E. SAFETY ASPECTS

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E.1. BASIC SAFETY FEATURES OF ADS

E.1.1. ACCIDENT TYPES

In this overview it is assumed that in an accelerator-driven system (ADS) the same type of accidents can be envisaged as in critical reactors. The ADSs proposed in this State-of-the-Art report include fast systems with solid fuel and Lead or *sodium* cooling *(also gas cooling was discussed at one time)*, fast systems with circulating molten salt/minor actinides, thermal systems with circulating molten salt/minor actinide/Pu and graphite moderation and thermal systems in which the latter mixture or a water/oxide slurry is circulated in pipes and heavy water is used as moderator.

The generic accidents that can occur in low pressure fast or thermal systems are cooling-failure accidents, either due to a rapid primary flow decay caused by loss of power to the pumps (Loss-of-Flow: LOF) or due to the loss of the heat sink (LOHS) due to loss of power to the pumps in the heat removal loops or to the feedwater pumps. For a gas-cooled fast reactor the loss of coolant accident (LOCA) is a possibility if a sudden depressurization occurs due to a leak. For the low pressure systems the loss of coolant accident is of low probability and a guard vessel should assure that the coolant cannot escape completely. Decay heat removal problems can also lead to accidents, e.g. if the diesels driving the blowers for the forced convection cooling in a gas-cooled system fail to start.

The ADS systems mentioned in the Studies of Accidents in Reactors (SOAR) are also susceptible to reactivity accidents which are called Reactivity Induced Accidents (RIAs) for thermal reactors and Transient Overpower (TOP) accidents for fast reactors. All types of ADSs that have some control rods could experience an inadvertent withdrawal of the latter. In pressurised systems the blow-out of one control rod cluster is considered to be a possibility. Since ADSs will probably use fewer control rods than a critical reactor this will reduce the potential for reactivity accidents. Different types of reactivity insertions can also be postulated due to the inadvertent insertion of moderator material in a fast system, accumulations of fissile material in a system with circulating salt/fuel or earthquakes causing core distortions. The proposed sodium-cooled fast ADS will probably have a positive void coefficient which could lead to a reactivity excursion if the sodium overheats and boils. If the core of a fast ADS melted down there would be the potential for the core to slump down and form a molten pool in which molten fuel sloshing can occur. These fuel motions can also cause reactivity ramps.

Whether an ADS-specific accident due to a sudden and significant increase of the accelerator power above its nominal value is possible, is not clear at this time but it should be investigated whether such increases are possible.

E.1.2. PREVENTION OF ACCIDENTS IN ADSs

As for critical reactors a high quality of the safety grade components, their inspectability and an in-service inspection programme during the whole reactor life are necessary. Components which should be particularly reliable are the accelerator shut-off system and the decay heat removal systems. The design of the ADS should ideally be such that it cannot lead to a severe accident or that accidents develop slowly enough so that there is time for a corrective response. Because the shut-off of the neutron source is of major importance for cooling-failure accidents it is discussed below and compared with shutdown systems in critical reactors.

E.1.3. SWITCHING OFF THE ADS NEUTRON SOURCE IN CASE OF AN ACCIDENT

The reactor part of an ADS is a subcritical neutron-multiplying medium with a more or less powerful neutron source. If one switches the external (spallation) neutron source off, the power will decrease to decay power levels. This will occur at a faster rate for larger neutron sources and their corresponding initial subcriticalies.

As will be discussed in the later sections on major cooling-failure accidents without beam shut-off, the rapid turning off of the neutron source is central for avoiding a core melt at least in fast systems with solid fuel. This is because the neutron source prevents a rapid power decrease even if some negative feedbacks come in [1] - see also the later discussion of cooling failure accidents in ADSs without beam shut-off.

For reactivity accidents in ADSs - even rather strong ones - the switch-off of the source may only be necessary after some time in order to prevent a limited core damage. The reasons for this will also be discussed in the later sections on reactivity accidents in which the source is left on.

E.1.3.1 Scramming a Regular Critical Reactor in Case of an Accident

To switch off the neutron source in an ADS is similar to the scramming of a critical reactor by rapidly inserting control rods. In reactor types in which a loss of coolant doesn't lead to a strong negative reactivity (i.e. gas cooled thermal reactors or thermal CANDU and sodium cooled fast reactors which even lead to positive void reactivities) a scram is an essential safety requirement in a major cooling failure accident at full power. PWRs or BWRs shut down by themselves in LOCA or station blackout accidents but it will be impossible to establish proper decay heat cooling if the scram is not actuated. The only type of reactor that could have survived a major cooling disturbance (LOF, LOHS) without scram would have been the now abandoned US Integral Fast Reactor (IFR) with metal fuel [1]. Even the Swedish PIUS concept uses a scram by adding large amounts of borated water into the core region in case of a cooling failure accident [2].

Reactivity insertions in LWRs or fast reactors at full power due to the inadvertent withdrawal of control rods, the ejection of a control rod cluster in a PWR or the dropping of such a cluster in a BWR require a fast scram in order to avoid core damage. The introduction of cold and unborated emergency cooling water into an LWR can also introduce an RIA which has to be terminated by a scram. All reactors have a certain potential for reactivity accidents and the main line of defence against them is the scram. The fact that an ADS can overcome sizeable reactivity insertions without a fast scram (see E.1.5.1 and E.1.5.2) is a unique property of this system.

E.1.3.2 Comparison of a Reactor Scram and Switching-off an Accelerator Beam

The delay time from the trip signal to a control rod release is about 0.5s for an LWR [3] and this delay will be similar for activating the beam shut-off system of an ADS. However, turning off the current to an accelerator should be considerably faster than the mechanical insertion of control rods which takes about 1.5 - 3s in an LWR [3] and should be less for fast reactors cores which are smaller.

Comparing the redundancy and diversity of a shutdown system with that of the beam shut-off system, the latter has a disadvantage because it is only one beam that can be shut off whereas many - even different - control rods can be inserted and e.g. in an LWR and an alternate shutdown mode is possible through the insertion of borated water. However, many diverse trip signals can feed into the beam shut-off.

Because the beam shut-off is mainly important for cooling failure accidents, the current to the accelerator should be coupled to the electrical current driving the primary pumps, the pumps for the secondary and - if existing - tertiary loops and also to the feedwater pumps. A different and fully passive system to shut the neutron source off, could involve the dropping of the spallation target by using a support made of a low melting point metal which would heat up and melt in a cooling failure or slow reactivity accident. The target could also be magnetically supported and if the magnets reached the Curie temperature, the target would drop. Another shut-off system could consist of deflecting the proton beam by demagnetising a magnetic lens through the cutting off of its current by bi-metallic devices located at the core outlet. In the ADS design by Rubbia, which is described earlier in this report, a passive beam interrupt devise is based on the rising Lead coolant level due to a cooling failure and leads to the overflow of the Lead into a container which is in the path of the proton beam. This appears to be a reliable and clearly transparent passive beam shut-off system.

E.1.4. COOLING-FAILURE ACCIDENTS IN ADSS WITH THE SPALLATION SOURCE STILL ON

E.1.4.1 Loss-of-Flow Accident in a Sodium-cooled Fast ADS

In chapter E.1.7 calculations of LOF accidents in a large fast ADS (800MWe) are discussed and compared with those of a corresponding critical reactor. The main results are that fast sodium-cooled ADSs with their source still on Lead to much lower and wider power peaks than in the critical reactor. These power increases are caused by the positive sodium void reactivity. The power in the ADS also rises somewhat earlier because the negative feedbacks due to Doppler, axial expansion and structure feedbacks do not decrease the power as much as in a critical system (see also [1]). The sodium voiding phase is considerably longer lasting but pin failures still occur earlier in an ADS. Once strong negative feedbacks come in due to dispersive fuel motion, the power decreases much less than in a critical system. This is due to the neutron source which makes the ADS less sensitive to feedbacks (positive and negative ones). This "inertia" of the ADS to feedbacks has been recognised earlier [4].

The more subcritical an ADS, the more the above statements hold, i.e. the initial power peak becomes even lower, but after a strong negative feedback comes in, the power doesn't decrease much. The latter will lead to a complete core meltdown unless the spallation source is switched off. Two calculations with a simulated beam switch-off show that the ADS can be safely brought to decay power levels if the turning off is done before much sodium voiding has occurred. The later the switch-off takes place, the more core damage is likely. If the switch-off is too late, the meltdown will proceed by fuel slumping down leading to a molten fuel pool. Fuel sloshing around can lead to recriticalities and a power excursion [5]. A basic reason for this possibility is that a fast system is not in its most critical configuration initially.

On balance a sodium-cooled ADS would have advantages over a critical fast reactor with regard to LOF and probably LOHS accidents in which no beam switch-off or reactor scram is considered. This is mainly because no rapid power excursions are possible at least when the ADS is in its initial configuration. A smaller but still important point is that the phenomena such as sodium boiling and pin failures in different parts of the core are stretched out in time and therefore easier to detect. That a beam switch-off is necessary for an ADS during a LOF accident is similar to the necessity for a scram in a regular fast reactor. Both systems have the potential for recriticalities if the beam isn't shut off or a scram is not activated. With regard to regular decay heat removal, both systems can rely on passive natural convection cooling with the liquid sodium. With regard to post-accident heat removal both systems have equal uncertainties whether an in-vessel coolability is possible or not. Also both systems have the potential for sodium fires and sodium/water interactions.

E.1.4.2 Cooling Failure Accidents in Gas-Cooled Fast ADSs

Relative to sodium-cooled fast ADS, a gas cooled variant has the advantage that there is no chemically reactive coolant and that there will be no positive reactivity effect due to a decrease in the coolant density. Moreover, it may be possible to use water cooling in a post-accident heat removal situation if a properly designed in-vessel or ex-vessel core catcher could be designed that avoids recriticalities.

On the other hand there is the possibility of a LOCA accident if a leak occurred in the pressurised primary system. LOF and LOHS accidents are also possible. In all these cooling failure type accidents the timely switch-off of the accelerator beam is also crucial for avoiding a core melt. If a core melt occurred it could lead to recriticalities as in the sodium-cooled ADS. A significant disadvantage is that the regular decay heat removal can not be done in a passive natural circulation mode (or at least not for larger systems). In a shutdown condition with no electricity available, the forced convection cooling has to rely on diesel generators.

E.1.4.3 Cooling Failure Accidents in Lead Cooled Fast ADSs

Lead cooling has many safety advantages relative to sodium cooling. Hot Lead does not react chemically with air or water. Equally or more important is that it is a very weak moderator that will not lead to a significant spectrum change or positive reactivity effect when the coolant should experience a decrease in density due to heating of the coolant or due to boiling and voiding. In comparison to a gas coolant, Lead would be at much lower pressure and would not be susceptible to a Loss-of-Coolant Accident (LOCA). A leak of the primary vessel would only lead to the flowing of the low pressure coolant into the surrounding guard vessel.

A disadvantage of a Lead coolant is its high melting point of 327°C which probably requires electrical heaters during reactor start-up and possibly also at very low decay power levels. The failure of such electrical heaters could lead to some Lead freezing and blockage formation which could impede the coolant flow in the core. However, it should be investigated whether conduction cooling would not be sufficient for very low power conditions.

In the conceptual design of C. Rubbia (see chapter D.3), presented earlier in this SOAR, Loss-of-Flow (LOF) accidents due to pump failures cannot occur because the Rubbia design is based on natural convection cooling. However, a Loss-of-Heat Sink (LOHS) accident is still conceivable if e.g. the steam generators dried out due to a loss of feedwater. For the LOHS accident or for slow but long lasting reactivity insertions (see chapter E.1.7) these could lead to a partial or full meltdown of an ADS if the proton beam was not interrupted or the accelerator switched off. The Rubbia design includes a passive shutdown device based on the rise of the coolant level caused by the heating up of the Lead coolant. As explained earlier this will lead to the overflow of the Lead into a container that is in the path of the proton beam which will thus become a new target on top of the reactor. This would rapidly decrease the reactor power, and thus, the coolant temperature.

However, the decay heat would slowly increase the coolant temperature again. In the Rubbia design, the renewed and further level swell will lead to an overflow of the Lead into the relatively small gap between the main and the guard vessel and will largely increase the heat transfer between the two vessels. this will start a natural air convection cooling of the guard vessel. This type of decay heat removal, which was earlier proposed by the US ALMR programme, has the disadvantage that the containment has to have openings (which could possibly be closed in an emergency). An alternate way for the decay heat removal could be in-vessel Lead-air heat exchangers.

E.1.4.4 Coolant Failure Accidents in Thermal ADS with a Circulating Salt/Fuel Mixture.

An important advantage of thermal systems is that they have a lower power density than fast systems (for the same power, their cores are therefore much larger than those of fast ADSs). This makes the heating up of a core slower in a LOF or LOHS accident and allows more time for the detection of off-normal conditions. Moreover, the thermal expansion and the potential boiling of the salt/fuel mixture will reduce its density and will decrease the full power to a certain degree. However, this would lead soon (possibly within minutes) to extensive boiling and pressure generation if the accelerator wasn't switched off. If the switch-off wouldn't take place, the spallation source might melt, disintegrate and lead to neutronic shutdown before the primary system would be challenged.

A positive safety feature of this system is also that a problem with the decay heat removal does not lead to a rapid heating up of the primary system but allows tens of hours to re-establish the regular decay heat removal (Bell, 94). This is due to the fact that about 2/3 of the fuel is not in the core but in a natural circulation mode in the primary system which therefore gets heated up in its entirety. A smaller fluid fueled ADS (< 800 MW_t) will probably loose all the decay heat to the surrounding. For a larger ADS of this type, the salt/fuel mixture will eventually have to be drained into a cooled reservoir. (In contrast a fast ADS with liquid coolant could have relatively small coolant/air heat exchangers which can passively remove all the decay heat from the primary system).

Another advantage relative to ADS systems with solid fuel is the on-line removal of short - lived fission products which will considerably reduce the fission product inventory.

Certain problems with the salt/fuel ADS could be due to the precipitation of the heavy fuel or minor actinides which might lead to a temporary increase in density of the latter in the core. As will be discussed under reactivity accidents, this would lead only to a limited increase in power. However, one could also imagine that such a precipitation could lead to an accumulation somewhere in the primary system away from the graphite moderator and lead to a fast criticality. However, such an accumulation may blow apart without doing damage to the strong primary system.

An interesting problem for fluid fuel/molten salt systems may be a strongly positive temperature coefficient for a pure salt / Pu / minor actinide mixture because no ^{238}U or ^{232}Th, with their absorption resonances, is present [6]. If this were true, a LOF or LOHS would lead to some power increase rather than decrease during the heating up of the salt/fuel mixture if the beam was not switched off.

A potential problem is also the explosive interaction between molten salt and water [7] which could occur in the Russian design in which molten salt / fuel is pumped through pipes which are surrounded by heavy water. In such a system a leak could lead to a molten salt / water explosion which could destroy other pipes and lead to a propagating explosion. In the LASL design there could also be a potential problem if water was used in the secondary loop .

A general weakness of a molten salt / fuel design is that it is a relatively "dirty" system in which radioactive material gets into the pumps and heat exchangers and makes the inspection of these important components difficult. A related problem is that the vessel is the first safety boundary and if a leak occurred, the whole containment would be radioactive.

E.1.5. REACTIVITY ACCIDENTS WITH THE ACCELERATOR BEAM STILL ON

E.1.5.1 TOP Accident in a sodium cooled fast ADS

In chapter E.3. calculations of reactivity accidents in the same sodium-cooled ADSas used for the case described in E.2. are discussed and compared with reactivity accidents in an equivalent critical fast reactor. The results are rather clear. The sodium cooled ADS has no significant problems to cope with very fast and medium ramp rates (170 $/s for a total insertion of up to 2.65 $ and 6 $/s for a total insertion of up to 3$) - the subcriticality of the ADS was -3$ in the first case and -5$ in the second. The corresponding runs for the critical system gave power peaks of around 2000 times nominal and led to complete core destructions.

For a rather slow ramp of 10 c/s inserted for 30 s to give a total insertion of 3$, the critical reactor will lead to pin failures in 1 out of 10 calculational channels. The negative feedback from the fuel dispersal makes the net reactivity low enough to prevent further failures. In the corresponding ADS case with a - 3$ subcriticality, a failure of one channel occurred also - but later, for a -5$ subcriticality it occurred even later, and for a subcriticality of -10$ not at all.

For fast ramp rates, which could not be counteracted in a timely manner by a scram in a regular reactor, the ADS behaves benignly. For slow ramp rate accidents the ADS may lead to late failures and limited core damage if the beam is not shut off and the subcriticality is not large enough. However, since a beam shut-off system has to be in place for cooling - failure accidents, there is probably no need to go to low subcriticalities to avoid late pin failures. The unscrammed regular reactor will definitely experience some limited core damage for slow ramps which will probably not spread to the rest of the core.

E.1.5.2 TOP and RIA Accidents in other ADSs

The gas cooled fast ADS should behave similarly benignly when subjected to fast transients. For slow ramp rates and late pin failures, the fuel dispersal may be more limited in a gas cooled system and give less of a negative feedback which could lead to further pin failures.

A thermal ADS with a molten salt/fuel mixture will also react benignly to fast ramp rate insertion [Bell, 94]. For slow reactivity insertions, the advantage is certainly that no pins can fail in the fluid-fueled system and that it can probably survive an enhanced power situation without problems.

E.1.6 CONCLUSIONS

The ADS has a clear advantage for coping with fast ramp rate accidents which would occur too rapidly for scram systems in regular reactors. This ability to overcome fast reactivity insertions is important to avoid Chernobyl type power excursions.

In cooling-failure accidents without beam shut-off, rapid power excursions are not possible - even for positive void worth cores. However, the power of an ADS cannot be decreased very much due to negative feedbacks. The only way to decrease the power to decay heat levels is the switching off of the accelerator beam - otherwise a core melt will occur in a cooling failure accident (which would eventually happen in LWRs too if no scram were activated). Therefore emphasis will have to be put on a highly reliable beam shut-off system in an ADS. If the ADS had a low pressure cooling system and a guard vessel there could be no problems with Loss-off-Coolant Accidents (LOCA). Of general importance for safety in any reactor type as well as for ADSs is a reliable emergency decay heat removal system which should preferably be a passive system.

Comparing fast ADS with solid fuel and thermal ADS with a circulating salt/fuel mixture a few points are important. The thermal systems have a slower response time in accident situations which makes the detection of the off-normal conditions easier. In severe accident situations without beam switch-off, the salt/fuel will expand and boil and could lead to leakages whereas the fast system could melt down and possibly lead to a recriticality which could cause a power excursion. In the salt/fuel system pumps and primary heat exchangers are all radioactive and therefore difficult to inspect. Moreover, there are uncertainties about the precipitation and accumulation of fuel and minor actinides leading to mild excursions and there is also an uncertainty about the temperature coefficient of reactivity.

E.2. FIRST INVESTIGATIONS OF THE BEHAVIOUR OF AN ACCELERATOR DRIVEN FAST OXIDE REACTOR DURING AN UNPROTECTED LOSS-OF-FLOW ACCIDENT

E.2.1 INTRODUCTION

A new concept for an Energy Amplifier (EA) has been proposed by C. Rubbia [8]. It consists of a subcritical fast system that is driven by the proton beam of a compact cyclotron which hits a target in the reactor and generates about 50 fast neutrons per proton through a spallation process. The proposed F-EA is cooled by Lead and uses $^{233}U/^{232}Th$ fuel.

Safety considerations of such new approaches and in particular the investigation of severe accident conditions are important. An investigation of a severe reactivity accident was earlier undertaken [9]. Although the reactivity ramp used was rather steep and it started from initial reactor conditions this study showed that accelerator driven fast systems are rather insensitive to fast reactivity insertions.

The present study deals with a Loss-of-Flow accident in which the primary pumps are assumed to coast down (e.g. due to a station blackout) and which can lead to a major coolability problem for a fast reactor if no scram occurs. Different from the study above in which only the point kinetics and the Doppler feedback were considered, this study used the EAC2 code [10,11] which calculates coolant heating up and voiding, fuel pin heating up and axial expansion, pin ruptures and subsequent molten fuel motion inside the pins and in the coolant channels. The reactivity feedbacks due to axial pin expansion, sodium voiding, fuel motion as well as the Doppler feedback are considered. So far only sodium cooling has been considered. The subcriticality is simulated by a programmed negative reactivity. To simulate the spallation neutrons coming from the target a source was introduced into the point kinetics module. This represents a source that is uniformly distributed in the reactor which is only a simple approximation for the real case of a central neutron source. The reactor under consideration is a 800 MWe reactor design used in the European WAC benchmark calculations [12]. The pump coastdown times and a negative ramp of -2 cent/s, which roughly simulates a structural expansion feedback, were taken from the WACLOF benchmark. The core set-up with half of the fuel near fresh and the remainder with a burnup of 275 days and the dividing of the core into 10 representative calculational "channels" were also taken from the WACLOF benchmark. Since this benchmark dealt with a sodium coolant, the comparison calculations were also made for sodium cooling. The investigation of the accident behaviour with Lead cooling may be a further step.

E.2.2. CALCULATIONAL RESULTS

Figs 1 and 1a show the EAC-2 results for the standard WACLOF case. The important reactivity effects all occur within one second. Sodium voiding gets the total reactivity to prompt critical despite negative Doppler and axial pin expansion reactivities. Subsequently the fuel pins fail near the midplane and some in-pin fuel motion towards the failure location leads to positive reactivity effects (see the small positive peak of the total reactivity) and this leads to superprompt critical conditions and a power peak of 1800 times nominal. Once the fuel moves in the coolant channels away from the midplane, the fuel motion reactivity becomes strongly negative and shuts the reactor down. However more than 85 % is of the fuel is now molten. The integrated power measured from the first pin failure is 4.5 full power seconds

Fig.2 and 2a show a modified WACLOF case for which stress failure criteria were used for failing the pins. These mechanistic criteria lead to earlier pin failures than the melt fraction criteria in the original case. This leads to a more limited in-pin fuel motion to the pin rupture site, and thus, only to a power peak of 265 times nominal and only 1.8 full power seconds integrated power after the first pin failure.

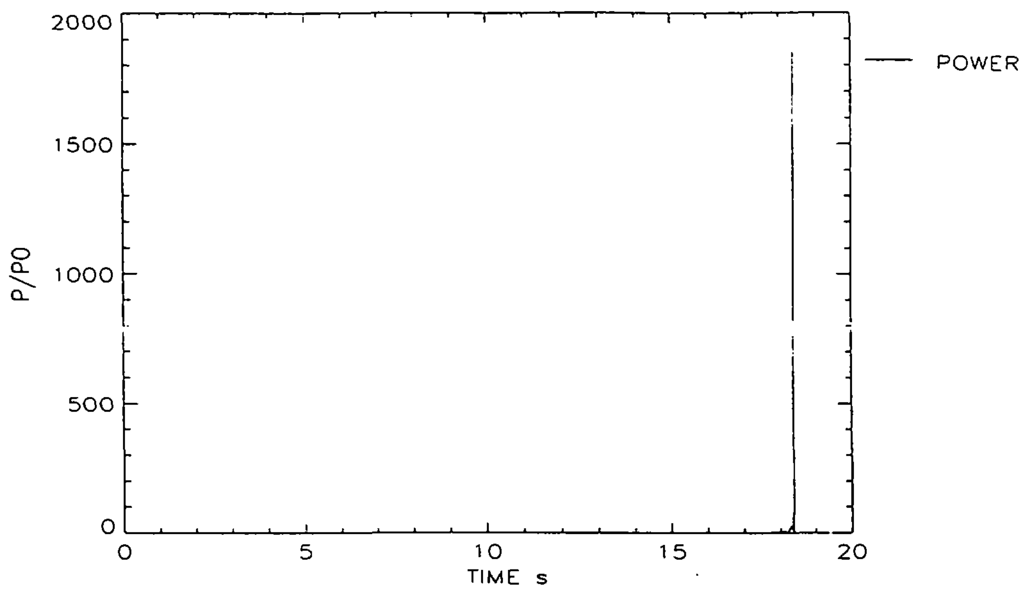

FIG. 1. Power history in the original WACLOF case (pin failures based on melt fraction criterion).

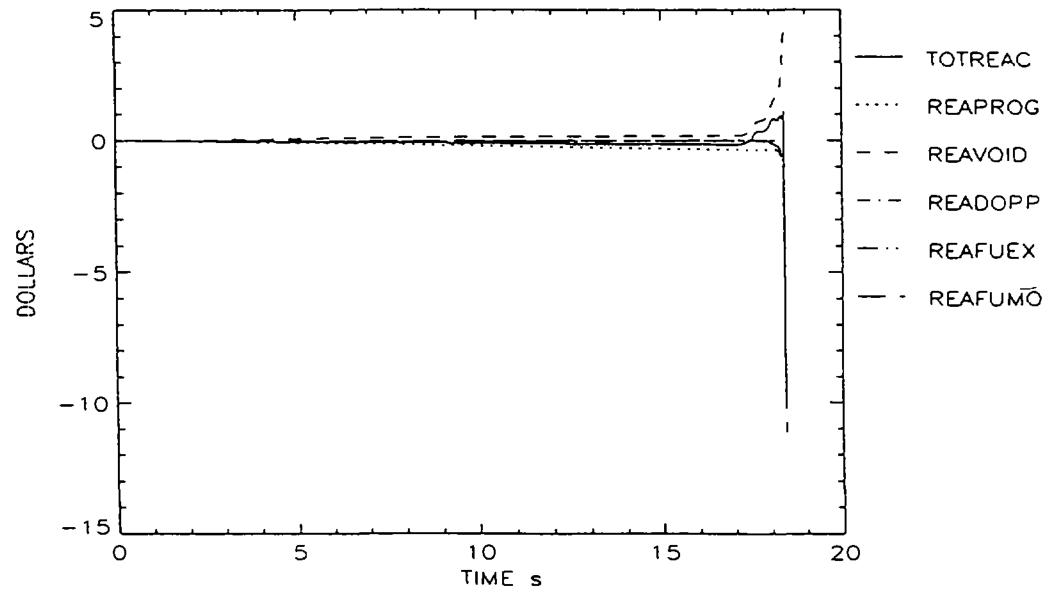

FIG. 1a. Reactivities causing the power history in Fig.1.

Fig.3 and 3a show the results of a run in which the WAC reactor was initially subcritical by -3$ and an accelerator driven neutron source was active and provided the neutrons necessary to maintain nominal power. The negative ramp of -2 cents/s was maintained in order to compare with the WACLOF case. For the pin failure criteria the melt fraction criteria from the WACLOF benchmark were also kept (70% maximum areal melt fraction for irradiated pins and 90% for fresh pins). The main difference in this

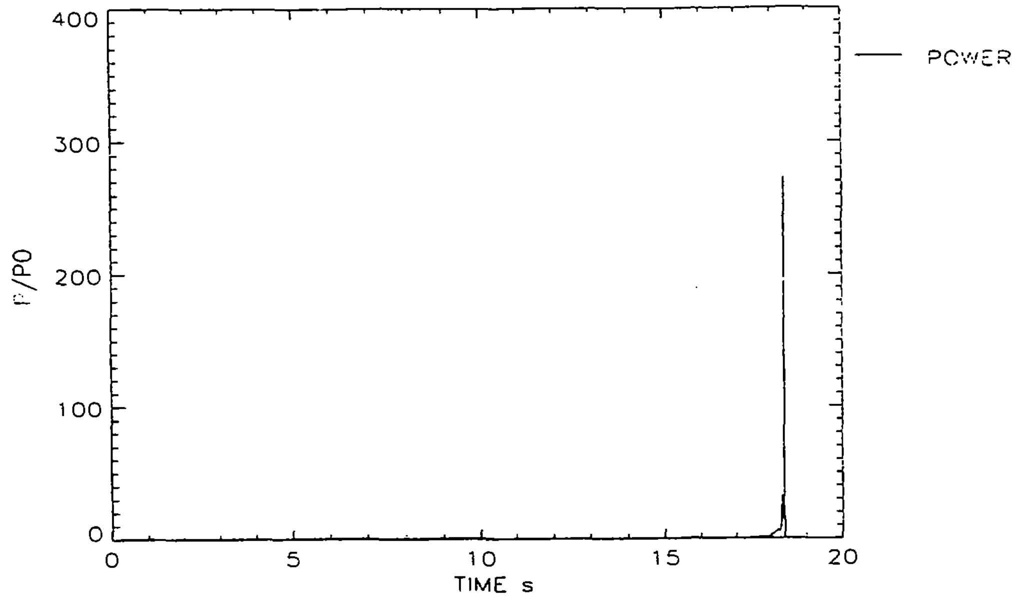

FIG. 2. Power of WACLOF case with more realistic pin failure criteria.

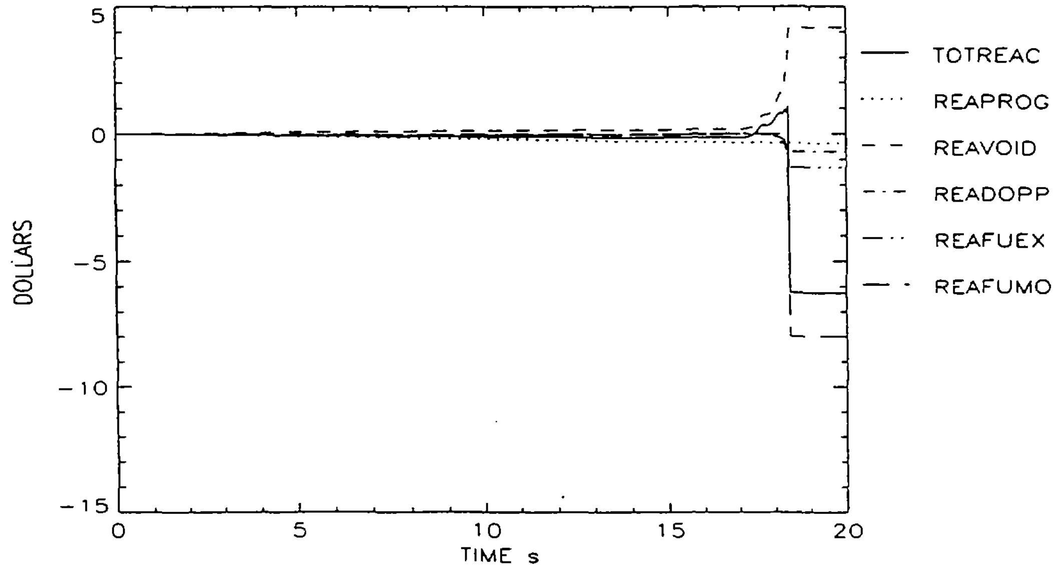

FIG. 2a. Reactivities causing the power history in Fig. 2.

calculation is that the power rises to only 5 times nominal and that the total reactivity gets only slightly above delayed critical. It can also be seen that the time from the onset of sodium voiding to the onset of fuel motion (i.e. pin failures) is about 3s, and thus, about 3 times longer than in Fig.1. However, fuel melting also occurs and leads to the failure of 3 of the 10 calculational channels. The subsequent fuel dispersal reduces the total reactivity to -10$, but the power reduces only to 0.3 times nominal because the neutron source is still on. This is further addressed in the discussion of Fig.5 below. The integrated power from the first pin failure to reaching 0.3 times power is 1.5 full power seconds.

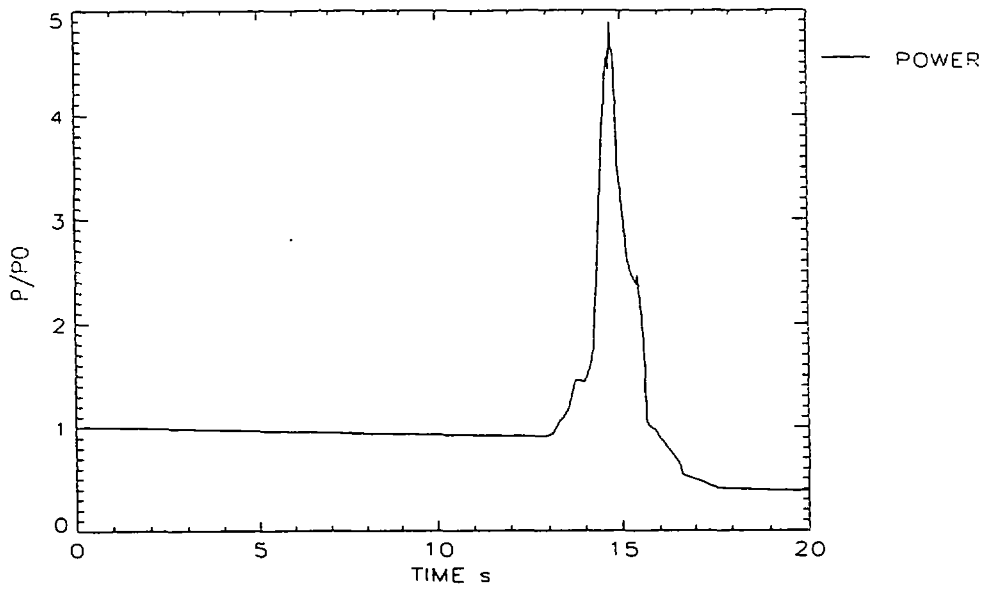

FIG. 3. Power history of WACLOF case with -3$ and neutron source

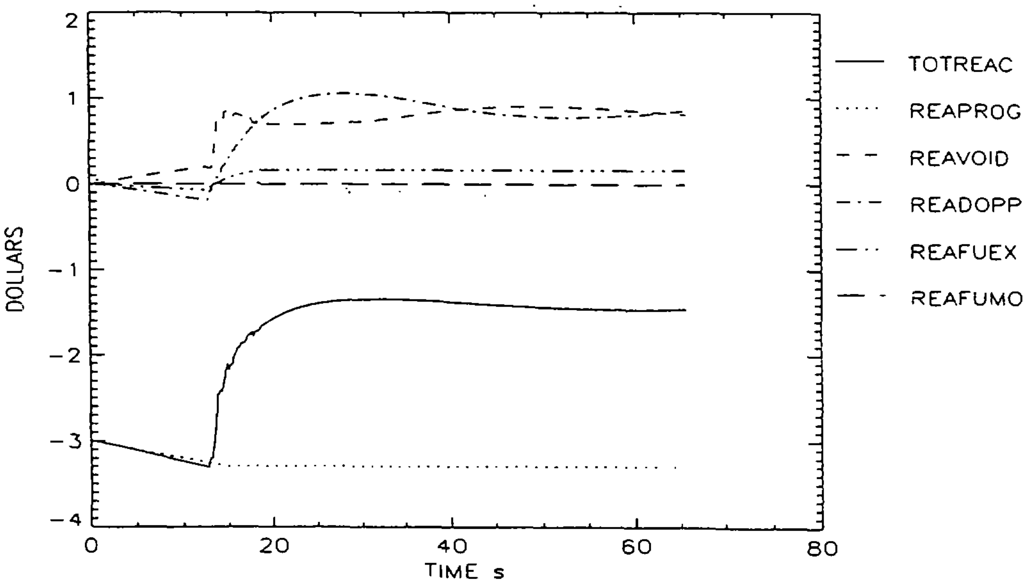

FIG. 3a. Reactivities causing the power history in Fig. 3.

In Figs. 4 and 4a the WAC reactor was initially at -10$ and the neutron source active and providing more neutrons than in the previous case. The power rises to only 1.4 times nominal and the time between voiding onset and pin failures is extended to 6s. The pins fail in 3 calculational channels and lead to molten fuel dispersal which causes a decrease in the total reactivity to -15$. However, the power only decreases

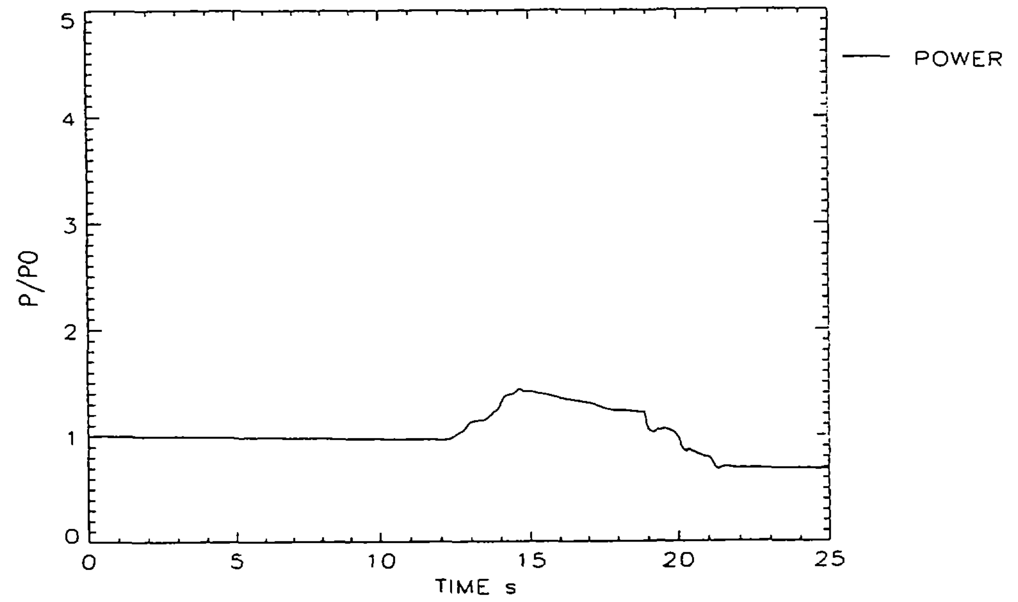

FIG. 4. Power history of WACLOF case - 10$ and neutron source

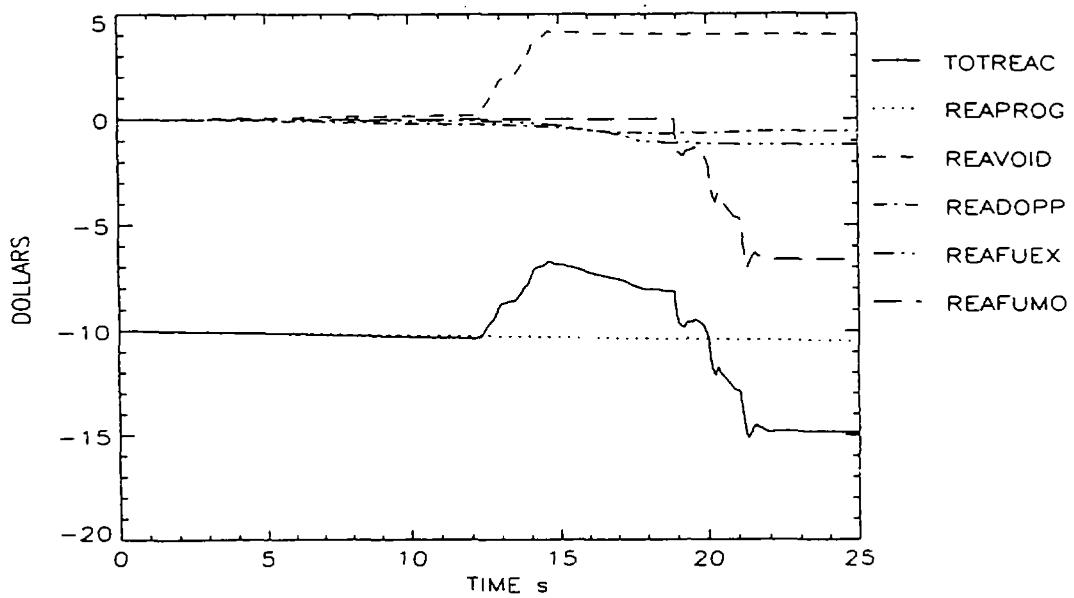

FIG. 4a. Reactivities causing the power history in Fig. 4.

to about 0.7 times nominal because of the relatively strong neutron source which is assumed to be still active. This rather high longer-term power level will lead to more core melting (see discussion of Fig.5). The integrated power from the first pin failure to reaching 0.7 times nominal power is 2.8 full power seconds. However, with the power remaining at 0.7 the integrated power would continue to increase with each additional second by 0.7 full power seconds . The EAC2 results presented in Figs. 4 and 4a cannot be considered very reliable because the cladding melted in this case before the fuel and EAC2 does not model molten cladding motion. The latter would have introduced additional positive reactivity and reduced the fuel dispersal.

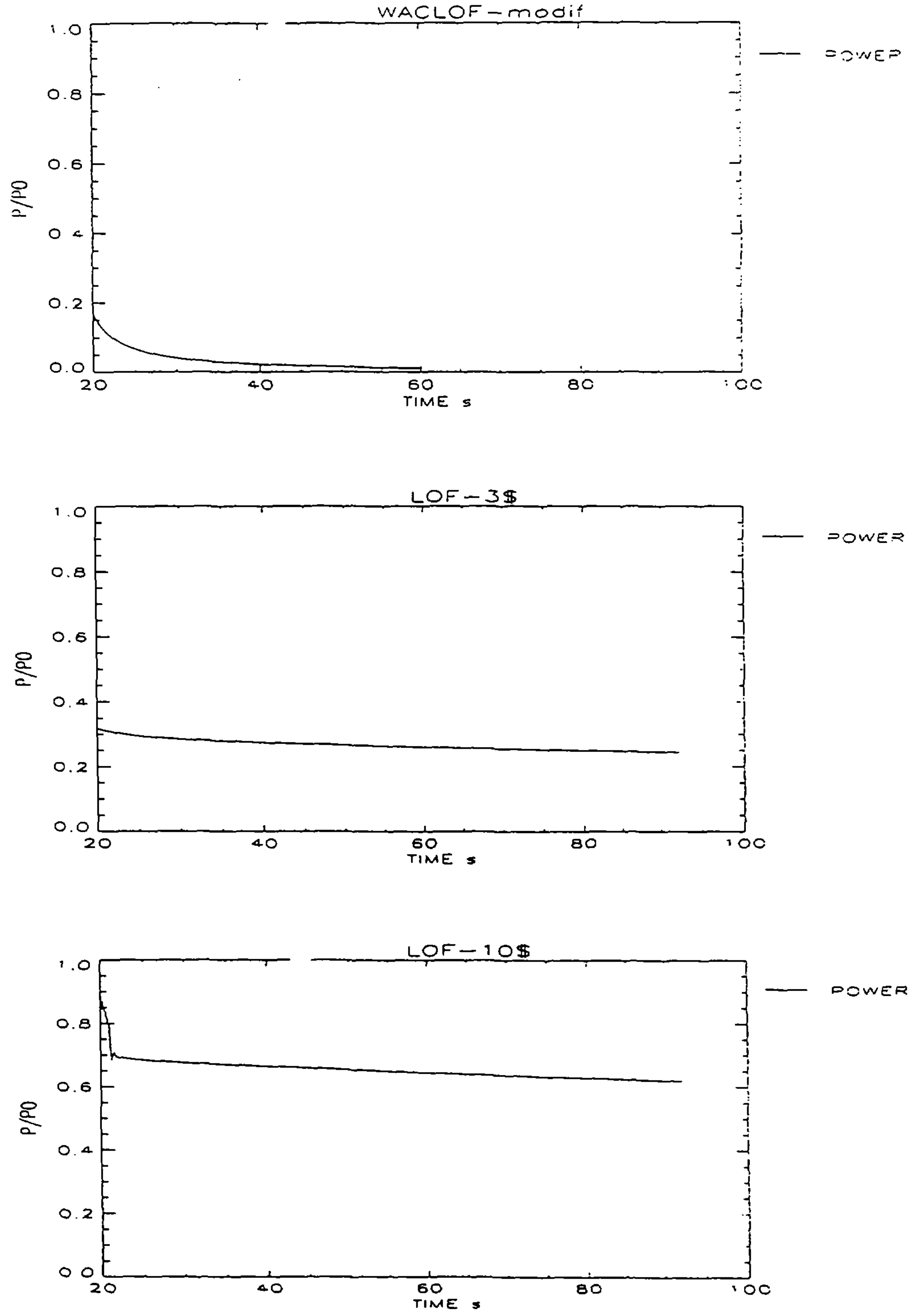

FIG. 5. Comparison of later power histories with core configuration fixed.

Fig. 5 shows the later power histories in three cases: no initial subcriticality, -3$, and -10$ initial subcriticality. These power traces are based on the final configurations calculated by the thermo-hydraulic models (near the ends of Figs. 2, 3, and 4) and a continuation of the calculation solely with the point kinetics model. It can be seen that the power in the subcritical cases decreases only rather slowly (and the decrease is even partially due to the negative ramp of -2 cents/s which is still introduced). The maintaining of a relatively high power level due to the still active neutron source will cause the reactor core to melt down further unless the neutron source is switched off.

Figs. 6 and 6a shows the power history and the reactivity histories for the -10$ case including a switch-off of the accelerator beam starting at 12.3 s and decreasing with

$$e^{-t/\tau}$$

where was chosen to be 0.1 s. The switching off of the source reduces the power level drastically. The effect of the switching-off of the source is similar to the introduction of many control rods in a critical fast reactor. When the source was switched off the core was already hot enough to cause sodium boiling. However, the latter removed enough heat from the core so that the liquid sodium could re-enter and the remaining small flowrate suffices to cool the core at the low power.

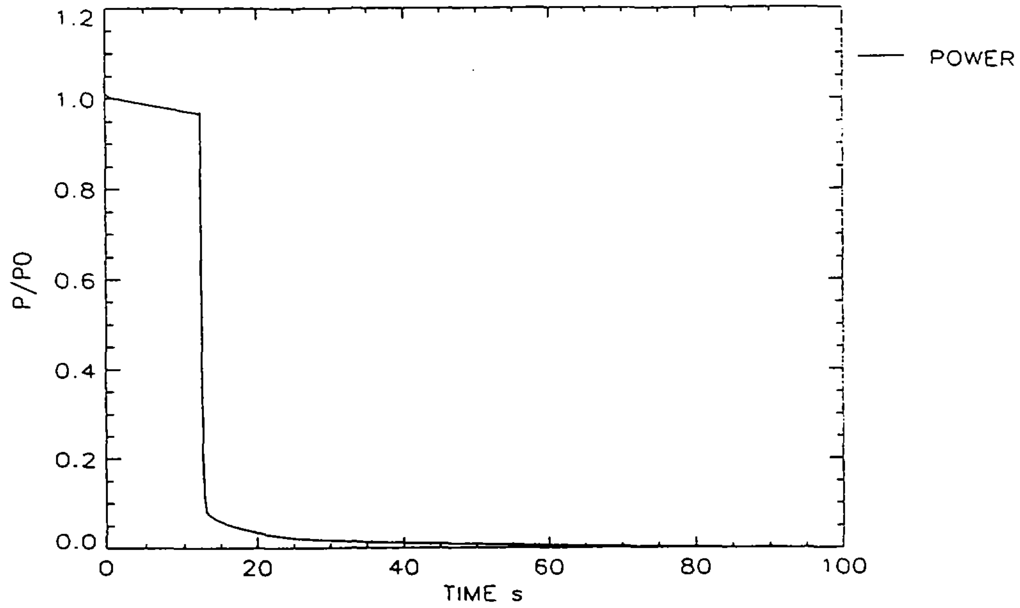

FIG. 6 Power for case - 10$ but neutron source switched off at 12.3s.

Fig. 7 and 7a show the power and reactivity histories for the -3$ case with the same switch-off of the beam as in Fig.6. However, due to the smaller subcriticality, the power doesn't drop as fast as in the case with the 10$ subriticality and the lead channel becomes vapour bound i.e. the liquid Na cannot penetrate anymore. Whether the cladding in this channel will start melting or whether the liquid sodium càn eventually get back into the channel depends on a more detailed calculation. At any rate, it would have been better to shut the beam off earlier.

E.2.2.1 Means of shutting off the beam

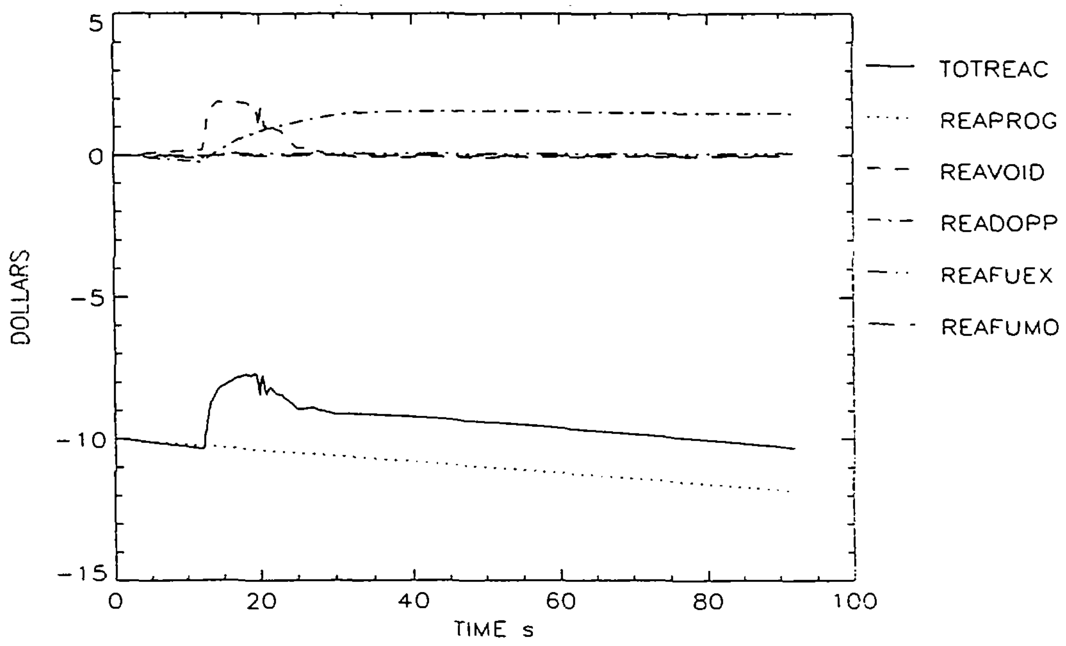

FIG. 6a. Reactivity changes responsible for power history in Fig. 6.

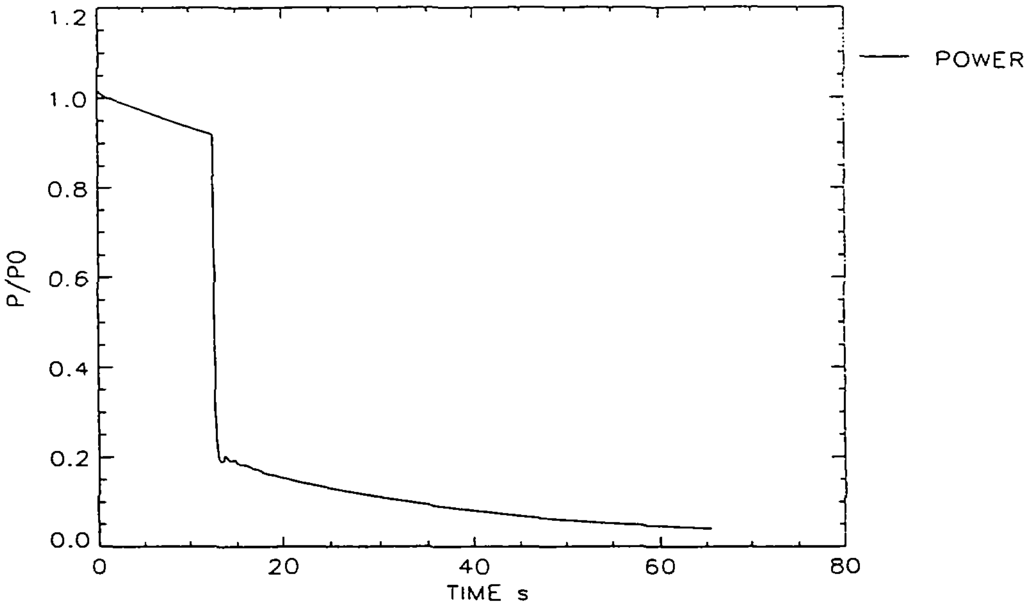

FIG. 7 Power of -3$ case with source switched off a little too late.

One can think of passive means to switch off the effect of a spallation source in case of an accident in which the coolant heats up. For a liquid lead target that is located in the middle of the core and hit by a

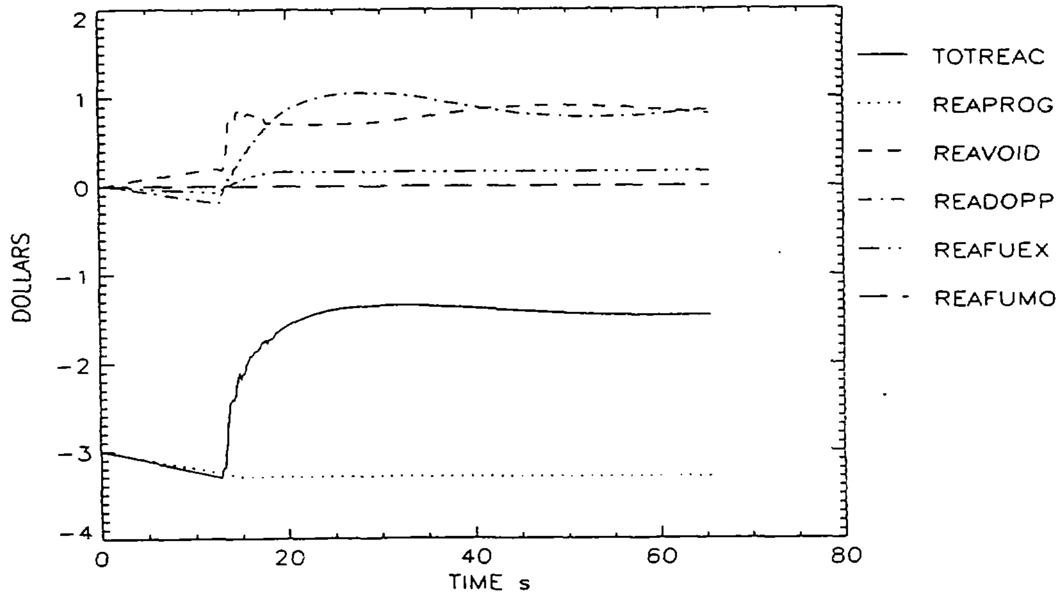

FIG 7a. Reactivity changes responsible for power history in Fig. 7

proton beam from above, one could use a metal plate with a low melting point as the bottom of a container for the target. If the cooling of the core and the target decreased, this bottom plate would melt and the liquid target would run down. The proton beam would then hit the target below the core where the neutron multiplication is low. - Off course all means for detecting coolant overheating (many different thermocouple indications, the de-magnetising of magnets) which are used in present LMFBRs for activating control rod insertion could also be used to switch off the cyclotron. Moreover there could be a connection between the electric current to the coolant pumps and the cyclotron which would cut the current to the latter off when the current to the primary or secondary pumps decreased.

E.2.3. CONCLUSIONS

The main safety advantage of a subcritical fast system driven by a spallation source is that no power excursions leading to high power levels are possible for positive reactivity additions which are of the order of the subcriticality. The possibility of power excursions during the initiation phase in present Fast Reactors is a disadvantage with regard to safety (recriticalities in the subsequent transition phase, post-accident coolability problems and sodium fires are the other ones)

An important remaining problem for subcritical fast systems undergoing a Loss-of-Flow or Loss-of-Heat-Sink accident is that a core melt-down cannot be prevented unless the spallation source is switched off (in present fast reactors the control rods have to be inserted to prevent a core melt down - it could be argued that the activation and the insertion of control rods is more complex than switching off an accelerator beam). If the spallation source is not switched off in any accident at full power, the latter will not decrease strongly even if a considerable negative reactivity has been introduced (e.g. negative Doppler feedback, ..)

As a general tendency it was confirmed that accelerator driven systems react benignly to the introduction of rather strong positive reactivities. On the other hand, massive cooling disturbances lead to core melting at low power if the accelerator beam is not switched off. Therefore investigations into passive means for shutting off the proton beam are of importance.

E.3. INVESTIGATION OF REACTIVITY ACCIDENTS IN A LARGE SODIUM-COOLED ADS

In this study the same 800 MWe fast reactor design is used as in the study of LOF accidents in chapter E.2. However, in this investigation all 10 channels which represent the core were irradiated for 275 days. Different reactivity ramp rates of 170\$/s, 6\$/s and 10 cents/s were investigated and the total reactivity insertions were limited to \$2.65 and \$3. The source strengths and the corresponding subcriticalities were also varied in some cases (between -3\$ and -20\$).

E.3.1. 170 \$/S TOP CASES WITHOUT AND WITH SPALLATION SOURCE

The first case considers no external source and an insertion of up to 2.65 \$. It is based on an old FZK benchmark case for space-time kinetics [13]. It should be mentioned that this ramp rate starting from steady state is probably unrealistic but it's slope is similar to the calculated voiding ramp rate shown in Fig. 10a. This benchmark case was earlier investigated by [9] with a point kinetics model and a point model for a reactor taking into account only the Doppler reactivity feedback. By recalculating this case with the EAC-2 code [10] important additional feedbacks due to axial fuel expansion, sodium voiding and fuel motion are also being considered. The results for the regular reactor case are shown in Fig. 1. The first two power peaks are due to the driving ramp and the counteracting Doppler and axial expansion feedbacks. The second peak is lower because of the axial expansion feedback which gets more negative due to fuel melting and expansion. The first pin failures due to cladding strain occur soon afterwards and lead to some voiding and fuel dispersal. At some time the voiding reactivity is not compensated anymore by the negative fuel reactivity and goes above prompt critical. The rapid power rise leads to stress failures which cause more voiding and the large power peak. However, eventually the fuel dispersal dominates and terminates this power excursion. At the end the entire core is molten and about 18 full power seconds of energy went into this power pulse.

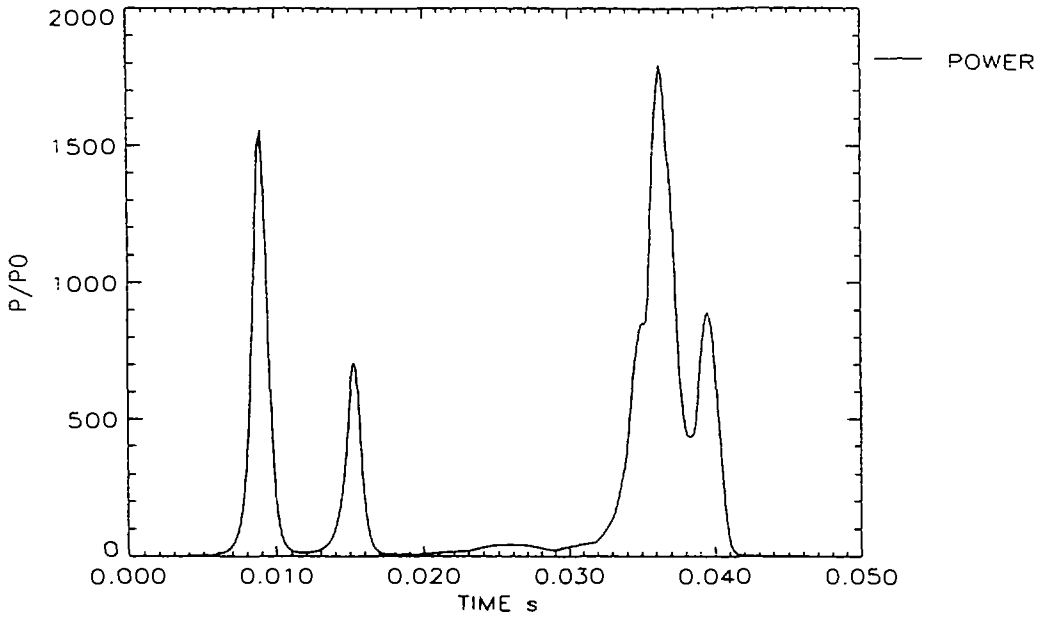

FIG. 1. Power history for 170 \$/s TOP case without the neutron source.

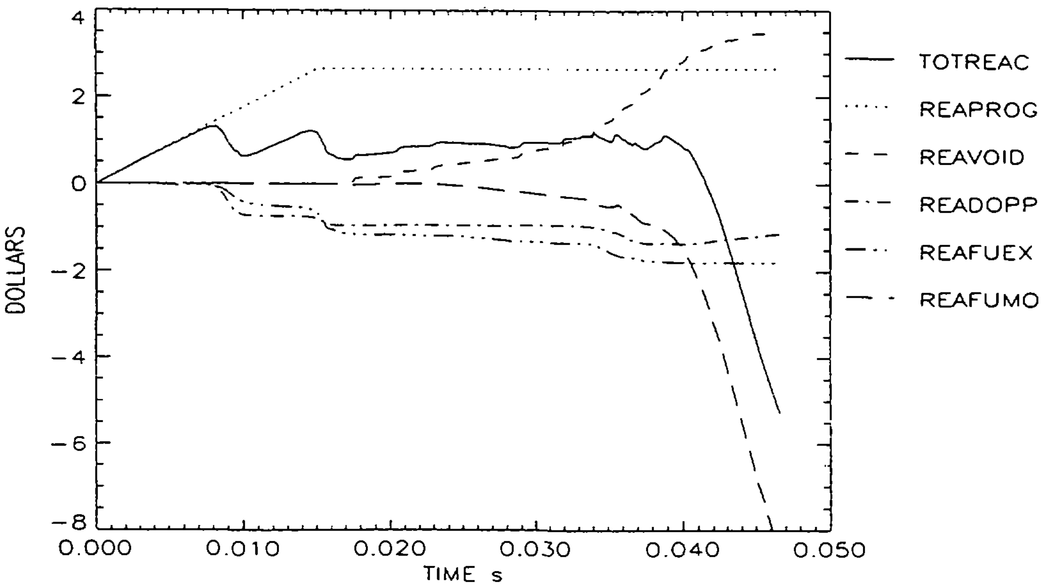

FIG. 1a. Reactivities causing the power history in Fig. 1.

The corresponding case with an external neutron source and a -3 $ subcricticality behaves benignly as can be seen in Fig. 2. The case was actually run up to 92 seconds when the power was 1.27 times nominal. After 60 s a few pin meshes indicated strain failures. But no fuel ejection was predicted because EAC-2 starts fuel ejection only when 25% areal melt fraction is reached and this did not happen. Most likely fission gases will get released under these conditions. On the one hand there is some time to switch off the spallation source and on the other hand one could make the subcriticality larger.

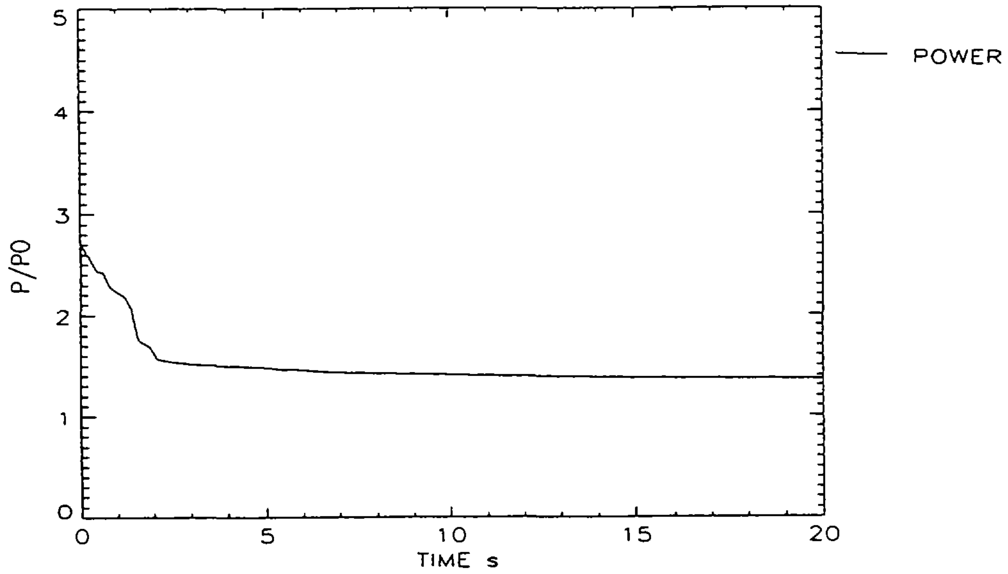

FIG. 2. Power history for 170 $/s case with the spallation source and -3 $ subcriticality.

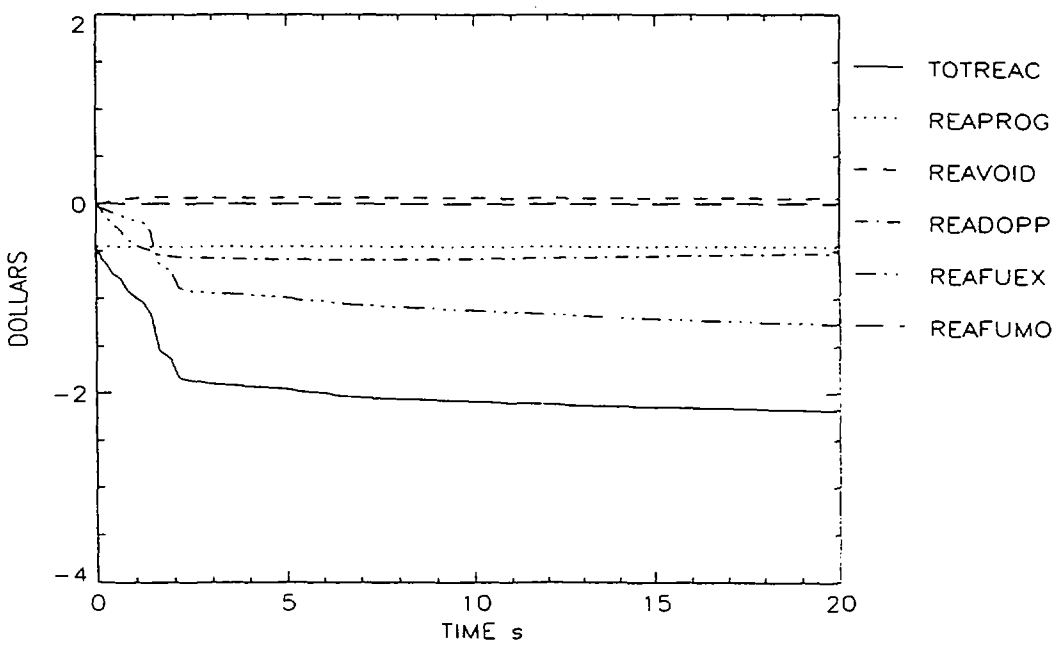

FIG. 2a. Reactivity changes responsible for power history in Fig. 2.

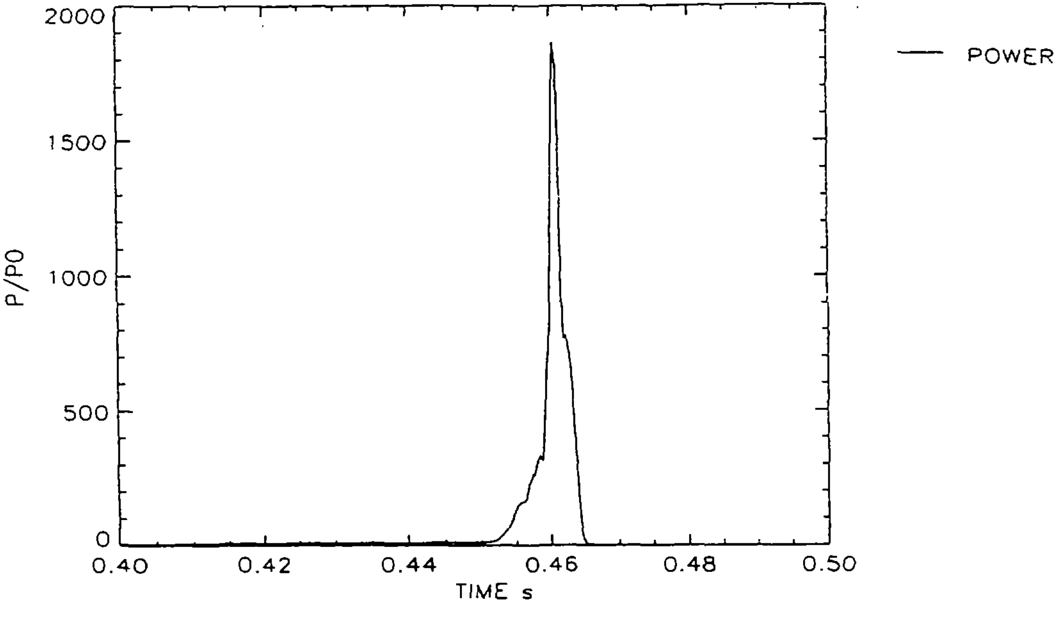

FIG. 3. Power history for 6 \$/s TOP case without the spallation source.

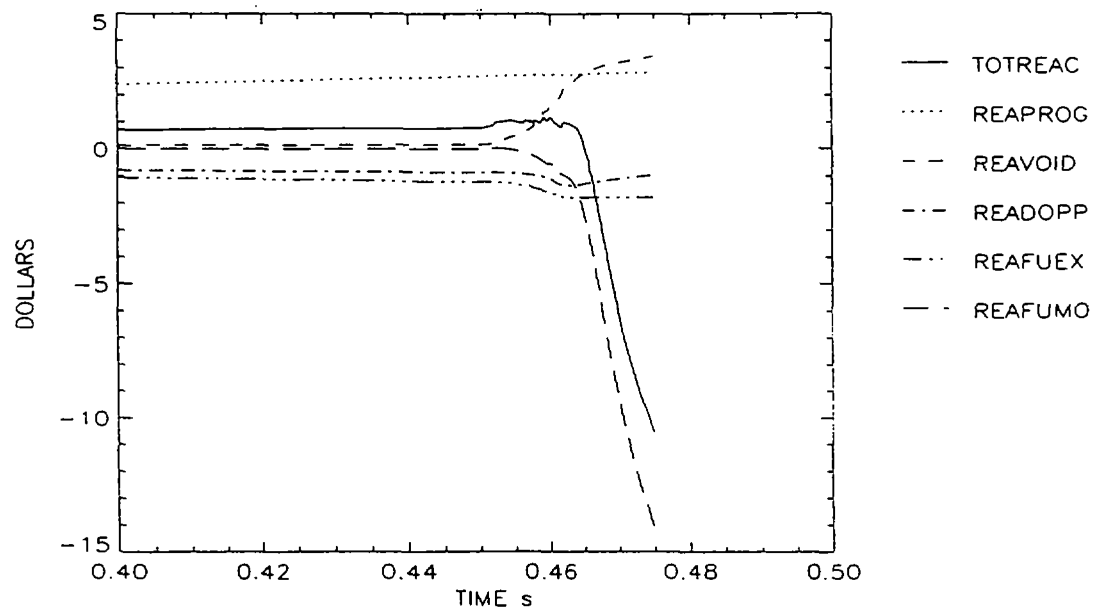

FIG. 3a. Reactivities causing the power history in Fig. 3.

E.3.2. 6 $/S TOP CASES WITHOUT AND WITH SPALLATION SOURCE

The first case is without external source and the ramp is introduced up to 3 $. It should also be mentioned here that this is a very unlikely ramp rate. Figs. 3 and 3a show only the time interval from 0.4 to 0.5 s because nothing special happens before. When the pins start failing and ejecting fuel, a rapid sodium voiding starts. The energy produced is about 9 full power seconds and the core is about 90%

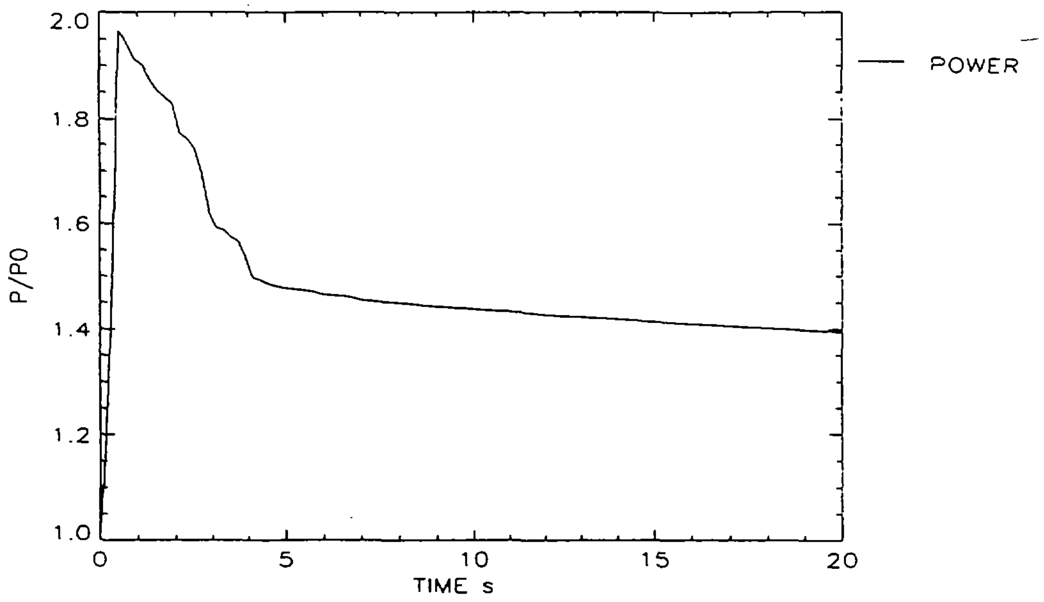

FIG. 4. Power history in 6 $/s TOP case with source and -5$ subcriticality

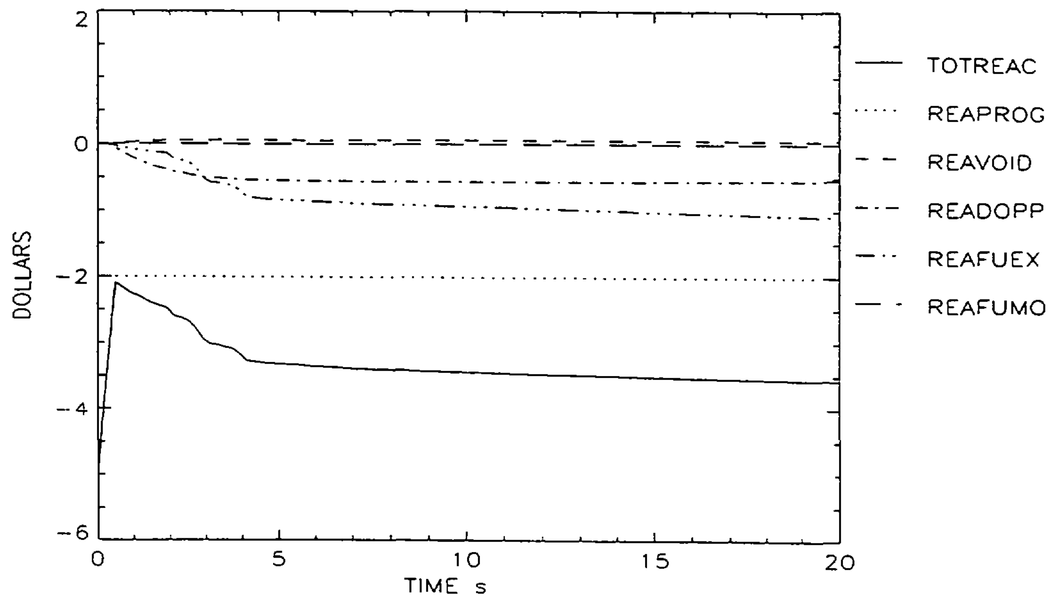

FIG. 4a. Reactivities causing the power history in Fig. 4.

molten. This large peak is still less powerful than the one shown in Fig. 1a. This is due to an earlier rapid fuel dispersal in this case and in turn due to initial failure locations that are higher up.

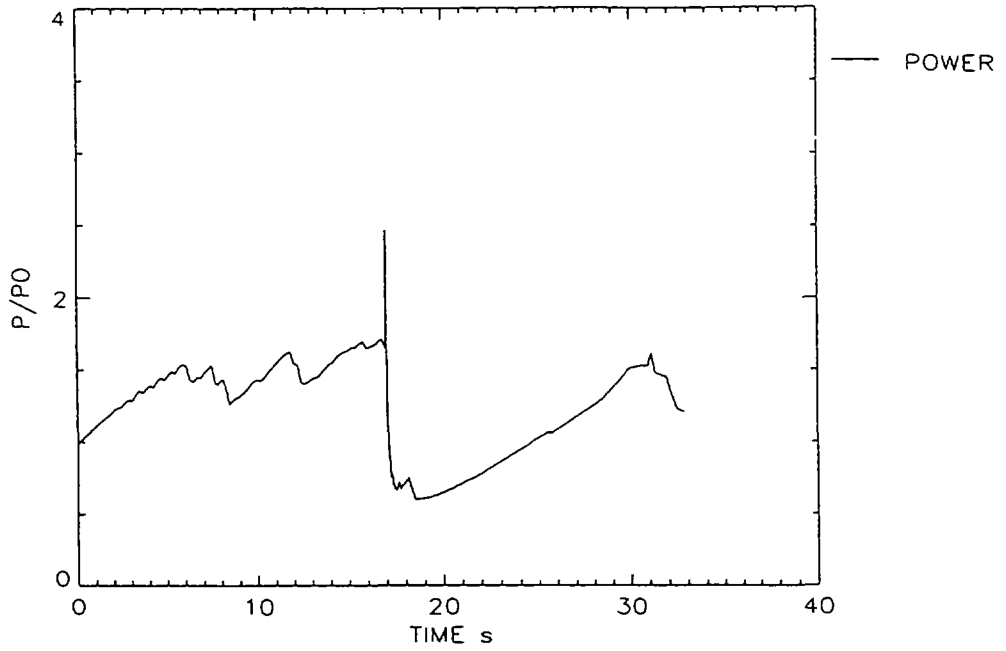

FIG. 5. Power history for 10 cents/s TOP without the spallation source

The case with external source and a -5$ subcriticality is shown in Figs.4 and 4a. The case was run out to 92 s and did not show any failure although the power at 92 s was 1.37 times nominal. With a subcriticality of only -3$ a strain failure led to fuel ejection in one channel. This caused enough of a negative reactivity to prevent failures in the other channels.

E.3.3. 10CENT/S TOP CASE WITHOUT AND WITH EXTERNAL SOURCE

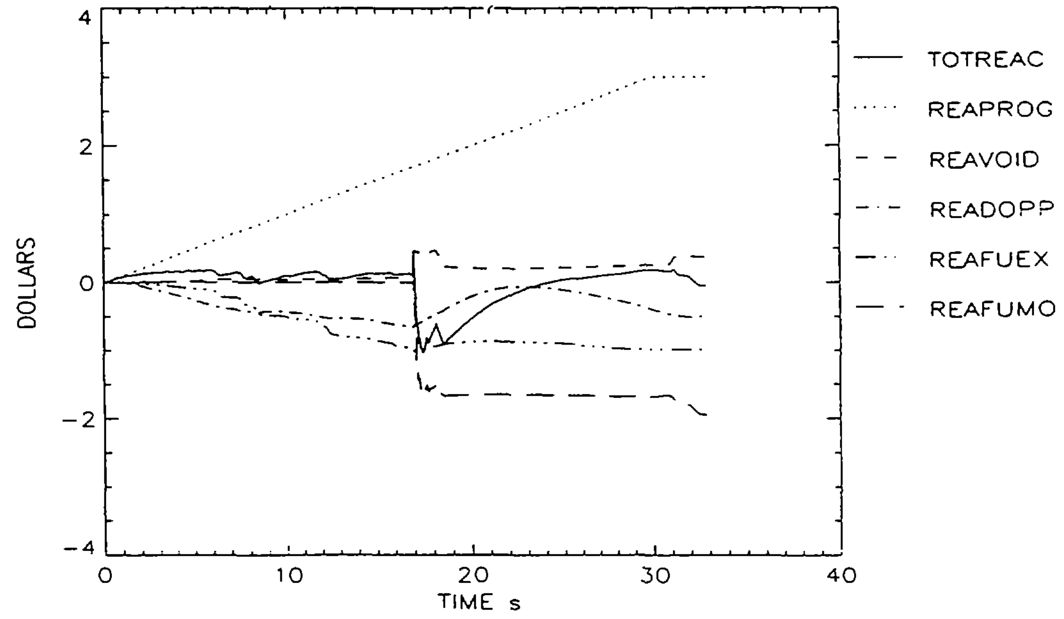

FIG. 5a. Reactivities causing the power history in Fig. 5.

The first calculation is for a regular fast reactor and the ramp inserts up to 3$. These slower ramp rates are considered more realistic but still of low probability. The power and reactivity histories are shown in Fig. 5 and 5a. The power rise is rather uneven and this is due to the axial fuel expansion reactivity which reflects the loss of fuel/clad contact in different channels which is modelled in the TRANSURANUS pin behaviour code [4] which is part of EAC2. This case leads inevitably to the failure of one calculational channel. The negative reactivity from the fuel dispersal just prevents another failure.

The alternate case with source uses a -10 $ subriticality to avoid any failure - Figs 6 and 6a. At 92 s the power level is about 1.3 times nominal. In another case a -$20 subcriticality was tried. This led to a power level of 1.15 times nominal at 92 s. With a -3$ subcriticality a strain failure occurred at 30 s at a power level of 1.65 times nominal power. With a -5$ subcriticality a strain failure occurred at 60s at 1.4 times nominal power. This means that one still gets the failures leading later than for a critical reactor and if one wants to avoid these failures one has to go to a larger subcriticality.

E.3.4. CONCLUSIONS

For fast or medium fast reactivity ramps the ADS has a major advantage in coping with such serious reactivity accidents. For slower ramps there is still somewhat of an advantage because pin failures will occur later or one can avoid them with a larger subcriticality. Moreover, they can be avoided with larger subcriticalities

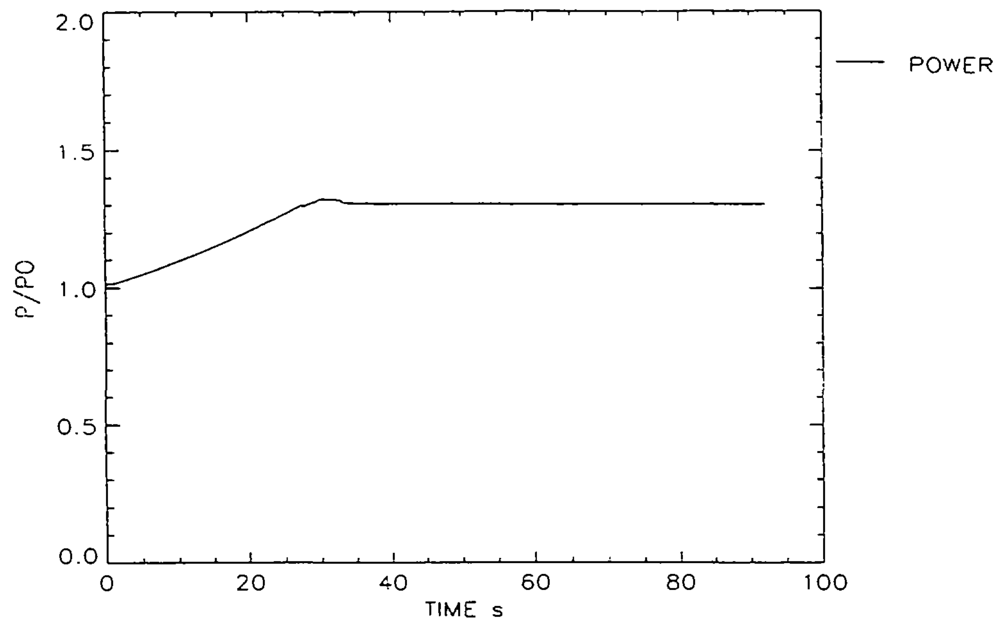

FIG. 6. Power history in 10 cents/s TOP case with the spallation source and -10$subcriticality

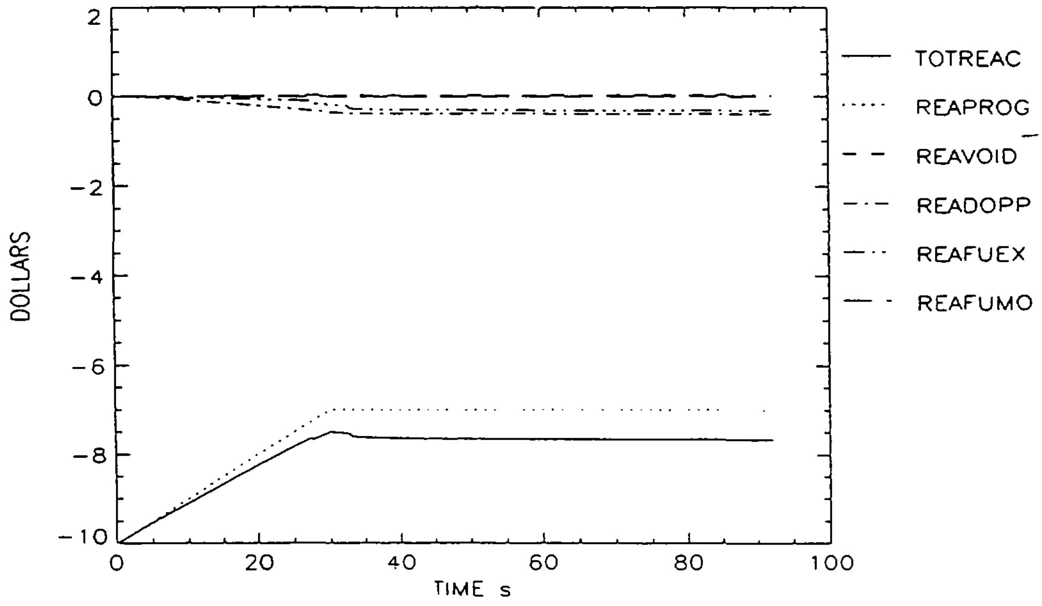

FIG. 6a. Reactivities causing the power history in Fig. 6.

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