# PREDICTION OF THE PRESSURE-TIME HISTORY DUE TO FUEL-SODIUM INTERACTION IN A SUBASSEMBLY

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## SUMMARY

A local cooling disturbance may lead to complete voiding of a subassembly and melt down of the fuel pins. Thus molten fuel may be accumulated and mixed with liquid sodium returning accidentally into the subassembly. The resulting fuel-sodium interaction (FSI) produces a pressure load on the surrounding core structures. It is necessary to prove that the corresponding core deformation neither initiates a nuclear excursion nor renders the shut down system inoperable. This requires the knowledge of the initiating FSI pressure time history. In this paper a theoretical pressure time history is presented which differs completely from all calculations known so far.

The FSI in this case is dominated by a progressive growth of the interacting masses of fuel and sodium. The models which are able to describe that process up to now assume a unique sodium temperature. In addition the only results published so far have been obtained using the quasi-steady state heat transfer approximation. So in these calculations the heating rate is low and the effective fuel to sodium mass ratio is reduced because sodium entering the mixing zone is brought to the mean temperature immediately while the rate of heat input increases with delay. These calculations predict pressures below 100 bar.

Recently the new code MURTI (MUlti Region Thermal Interaction) which has been developed on the basis of the earlier described code BRENDY has been applied to this problem. In MURTI the mixing zone can be subdivided into subregions in each of which the interaction starts at some given time. In order to simulate the progressive mixing of fuel and sodium after sodium reentry into the subassembly, the reaction is initiated successively in several subregions with a small time delay. Each fuel mass is assumed to be initially molten and to be instantaneously fragmented into droplets with 117 $\mu$m radius and mixed with an equal volume of cold (~900 K) liquid sodium. The heat transfer is calculated exactly assuming ideal thermal contact and the sodium obtains heat only from the fuel with which it is mixed. Therefore temperature balance is reached already after ~2 msec and the mass ratio is that defined by the input.

With these assumptions it is found that:

— there is no liquid pressure peak like with instantaneous mixing,
— the pressure reaches a saturation level after 2...3 msec,
— the pressure drops quickly after the acoustic period,
— the maximum pressure is in the range 350...400 bar.

Detailed parametric studies on these results are presented.

## 1. Introduction

In fast reactor engineering, for safe and reliable operation local cooling disturbances within a single subassembly play an important role, see for example Gast et al. [1]. There are two reasons: The occurrence of such a disturbance cannot be ruled out completely and via damage propagation it may entail severe consequences. These can best be avoided by detecting the disturbance early enough to allow shutdown of the reactor before the disturbance causes damage to the fuel pins. Therefore, the primary attempt is directed to a fast and sensitive detection device. However, to cover the improbable case of failure of the detection system as well, the ultimate consequences are also studied which may arise under the most unfortunate circumstances: After local boiling and gross boiling the subassembly is voided and melts down. In that case molten fuel could accumulate and be mixed with liquid sodium reentering into the subassembly. At present, it cannot be excluded strictly that an energetic fuel-sodium interaction (FSI) would follow which would produce a pressure load on the subassembly wrapper and the surrounding core structures. This could rupture the subassembly walls and damage the core; but even such an event can be accomodated safely if the deformation of the core neither initiates a nuclear excursion (by ejecting sodium from the core) nor renders inoperable the shutdown system. To prove this, is primarily a problem of structural mechanics. However, this task requires the knowledge of the pressure-time history of the FSI within the molten subassembly. In this paper the pressure-time history is calculated by a one-dimensional model.

## 2. Problem description and modeling

The analysis considers a situation in which the pins are molten down and some liquid fuel is kept like in a crucible within the subassembly wrapper which is blocked at the bottom. Liquid sodium from the upper reactor plenum reenters into the subassembly and mixes at a finite and constant mixing rate with the fuel. It is assumed that the mixing zone occupies the entire cross section of the subassembly. Thus, the mixing zone expands axially in upwards direction only. The mitigating effects of possible radial motions (elasto-plastic deformation and failure of the wrapper) are neglected.

The computer programme MURTI (MUlti Region Thermal Interaction) can be used to predict the pressure-time history for this problem. It was developed recently on the basis of the code BRENDY described earlier, Jacobs and Thurnay [2], Jacobs [3]. Both codes allow numerical solution of the exact thermo-hydrodynamic differential equations which describe the irreversible thermodynamic processes taking place in a mixture of two fluids which are at very different temperatures initially, Jacobs and Thurnay [2].

For pratical reasons these equations can be solved in one dimension only. MURTI can be applied to very different situations, e.g. problems in which a mixing zone exists as well as problems in which unfragmented lumps of hot material are in contact with the coolant without formation of a mixing zone. Since the code will be described in detail elsewhere, only the main aspects relevant to the present problem will be mentioned here.

It is assumed that a mixing zone exists at the bottom of a rigid cylindrical tube (overstrong shock tube) under a column of unheated sodium whose mass is constant with time. The constraint imposed on the mixing zone by the unheated sodium is approximated during the acoustic period by the known acoustic approximation and afterwards by the inertial constraint approximation. The initial velocity of the incompressible sodium slug then considered is found by an energy balance; gravity and friction are neglected.

The mixing zone can be subdivided into sections, each containing fuel and sodium. The sections do not exchange heat and the motion of their boundaries is calculated from their internal pressures. So they behave like Lagrangian fluid elements in an adiabatic and compressible flow. The pressures of the sections are calculated according to the method developed for the BRENDY code. From each section those masses of fuel and sodium are considered representative which exchange heat through one unit of interfacial area. These masses are arranged in adjacent slabs. In this geometry the heat conduction equation is solved for both materials, coupled with the differential equations of compressible fluid flow within the sodium. So the sodium is treated as a heat-conducting and compressible fluid while the fuel in the model is heat-conducting and has a constant volume. Since the differential equations are solved numerically by a finite-difference method no assumption has to be made on the shape of the temperature gradients within both materials and on the local pressure and density gradients within the sodium in the vicinity of the fuel surface. The pressure so obtained at the 'free end' of the sodium slab (opposite to the fuel) is used to calculate the motion of the section boundaries which in turn defines the boundary conditions for the variation of the sodium volume within each section. The different representative pressures give the axial pressure gradient over the mixing zone.

In the model calculations the progressive mixing of the fuel and sodium is taken into account in the following way: The mixing zone is assumed to consist of many (in this case) identical sections. But they do not interact coherently. On the contrary, the interaction starts successively in the sections one by one with a small time delay. Thus, the masses of fuel and sodium taking part in the interaction are growing stepwise (simulating a linear growth) and it is assumed that each mass of fuel starting to interact is instantaneously fragmented and mixed with (an equal volume of) yet unheated and liquid sodium.

The thermal properties of the fuel are assumed to be independent of the temperature (i.e. thermal conductivity 0.021 W/cm, specific heat 0.389 J/(g · deg)), but the heat of fusion (282 J/g) is taken into account properly. The equation of state of the sodium is defined by a consistent system of temperature - and density dependent thermophysical properties, which was developed at Karlsruhe, Thurnay [4]. The calculations in this paper rely on a version which is valid up to the critical point ($T_c$ = 2850 K, $P_c$=418 bar, $\rho_c$ = 0.189 g/cm$^3$). When the sodium is vaporized partially, the vapour and liquid are assumed to form a mixture. The insulating effect of the vapour is taken into account by reducing the sodium thermal conductivity according to the volume and the thermal conductivity of the vapour.

## 3. Results and discussion

The following initial conditions have been used: The fuel temperature is 3100 K, just above the melting temperature (3073 K). Its density is 8.75 g/cm$^3$. The fuel-sodium interface corresponds to a fragmentation into spherical particles of 117 µm radius. The sodium temperature is 860 K, a value which is typical of the upper plenum of an LMFBR. The sodium density is 0.8114 g/cm$^3$. Each section contains 0.1 cm$^3$ of fuel and sodium respectively. So the fuel to sodium mass ratio is 10.8. The distance to the free surface is 4 m which results in an acoustic period of 3.54 msec. The constant pressure above the free surface is 1.3 bar. The interaction starts at the top of the mixing zone and after 0.1 msec each the interaction is initiated in the following section. To some extent this models a jet of sodium penetrating into a pool of liquid fuel at the constant velocity of 10 m/sec, a value well beyond usually observed reentry velocities.

In the first calculation 46 sections were considered, so that the mixing process continues for 4.5 msec. The pressure-time history thus obtained is shown in figure 1. The most important feature of this curve is that the liquid pressure peak is missing, which is typical of coherent interactions in large mixing zones. Here vaporization starts early after the first contact between fuel and sodium and the pressure shows a saturation behaviour as the sodium temperature approaches the equilibrium temperature of the fuel and sodium. At the end of the acoustic period the pressure starts dropping though the interacting masses are still growing.

It follows from these observations that a longer mixing process which would further increase the interacting masses would not cause higher pressures. Similarly a shorter mixing process would not imply a drastic change of the result. At the same time it seems improbable that the sodium in the narrow channel geometry is able to penetrate continuously into the fuel while a part of it already starts to vaporize. Therefore, it is assumed that the mixing process comes to an end when the momentum produced by the thermal

interaction is equal to the momentum of the loading sodium column moving at a velocity of 10 m/sec, i.e. 0.32 bar · sec. In the case described above this balance is established after 1.49 msec. According to this criterion the mixing process is assumed to stop after 1.5 msec in the following calculations, when 16 of the sections described above have been brought to interact.

The pressure-time history represented by the solid line in figure 2 as compared to figure 1 shows the effect of this assumption together with the long-time behaviour of the pressure: The maximum is reduced to about 350 bar and the pressure drops faster after the end of the acoustic period.

The dotted line in figure 2 demonstrates that a variation of the initial sodium temperature within the limits given by the normal operation temperature (lower limit) and the saturation temperature (upper limit) in the upper plenum does not change the result significantly. Similarly, increasing by 20 % the specific heat of the fuel rises the pressure maximum by only 3 bar, because most of the heat dumped into the sodium during the first milliseconds consists of the latent heat of melting.

Variation of the velocity of the mixing process also has a remarkably little effect on the pressure-time history. With 5 m/sec the pressure maximum decreases to 320 bar and with 20 m/sec it rises to 400 bar. As a matter of fact, in this case a liquid pressure peak is about to appear. During the mixing process the pressure oscillations within the mixing zone sometimes pile up in small volumes and for short times to yield single phase pressures around 450 bar. These localized events are not yet very important and, furthermore, such a high reentry velocity is much higher than would be expected.

Another parameter which has to be varied in a certain range is the fuel to sodium mass ratio in the mixture. Evidently, a higher sodium portion reduces the vapour pressure. If the sodium volume is twice the fuel volume, the peak pressure is reduced to 300 bar. In the opposite case, even with a mass ratio 21.6 (the sodium volume is half the fuel volume) there are still only vapour pressure. With 16 sections (i.e. the same amount of interacting fuel as before) the pressure reaches almost 410 bar. But in this case the momentum criterion is fulfilled already after 1.2 msec. When this is taken into account, the pressure rises up to 380 bar and it drops very fast after the end of the acoustic period because of the small sodium mass which is soon vaporized completely.

The results of these calculations can be summarized as follows:

1. Single phase liquid pressures are very unlikely to occur. The highest pressures that must be expected are below the critical pressure of sodium as long as the initial temperature of the fuel is not well above 3100 K.

2. The pressure drops quickly after the end of the acoustic period. So the latter is an upper limit of the duration of the maximum pressure.

3. The half width of the pressure pulse mainly depends on the amount of sodium involved in the interaction. Seemingly 8 msec is a reasonable value.

These results can be understood (and also extrapolated to some extent) on the basis of the fact that single phase (liquid) pressures do not enter into this problem and, hence, the pressure-time history via the vapour pressure curve reflects the temperature history: Initially, the equilibrium temperature of fuel and sodium is approached, which defines an upper limit of the pressure. But before this equilibrium is reached, the sodium starts to vaporize and a lot of heat is consumed by the latent heat of vaporization. So the theoretical equilibrium temperature will not be attained. During the acoustic period the expansion rate of the mixing zone which defines the rate of sodium vaporization is proportional to the pressure and therefore rather small in these cases. Both rates increase suddenly when the rarefaction wave returns to the mixing zone and continue to grow afterwards. Therefore, the pressure drops faster after the end of the acoustic period.

## 4. Comparison with results from the ANL parametric model

In 1972 Cho [5, 6] of the Argonne National Laboratory (ANL) published results on a very similar case. He studied molten fuel being ejected from a voided core region into liquid sodium near the subassembly exit. In one of the calculations assumptions were made which are very similar to those used in this work: A slug of molten fuel is ejected from the subassemblies at the constant velocity of 10 m/sec. This fuel continuously mixes with equal volumes of liquid sodium in such a way that the fuel to sodium mass ratio remains constant (at a value of 12.0). The fuel particle radius is 117 µm, the initial sodium temperature 1100 K, the initial mixing-zone pressure 1.4 bar. The mixing zone expands by accelerating a 5.5 m long sodium slug against a constant pressure of 1 bar. The only initial value deviating significantly is the fuel temperature which is assumed to be 3400 K.

Because of the high fuel temperature (and the slightly higher mass ratio) it would be expected that this calculation yield pressures in excess of those found in this work. But the contrary is true: The pressure maximum according to the ANL model is only 54 bar. (The ANL model and MURTI agree in the prediction that vaporization starts early in the process.) The reason for the large discrepancy in the pressures must be searched in the model assumptions. In this special case only two differences between the codes are significant:

a. In the ANL model the quasi-steady-state heat-transfer approximation is used. On the other hand in MURTI instantaneous fragmentation and mixing

are assumed in each section followed by transient heat exchange without any wall resistance between materials whose initial temperatures are constant respectively. So the heat transfer rate is much higher in MURTI.

b. In the ANL model the usual assumption is made of a uniform sodium temperature throughout the mixing zone. Under conditions of sodium being added to the mixing zone by and by, this assumption implies that already heated sodium and cold sodium which is added to the mixing zone exchange heat infinitely fast in order to reach a common temperature level.

By contrast, in MURTI the sodium added to the mixing zone receives heat only from the fuel mixed to it. This means at the same time that the sodium in the hotter (older) parts of the mixing zone is not allowed to dump heat into the colder (newer) parts.

Without a comparison of calculations in which only one assumption is varied it is difficult to judge the relative importance of these two points. The slower heat transfer rate at an earlier stage can be overridden by the heat consumption due to the latent heat of vaporization. The instantaneous heat exchange between the different parts of the sodium directly reduces the sodium temperature and the pressure. This mechanism is especially effective at the beginning of the interaction when the interacting sodium mass is still small. Since the pressure maximum is attained after 2 ... 3 msec, it will also be affected.

In both cases the assumptions used in MURTI seem to be the most pessimistic (in the sense that a higher pressure is pessimistic) that can be made. From this point of view and subject to the choice of the input parameters the pressures calculated by MURTI can be regarded as an extreme upper limit.

The comparison of the results demonstrates that the choice of the assumptions discussed in this chapter has a very strong influence on the pressure-time history in cases in which fuel and sodium are mixed at a rather slow rate. It requires thorough consideration, especially in a case like that discussed here.

Notation

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| c | subscript denoting critical variables |
| P | pressure |
| T | temperature |
| $T_{Na}$ | sodium initial temperature |
| t | time |
| $\rho$ | density |

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Fig.1: Pressure-time history of FSI; duration of mixing process 4.5 msec

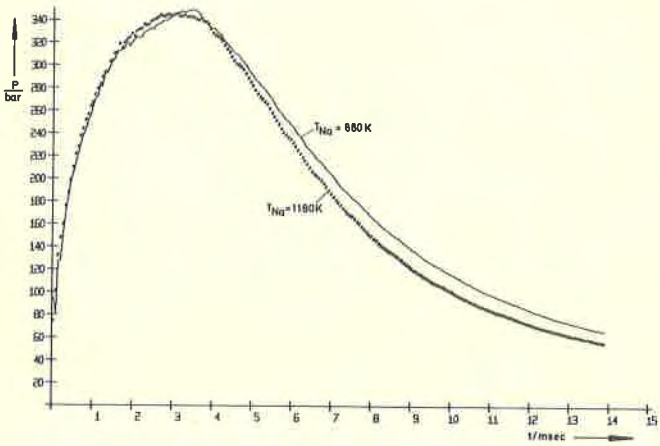


Fig.2: Pressure-time histories of FSI with different initial sodium temperatures; duration of mixing process 1.5 msec