

Reactor Physics Aspects Related to LMFBR Safety

by
H. Küsters

1. Introduction

During the last 15 years there have been done studies of fast reactor safety, continually increasing in depth. With the development of the prototype generation of 200 - 300 MWe power, the licensing procedures for these advanced reactor systems, at least in Germany, requested that a complete failure of the safety system has to be considered simultaneously with an unforeseen disturbance of the adequate power/coolant relationship, and that, in course of such a unnormal situation, the released energy and radioactivity has to be contained in the system. Near commercial reactors of about 1500 MWe yield a correspondingly larger energy release, if conventional two-zone core designs are to be built.

In this contribution, we try to outline the rôle of reactor physics in the analysis of fast reactor safety.

With regard to safety, we briefly give here a survey on those accident situations, which are of special interest today, i.e.

- a) Local failures and the possibility of failure propagation
- b) Unprotected whole core accidents, e.g. caused by pump coast down or reactivity insertion.

For the discussion of the related reactor physics aspects, we mainly deal with reactor physics in its classic definition: the distribution of neutrons in space, energy, and time (neutronics). This aspect is broadened and some of the important non-neutronic physical features in LMFBR safety studies are described (see especially section 3).

2. Local Failures in Fast Reactors

Local pin failures in a fast reactor core can not be excluded during operation of the plant. They might be caused for instance by undetected material defects prior to assemblage of a subassembly or during assemblage (e.g. scoring by spacer grids). Important for safety considerations is the case, if this pin failure leads to a release of fuel into the coolant channel, which then will be partly deposited in spacer grids, thus forming a local blockage. This local blockage can lead to local sodium boiling. If the blockage is not detected and propagates further, the coolant-flow through the subassembly finally will be stopped. Integral boiling in a subassembly around the center region of the core caused a power rise with consequent melting of part of the fuel and cladd material: Local fuel coolant interactions (FCI) and the meltthrough of the subassembly walls may proceed to a subassembly to subassembly propagation and finally to a large accident situation. This fault chain, naturally, can occur only, if pin to pin propagation acts fast, thus that there are no means to detect an early blockage, or if the detection devices fail.

From this scenaris following research objectives follow:

- a) Early detection of local failures (Acoustic and neutron noise, DND etc)
- b) Determination of the time scale of blockage growth and fuel mass in the blocked area.
- c) Effects of local boiling and local FCI on the subassembly structure.
- d) Proof that a subassembly accident is unlike to proceed to a core destruction (e.g. via FCI).

It is not the aim of this paper to discuss in detail the present status of the art; this can be found in the corresponding literature.

3. Whole Core Accidents

Presently two classes of unprotected accidents are being considered:

- a) The primary sodium pumps and simultaneously the safety system fail.
- b) Positive reactivity insertion into the core.

In case of pump coast down the following sequence of events can be envisaged:

After a few seconds the coolant will boil, starting at the upper core/blanket interface. Because the sodium void coefficient is negative in this region, the reactivity response will be negative. The voided zone will grow towards the reactor midplane, thus introducing positive reactivity.

The coolant channel subsequently will dry out, clad and fuel melt. By the dragging forces of the steam, clad material may be moved in axial direction towards the axial blanket regions; freezing of the clad on the pins is possible, thus a blockage of lower and upper parts of the coolant channel is possible. The fuel movement, if directed from the top to the reactor midplane will cause additional positive reactivity insertion, thus the molten fuel will vapourise and by pressure build-up will disassemble the core.

In case of a primary reactivity insertion, e.g. by a control rod ejection, the pins will fail; fission gas and molten fuel will enter the coolant channel. If the FCI vapourises the coolant, an additional reactivity ramp is generated due to the positive sodium void effect. If there is a negligible fuel movement to the outer core region, again a core disassembly follows. The situation is even more complex with the release of fission gas; it can behave as a driving force to push the sodium out of the channel, or it can cause the fuel to foam such that no energetic FCI can take place.

As research objectives in this area we summarize the important aspects:

Fuel Pin Failure

The importance of a relatively accurate prediction of fuel pin failure in an overpower transient emerges from the sensitivity of subsequent accident sequences on this process, in particular,

- fuel movement in the central pin cavity upwards if the pin fails in the upper part of the core, leading to a negative reactivity feedback contribution,
- mode and amount of fuel expulsion into the coolant channel, initiating FCI and fuel sweep out,
- mode and amount of fission gas release during fuel melting, leading possibly to a strong and fast disassembly mechanism.

The experimental evidence on mode of pin failure mode is rather poor. One of the main reasons is that post mortem inspections do not provide reliable answers, except on the location of failure, and "on line" inspection for in-pile experiments up to now are difficult or impossible. Furthermore in experimental investigations no reliable results can be found on whether the retained fission gas causes the fuel to foam during melting and expulsion or whether an effective separation of gas and fuel occurs.

Fuel Coolant Interaction

Experimental results with UO_2 and sodium show that UO_2 fragments extensively, but no explosive interaction has occurred up to now except in the case where a few grams of sodium were injected into molten UO_2 .

The basis of explosions in the metal-water system is the fact that the contact temperature in practically all cases is far above the stability limit of the water at which spontaneous nucleation starts. Thus hot metal entering the water is covered by a 'stable' vapour film which enables the metal to develop a large interface with the water without any violence as is connected with nucleate boiling, and without large heat losses. If now the vapour film is caused to collapse, a surface explosion occurs, i.e. a volume of water, which is given by the contacted metal surface times some penetration depth of the heat, is raised to a mean temperature a little below the contact temperature but still far above the stability limit so that it evaporates suddenly with considerable vapor pressure. If the triggering mechanism causing the film collapse or fast subsequent processes produce new metal surface, the violence of the explosion obviously is increased. When the initial metal temperature is so low that the contact temperature is below the stability limit, transition boiling and/or nucleate boiling may contribute to fragmentation of the metal but no explosive vaporization occurs. This condition also is met in the UO_2 -Na case. Fauske and co-workers have derived that the bulk temperature of the UO_2 must exceed 5000 K to 7000 K in order that the contact temperature exceeds the stability limit of the sodium. At lower temperatures the UO_2 -Na system lacks the insulating vapor film which is the basis of the above described vapor explosion mechanism. Rather boiling will occur, leading to rapid cooling of the fuel. The problems of fragmentation and mixing zone formation have become important questions of FCI. In the theoretical models these processes are characterized by two parameters: The fuel particle radius and the mixing time.

In connection with the consequences of FCI, the aspect of incoherent onset of FCI in subassemblies with different burnup will have considerable influence on the associated voiding reactivity pattern and therefore also on the production of thermal energy. The cylindrical ring coherence of our models is conservative. A cycle strategy, which is based on three types of subassemblies with different burnup, would therefore result in only 1/3 the void reactivity ramp rate of the present cylindrical ring voiding ramp together with a corresponding lower reactivity level. If according to the preceding discussion explosive vaporization (due to pressurization) can be considered as a very unlikely process, violent boiling in only a small part of the subassemblies would yield only moderate reactivity changes. Fuel sweep out finally would make this accident sequence a relatively unimportant one, if the release of fission gas into the channel does not take over the role of a fast-acting voiding mechanism.

Fuel Movement

The importance of the fuel release mode and the fuel sweep out was already mentioned. In spite of the fact that the neutron hodoscope at the TREAT facility has quite well detected slow eruptions of molten fuel in flow coast down experiments. But it is not sufficient to find some fuel outside the test section in post mortem inspections, since an effective shut down mechanism is provided only if fast fuel movement occurs.

A consistent treatment of fuel movement in the channel seems to be the use of the usual FCI models with a mixing zone concept and consideration of hydraulic fuel sweep out. The questions are, where the mixing zone initially is situated, and how much fuel actually reacts with the coolant and reliably is swept out. The effect of such a consideration on the released excursion energy has been demonstrated by various parametric studies. Obviously the results depend on the choice of the above mentioned open parameters. The released energy yield can be reduced by a factor 2 to 4.

Fuel Slumping in Pump-Coast-Down Accidents

In an unprotected pump coast down accident the first important feature is the boiling and dryout sequence. Up to now boiling phenomena have been treated theoretically only in a one-dimensional geometry. But there exists a temperature gradient across a subassembly which is enhanced for reduced flow conditions. This means that the subchannels near the subassembly wall are below the saturation temperature and therefore boiling in these channels will occur with an appreciable time delay. This boiling incoherence in a subassembly will modify the

void reactivity pattern and this influences the subsequent course of events.

To the above mentioned incoherence one must add the incoherence of fuel slumping in subassemblies with different burnup. To our present understanding four major effects may simultaneously occur during the fuel slumping phase:

- a) After dryout the clad will melt and under the gravity and Na vapor drag forces the clad will be moved towards the blanket regions. Besides the associated positive reactivity effect (which possibly will be small due to neutron streaming), this clad motion may lead to a partial or complete blockage of the coolant channels. This was indicated in the experiments of the L series in TREAT.
- b) The melting fuel releases the retained fission gases and/or fuel jets may be driven out of the pin to relieve the pressure.
- c) Fuel will move down the central pin cavity and fill it up. This will lead to a decrease in reactivity at the beginning of 'downflow', but later an increase of reactivity can follow, when the central pin cavity has been sufficiently filled.
- d) In irradiated pins the fission gas pressure inside may burst the pins relatively early, while in fresh fuel melting can be the dominant mode.
- e) After the loss of mechanical pin stability the upper, no longer supported parts of the fuel may move towards the midplane of the system, thus increasing the reactivity.

At present experimental results are insufficient to draw satisfactory and reliable conclusions on the modes mentioned above. so that theoretical modelling must include the various events in parametrized form, the true importances being unknown. The main interest in the events a) - d) is related to the accompanying reactivity effects. One of the most essential quantities in current models is the parameter on which depends the motion of the upper parts of the fuel pins. We have found by sensitivity analysis that with a completely blocked upper region, a pump coast down accident might not reach a disassembly condition while for the assumption of a free or hindered fall, transition to core disassembly takes place. Thus the uncertainty in the behavior of the core after loss

of mechanical pin stability has large consequences. The radial incoherence of slumping in a subassembly very probably will result in reduced reactivity insertions so that a more realistic description may yield less conservatism and milder consequences.

Recriticality

Besides the problem of decay heat removal, the possibility of recriticality of the distorted core after disassembly is of great importance. Due to the high enrichment of fissionable material in fast demonstration plants of about 300 MWe, recriticality can be achieved in principle either in the core itself, or in the tank, or in an external core catcher below the tank. The uncertainties are rather large in this area, since there is only poor experimental support from some out-of-pile investigations, especially concerning thermodynamic behaviour of molten core materials. Because of this situation, the theoretical procedure can only give rough and plausible estimates on possible configurations, accident sequences and related energy yields. Of course in such a situation one must keep the analysis strictly conservative; nevertheless one should try to avoid overly pessimistic assumptions.

The consequences of an unprotected power excursion of a fast prototype reactor are unlikely to result in a wide dispersion of hot core material; more likely, most of the molten fuel and steel will remain somewhere at the location of the core just after nuclear shut down. If this is assumed, the compact molten or granulated core material can and probably will go critical with some moderate reactivity insertion rate; the ramp rate depends strongly on the assumptions made with respect to the dynamics of molten material on the way to criticality and superprompt criticality. If the excursions are mild, one can expect also a mild energy yield and possibly the removal of some fuel out of the core region. This process can be repeated, probably several times. We will not discuss in detail the melting of the fuel through the grid plate and also through the tank, where again recriticality cannot be excluded in the absence of preventive measures. The addition of neutron absorbing materials to the molten or granulated material in the bottom of the tank will reduce the chance for a further excursion. In principle, low reactivity ramp rate excursions in the tank or core catcher operate as a dispersion mechanism for the molten material and therefore should be tolerated. However, it could not be demonstrated so far that only such mild excursions can occur. In fact, if one makes the pessimistic assumption

that two subcritical blocks approach under gravity, and that the blocks consist of low density granulate, one can calculate excursion energies which probably cannot be contained.

Thus, at present, one can only carry out sensitivity studies to assess the influence of different parameters. One can expect that the growing knowledge on the dynamic behavior of molten materials will help to narrow the uncertainties to an acceptable range.

4. Related Reactor Physics Aspects

We have discussed some of the present problems in fast reactor safety analysis in order to judge the connection between reactor physics and safety. It can be concluded from section 3, that the uncertainties in fast reactor safety analysis are dominated by the non-neutronic characteristics of the accident sequences: material dynamics, thermohydraulics and thermodynamics. In addition it is seen that constitutive and confirmative experiments, in pile as well as out of pile, are needed to support and check the theoretical modelling of the various phenomena.

Reactor physics plays a clearly defined rôle in the analysis of fast reactor safety, although the degree of uncertainty of the related physics parameters is much less than the uncertainty in the non-neutronic parameters. This is so, because the physics methods widely could be checked experimentally and theoretically in numerous examples in zero power facilities. These facilities are even more complicated from the neutronics point of view as the power reactor itself (small cores, heterogeneity and streaming effects). With the SEFOR reactor and since some years also from Phénix and PFR experience was gained from larger test and prototype reactors.

The most important reactor physics aspects in fast reactor safety analysis are the appropriate prediction and verification of

- Doppler reactivity effect in the predisassembly and disassembly phase of a nuclear excursion
- Sodium Void reactivity distribution in the complex core situation with control rods

- Reactivity effects of fuel and clad motion
- Control rod worth distribution
- Development and check of space time dynamics, especially for large reactors.

The accuracy of the first four items have been discussed intensively and presently has reached a degree, which in almost all cases satisfies the requirements in fast reactor safety analysis (Dopplercoefficient: 15 - 20 %, Na-Void coefficient: about 15 %; control rod worth: 10 %).

One of the main problems, is to really find out the necessary simplification over sophisticated static analysis, which can be tolerated in excursion analysis, thus that an efficient computerized description of the complex situation is possible. This is true especially for those cases, where space-time dynamic investigations are felt to be necessary.

At first we draw the attention to the energy representation in multigroup calculations. Because material movements as the boiling ejection of sodium cause spectrum changes, the number of energy groups required, are between 10 and 20 , much more than is necessary for thermal reactors. Efficient methods have been studied already as energy synthesis and coarse group methods with bilinearly weighted group constants, they are not yet used in routine safety analysis coded.

Space-time dynamic codes in 1 and 2 dimensions are already in operation, although a proper balance with the thermohydraulic and materialdynamic phenomena has not yet achieved. For the excursion analysis of 300 MWe prototype reactors it seems, as if point kinetics (at least in some sophistication with pre-described reactivity tables) gives not too poor results. Special attention must be given to

- the reactivity effect of control rod movements, calculated in first order perturbation theory
- the reactivity response connected with local sodium boiling (e.g. near core/blanket in a pump coast down accident), and material (clad, fuel) movements before core disassembly,
- the reactivity effects associated with gross material movement in the disassembly phase.

As already mentioned, these problems become even more important for large reactors. A special treatment requires also the space representation in case of material movements: many zones have to be used with varying zone boundaries during material movement. In some cases also transporttheoretical tools at least have to be used for checking the accuracy of diffusion theory, e.g. for the description of neutron streaming in emptied channels or for situations in which fuel slumping has resulted in compact configurations, or where after a primary excursion some portion of fuel approaches under gravity another already molten part of core material.

One major task of reactor physics is to provide relevant core physics data for large reactors, which are able to improve the safety- and breeding potential of these plants. However, one has to keep in mind that already 10 years ago ring- and modular core designs have been discussed in order to minimize the sodium void reactivity effect. Besides of technological difficulties at that time the final safety characteristics were not improved. The main conclusion was that, if primary reactivity insertions (as the flow of large gas bubbles through the core or control rod ejections) lead to the melt down of the center part of the core, the subsequent slumping of core material by far dominates the excursion behaviour. Thus, also in modern heterogeneous core designs, one has to prove that gross fuel slumping or fuel compaction does not occur, otherwise the advantage of a low sodium void reactivity effect is overruled.

To conclude, most attention should be devoted to the development of a reliable instrumentation and safety system. In this area especially experimental reactor physics work may improve the present situation.

References

See e.g. Proceedings of the Conference on Fast Reactor Safety. Los Angeles, 1974 and the corresponding contributions to the subsequent ANS-Meetings.

Also:

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