REVIEW OF THE ACCIDENT SOURCE TERMS FOR ALUMINIDE FUEL: APPLICATION TO THE BR2 REACTOR

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ABSTRACT

A major safety review of the BR2, a material test reactor, is to be conducted for the year 2006. One of the subjects selected for the safety review is the definition of source terms for emergency planning and in particular the development of accident scenarios. For nuclear power plants the behaviour of fuel under accident conditions is a well studied object. In case of non-power reactors this basic knowledge is rather scarce. The usefulness of information from power plant fuels is limited due to the differences in fuel type, power level and thermohydraulical conditions. First investigation indicates that using data from power plant fuel leads to an overestimation of the source terms. Further research on this subject could be very useful for the research reactor community, in order to define more realistic source terms and to improve the emergency preparedness.

1. Introduction

BR2 is a material test reactor with a thermal power of 100 MW in operation since January 1963. A major safety review is to be conducted for the year 2006. This is a licence requirement. The objective of the safety review is to guarantee that a safe and reliable operation of the reactor is possible till at least 2016. One of the subjects selected for the safety review is the definition of source terms for emergency planning and in particular the development of accident scenarios. During the last years, the Belgian Authorities were already asking to prepare accident scenarios for the research reactors and for other nuclear installations. This article gives an overview of the information which is being used for defining BR2 accident source terms.

For nuclear power the behaviour of fuel under accident conditions is a well studied with the PHEBUS project as one of the most important examples. The basic knowledge (the behaviour of the fuel under heavy transient or accident conditions) for defining such scenarios for non-power reactors is rather scarce. The usefulness of information from power plant fuels is limited due to the differences in fuel type, power level and thermohydraulical conditions. This article gives some thoughts about the behaviour of aluminide fuel plates under accident conditions. Information is gathered from publications about release of fission products from fuel plates, from reports on accidents where the SL-1 accident is a very rich source of information and from some own experience.

2. Accident scenarios and source terms

Pre-defined accident scenarios have several advantages. They are an information source for the authorities to estimate the possible consequences of an accident and to assess the appropiate requirements for countermeasures. This information is useful for emergency preparedness exercises. In case of a real emergency, the scenarios can be used for fast communication with the authorities.

Defining the scenarios is normally not a difficult task. A simple fault tree model (without probabilities) will be sufficient. Defining acceptable source terms is a more serious problem. Source terms for power reactors are a well studied issue, with the PHEBUS research project as an important example. The use of this information for research reactors will however lead to unrealistic source terms, due to differences in fuel type and thermohydraulical conditions.

Research reactors operate in most cases at cooling water temperature and pressure, but have in contrast a high power density and high coolant flow rates. This makes the thermo hydraulic analysis in transient conditions, after an initiating event, complicated. In many cases flow instability could occur caused by steam formation in a hot channel, although the coolant globally is still sub cooled. Calculation programs developed for power reactors have to be modified [1].

Reactivity effects are also different. Most of the research reactors with a higher power level can load a significant quantity of reactivity (several times prompt criticality). This can give more severe reactivity transients. On the other hand, the proportion of surface compared to quantity of fuel is much greater for plate type fuel than for pin type fuel. This will lead to more local boiling during overheating of the fuel plate and more negative temperature coefficients. Much information can be found about these effects can be found in the published reports of the SL-1 accident [2].

3. Release of fission products from aluminide fuel plates in accident conditions

BR2 uses at this moment uranium aluminide fuel plates with high enriched uranium. This fuel was developed the seventies and is known to have excellent irradiation behaviour [3]. However knowledge of what is happening under abnormal conditions is scarce. In case of insufficient cooling, the temperature of the fuel plate will rise and volatile fission products will be released. Information about the release of fission products is summarized in an overview article [4]. This reference is based on data from tests during which irradiated fuel is heated and the release of fission products is measured and from measurements during reprocessing of the fuel. The release rates are given, for each volatile isotope, as correlations that may vary with time, ambient temperature, burn up and fuel temperature.

Predicting the fractions of fission predictions that will be released requires detailed modelling. In this context it must be understood that it concerns accident conditions, not releases occurring during normal operation. Release of fission products from aluminide fuels is observed when the temperature reaches about 560°C, at which blistering starts. The release increases when the solidus temperature of the cladding alloy is reached (about 585°C) and also at a temperature corresponding with the eutectical temperature of the aluminium-uranium alloy (650°C). More than 80% of fission gases and iodine will be released if the fuel is kept above the eutectical temperature. For other volatile isotopes, such as cesium and tellurium, the release will be slower and depends strongly on the burn-up. Release fractions depend also on the type of fuel and the correlations could be very complicate. As an example, smaller amounts of volatile fission products are released from dispersed fuel than form alloy fuel, but in case release of cesium from U_3Si_2-Al fuel the reverse was found [4].

4. Incidents with research reactors leading to fission product release

In order to have an idea of potential source terms for research reactors two possible accident scenarios will be discussed. One of these examples deals with fuel channel blockage and comes from experience with the BR2 reactor. The second comes from the accident of the SL-1 reactor in Idaho USA, which was destroyed due to a great reactivity insertion.

4.1 Blockage of fuel canal

In the design of the Advanced Neutron Source Reactor by DOE (USA) much attention was paid to the potential consequences of fuel channel blockage which was considered as the main contributor to core damage initiating risk [5]. This paper calculates the consequences of blockage of a fuel channel. It starts from the assumption that the failure will propagate through the whole fuel assembly due to overheating of fuel channel. Calculations are continued until scram of the reactor which is supposed to be effective 4 seconds after the initial event. The report also studies the consequences of complete fuel destruction [6].

The partial blockage of fuel channel occurred in BR2 in 1975 at the start of cycle 5/75 [7]. The core of BR2 contains positions where fuel elements with an outer diameter of 200 mm can be irradiated.

Figure 12: The damaged fuel element

These elements can be made of up to 13 concentric rings of fuel plates. The ring is composed of 8 sectors. These sectors are identical to the sectors of the Advanced Test Reactor of Argonne National Laboratory – USA. In 1975, during cycle 05/75, such an element (identification number A034) with thirteen rings of plates was loaded. A few hours after the start of reactor an automatic stop of the reactor occurred due to high activity of the primary water. The power of the reactor was at that moment 48.3 MW (60% of the reference power of that cycle). Analysis of the activity of the primary water indicated immediately that a significant surface of a fuel element must have been melted with an estimated surface between 40 and 120 cm^2). The quantity of uranium lost in the primary circuit was calculated to be about 6 grams. Unloading of the core showed that the entrance of fuel element A030 was blocked by a foreign object. Figure 1 shows a photograph of the entrance of the element. The foreign object was identified as the plastic handle of a screwdriver that had fallen in the fuel channel during loading.

The accident is a good real case example of a fuel channel blockage. The initial signal for stop of the reactor came from the high pressure ionizing chambers mounted on the exit of the primary pipe. These chambers are used to measure nitrogen 16 activity in the primary circuit in order to have a direct indication of the power of the reactor. One of the three chambers is used for automatic regulation of the reactor power. High alarm on two out of three of the N-16 gives an automatic stop the reactor to protect against overpower. It is interesting to note that these chambers gave action before those designed to detect fission products. This is due to their close location to the core and their high sensitivity for γ- radiation.

In the minutes following the accident the activity of krypton 88 in the primary circuit was measured by the on-line chains to be about 100 GBq/m^3 giving a total quantity in the primary circuit of 15 TBq. Concentration of iodine 131 was measured to be 3.7 GBq/m^3 or a total quantity of 550 GBq. Since BR2 has a closed loop, pressurized primary circuit, this activity remains mainly in the primary circuit and is removed by purification on resins, degassing and natural decay. Main inconvenience was that a number of locations were temporary inaccessible. After the accident, the purification with ion exchangers was set to maximum capacity (40 m^3/hr for a volume of 150 m^3). The concentration of krypton 88 decreased to 40 MBq/m^3 and the iodine 131 to 22 MBq/m3. At this moment the reactor could be opened and the fuel unloaded, included the failed fuel element which could be unloaded without difficulty. During inspection of the fuel element in the hot cell some deformation of the fuel plates was observed due to the pressure drop behind the blockage. Higher than usual radiationlevels in the primary circuit were found at the heat exchangers. Radiation levels of the heat exchangers were up to 800 mSv/hr in contact with the heat exchangers and from 2 mSv/hr to 15 mSv/hr for the ambient. The reactor could be restarted two weeks after the accident

From this accident it can be concluded that blockage of a fuel channel has no severe consequences for a loop cooled reactor if the primary circuit is equipped with fast detecting systems for activity of the water with automatic stop of the reactor in case of high activity levels. The situation is different for pool reactors. A significant quantity of noble gases and some of the more volatile fission products would have been released to the reactor building and possibly towards the environment, leading to irradiation doses for personnel or public.

4.2 Reactivity induced accident [8]

On 3 January 1961 an explosion occurred in the SL-1 reactor in Idaho Falls, USA. The SL-1 reactor, with a thermal power of 3 MW, was designed to produce electricity and heating in remote areas. The reactor was fuelled with 41 high enriched uranium plate type elements. The reactor contained 14 kg uranium. Cladding used was an aluminium nickel alloy. On the day of the accident the reactor was shut down for installation of flux wires. The work was finished and the operators were reconnecting the control rod drive mechanisms. During these operations the reactor became prompt critical, probably due to a pull out of a control rod leading to a nuclear excursion of the reactor. This resulted in an explosion which destroyed the internals of the reactor. The exact cause for the lifting of the control rod has never been clarified because the three operators were killed in the accident. The reactivity insertion was calculated to 2.4 ± 0.3 %, giving an energy release 130 ± 10 MW.sec [2].

Examination of the damaged fuel plates indicated that limited melting had occurred. 15% of core plate material was not recovered in an identifiable plate form. This missing portion of the core, having been in the high flux region, should have contained approximately 30% of the total fission product inventory and 1790 grams of U-235. It was further estimated from the fuel inventory that as much as 10% of the fission product inventory escaped from the reactor vessel.

The radiological consequences were serious [9]. In the reactor building radiation fields of 5 Sv/hr were measured. Outside the building radiation fields varied between from 250 mSv/hr near the reactor building to 1.2 mSv on the road. 5.3 miles downwind of the reactor the average iodine concentration in air was approximately 0.2 Bq/m^3 for the first 16 hours after the accident. Estimations of other releases were 4 GBq of strontium-90, 20 GBq of cesium-137 and appreciably lesser quantities of zirconium-niobium-95, cerium-144 and barium-lanthanum-140.

The SL-1 accident gives a good idea about the consequences of an excursion of an aluminide fuelled reactor. It is not essential if the reactor was operational or in shutdown, as for the SL-1. For a reactor in operation the quantity of short lived fission products will be higher. It is important to mention that the SL-1 reactor had no containment building. Off-site consequences would have been limited if a containment building had been foreseen.

5. The maximum accident for an aluminide fuelled reactor

In a number of publications, as for example [10], much attention is paid to the reaction of hot aluminium with steam. This is an exothermal reaction and produces hydrogen which could additionally explode. The actual BR2 maximum accident is based on this assumption. By using simple thermo dynamical consideration it can be shown that for most reactors not enough heat is produced for initiating this reaction in the full core. However it is still possible that the reaction occurs in certain locations such as a very hot fuel channel. This is, of course, very difficult to model.

For preparing accident scenarios and estimating the source terms, following two accidents should be considered:

- Blockage of a fuel channel. This could have serious consequences if it is combined with the non-detection of heavy contamination in the primary water or a serious delay of the reactor scram. In case of early detection and stop of the reactor the consequences seem to be limited, especially in case of a reactor with closed primary circuit.
- Reactivity induced accidents. Due to the number of manipulations performed at research reactors, a potential for a reactivity induced accident is present. The precursor could be a loading error or the failure of a lifting device. However consequences for the environment seem to be limited if a containment building is present and if the violent aluminium-steam reaction could be ruled out.

6. Conclusions

The behaviour of the fuel elements under abnormal condition is an essential topic in the development of accident scenarios for research reactors. Knowledge about this subject is rather scarce. Some research exists and experience from incidents and accidents is available, but there is no coordinated research as for power reactors.

7. References

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