capable of preventing the relief valve from opening.

If the purification plant fails the question arises at what time and how often the relief valve would open. Apart from the steam content in the primary circuit the answer depends on the mean temperature increase of the gas in the case of afterheat removal via the surface of the reactor vessel and on the production of water gas. The latter can be taken from Fig. 5 together with the corresponding pressure increase. Both curves are based on a steam content in the circuit of 600 kg (design basis accident) and on the assumption that the blower valve fails to close. The open blower valve results in a slight gas circulation in the primary circuit with the consequence that all the steam comes into contact with the hot graphite. If inhibiting by the reaction products is not taken into account, it takes about 12 h to convert 80 % of the steam into water gas. In this case the pressure relief valve would open after 4.5 h /2/. The time interval is extended to 5.5 h, if the blower valve duly closes so that only the steam in the core can react. In reality one has to expect an opening of the relief valve not earlier than 5 to 6 h because

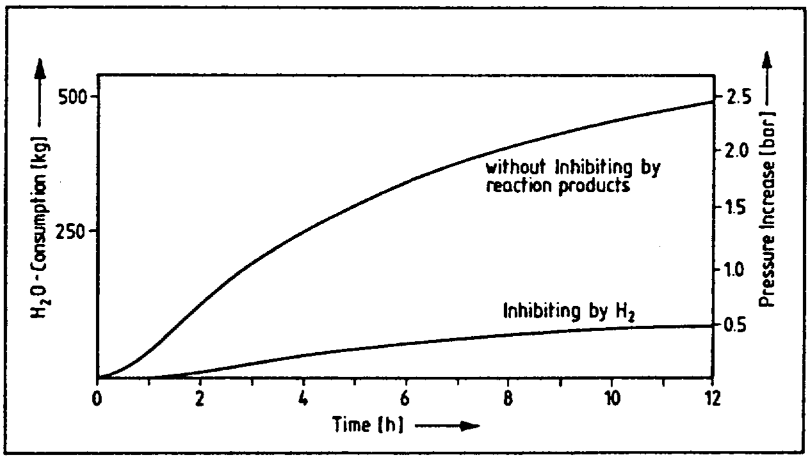


Fig. 5: Time Dependent H_2O-Consumption and Pressure Increase after the Ingress of 600 kg Steam into the HTR-MODUL with the Blower Valve Open

of the inhibiting effect of the reaction products. At that time the water gas content does not exceed the flamability limits so that the formation of burnable mixtures in the release path can be excluded.

On opening of the relief valve about 10 % of the gas inventory is released from the primary circuit. After having closed the valve would not open again since the new pressure build up is not sufficient to reach the set-point of the relief valve.

3.3 Radiological consequences

The opening of the relief valve may result in a release of 30 % of the remobilized fission products due to the fact that the gas is released from the steam generator vessel in which a higher concentration of the remobilized fission products must be expected. At least this is true in the most probable case when natural convection via the primary circuit is completely stopped by the closure of the blower valve.

If the dump line of the steam generator fails to close in the case of a leak larger than 1F the primary circuit would be depressurized at the latest after 10 h. This proved to be the worst case from the radiological point of view because all the remobilized fission products plus the fission products released from the core by temperature increase during depressurization would be transported into the environment. Under very pessimistic assumptions 70 Cs-137 (dominant nuclide) and 400 Ci I-131 were estimated in /2/. There are a lot of indications that these values are much too high. For instance, it is to be expected that the application of new experimental results will reduce the Cs-137 release to about 1 Ci.

4. Conclusion

The analysis of air ingress accidents has shown that in the case of the design basis depressurization accident the total quantity of air entering the primary circuit is so small that graphite corrosion can be neglected. Even in case of a chimney draught, the occurrence of which is hardly imaginable, at least 19 h elapse before corrosion-induced fission product release from the coated particle is to be expected. Therefore the general conclusion is justified that in any case there is plenty of time for countermeasures. From the risk point of view graphite corrosion by air is negligible.

The analysis of water ingress has shown that the pressure increase by steam alone will not cause an opening of the relief valve. This is also true if the dump line of the steam generator fails to open although the total inventory of the steam generator may enter the primary circuit. In any case the relief valve will only open if the gas purification plant fails. The additional pressure increase necessary to reach the set-point of the valve is mainly caused by thermal expansion. The water gas production is too slow to influence the short-term pressure build up especially if the inhibiting effect of the reaction products is taken into account. From the radiological point of view not the opening of the relief valve but failure of the dump line to close proved to be the worst case.

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