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Abstract

In the safety analysis of fast reactors, unprotected accidents, such as ULOF and UTOP have to be considered, even when their frequency of occurrence lies far beyond the design basis accident. In the European Fast Reactor (EFR), the safety approach foresees further measures of risk minimization in the frame of the so-called *Third Shutdown Level*. One of the measures is a control rod enhanced expansion device, called ATHENa, which has been developed by KfK in collaboration with SIEMENS as a passive device to separate the absorbers from the drive lines in cases of accidental coolant temperature rises and to force the absorbers further into the core in case of failure to drop.

The efficiency of the ATHENa devices to prevent sodium boiling and fuel melting in unprotected accidents in EFR has been investigated by calculations with the dynamics code DYANA2. In the case of ULOF accidents, sodium boiling can be prevented, if at least one out of 24 absorber rods equipped with ATHENa devices drops into the core after delatching from the drive lines. In the extremely remote case that all rods remain jammed after delatching, they are pushed by the ATHENa decices into the core with an enhanced expansion coefficient ($\sim$10 times). Even then, sodium boiling could be prevented by extending of the pump coast down halving time from 10 to 12 s or by adjusting the delatching temperature to a value not higher than about 40 °C above nominal coolant outlet. In UTOP accidents caused by the uncontrolled withdrawal of a control rod, the main concern is incipient fuel melting. The results of the calculations have shown that the power rise can be terminated by delatching the absorbers, before fuel melting occurs, if the ramp rate is mechanically limited to values of 1 ¢/s or less. Again, even in the worst case that all rods remain jammed, fuel melting could be prevented by adjusting the delatching temperature to a similar value as in the ULOF case.

Über den Einfluß von Kontrollstab-Dehnungsverstärkern auf den Verlauf auslegungsüberschreitender Störfälle im EFR

Zusammenfassung:

Bei der Sicherheitsanalyse Schneller Reaktoren werden auch Durchsatz- (ULOF) und Reaktivitätsstörfälle (UTOP) betrachtet, die wegen der extremen Seltenheit ihres Auftretens zum Bereich der auslegungsüberschreitenden Störfälle gehören. Beim EFR wird die schon geringe Eintrittswahrscheinlichkeit dieser Störfälle durch Einführung einer "dritten Abschaltebene" weiter reduziert. Eine Maßnahme besteht darin, die Kontrollstab-Gestänge mit einem eigens dafür von KfK und SIEMENS entwickelten Dehnungsverstärker ATHENa zu versehen, der aufgrund des passiven, thermischen Dehnungseffekts bei einem Anstieg der Kühlmitteltemperatur die Abschaltelemente vom Gestänge trennt.

Die Wirksamkeit dieser Vorrichtung bei der Verhinderung von Kühlmittelsieden und Brennstoffschmelzen im Falle auslegungsüberschreitender Störfälle wurde mit dem Dynamik-Programm DYANA2 untersucht. Die Ergebnisse zeigen, daß bei einem Durchsatzstörfall Kühlmittelsieden verhindert wird, wenn mindestens einer der vom Gestänge entkoppelten 24 Absorberstäbe abfällt. Selbst beim Nichtabfall aller abgehängten Stäbe werden die Absorber infolge der ca. 10-fach verstärkten Expansion der Dehnungsverstärker ATHENa in den Kern geschoben. Auch dann

kann Kühlmittelsieden verhindert werden, allerdings muß dafür die Pumpenauslaufzeit von 10 auf 12 s verlängert oder die Schalttemperatur nicht höher als 40 °C über den Nominalwert der Kühlmittelaustrittstemperatur eingestellt werden.

Bei Reaktivitätsstörfällen, bei denen die Reaktivitätsrampen auf Werte $\leq$ 1 ¢/s beschränkt werden, genügt ebenfalls das Abfallen eines Abschaltstabs, um Brennstoffschmelzen zu verhindern. Sollten alle Stäbe klemmen, so genügt wiederum zur Verhinderung von Brennstoffschmelzen eine ähnliche Anpassung der Schalttemperatur für die Gestängekupplung wie im Falle eines ULOF oder eine Verringerung der Rampensteilheit.

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I. Introduction

The principal objective of nuclear safety is to protect individuals, society and the environment against radiological hazards. Traditionally, core disruptive accident sequences, although of extremely low probability, have constituted the primary risk of nuclear reactors to public health and safety. In order to regain public acceptance of nuclear power in the future, it is therefore of fundamental importance to reduce this risk still further to a minimum practicable level. This coincides with the requirement to minimize the economic and financial risk for the utilities. Another issue is that nuclear power has to compete favourably with other energy sources on a commercial basis. There are a number of requirements to reduce the cost of nuclear power - reduction of system complexity, shorter licensing periods, increase of standardization, solution of the problem of spent fuel disposal, etc. -, but they will not be treated in the present paper.

The safety of a reactor basically resides in its capability of providing reliable reactivity control (and shutdown) and heat removal, both during operation and after shutdown, with the ultimate objective of being able to contain any radioactive material inside the plant. This is achieved by the *defence-in-depth* strategy which relies on

1. prevention of faults,
2. detection of faults and
3. mitigation of accident consequences.

All reasonable practical steps must be taken at the first line of defence, the prevention of accidents, but also at the final line of defence, mitigation of radiological consequences.

The response of the *Light Water Reactor* (LWR) technology to this challenge has been to adopt both an evolutionary and a revolutionary path [1,2,3]. Present LWRs offer a broadly developed and mature technology basis and a potential for further improvement. The high quality in operation and maintenance has been reached in compliance with the stringent safety requirements, incorporating the feedback from plant operation experience and the results from extensive R&D programmes as well as the lessons learned from incidents and accidents. In view of this vast wealth of experience, future technology is seen to be based as much as possible on existing experience. In this way, this approach can be seen as an evolutionary development. LWR plants are designed with enhanced engineered safety and even passive safety features are now considered where they appear to offer advantages. For this approach it is not necessary to build demonstration plants and to enter into long-term development programmes.

There are also programmes for reactor concepts which mostly depend on innovative systems that differ from current technology: the revolutionary path. They incorporate in advanced plant designs as much as possible of passive safety features which are conceived to be more reliable than engineered systems, since depending on gravity, thermal hydraulics and other physics laws and not requiring the intervention of operators or the use of externally activated electrical or mechanical devices. This path is also characterized by a tendency to develop smaller unit sizes which appear to offer some advantages in simplification and construction which compensate for the sacrifice of economy of scale.

A similar tendency as described for LWRs can be observed in the field of *Liquid Metal Cooled Reactor* (LMR) technology. Some key safety features are intrinsic to LMRs and are already present in currently operating reactors, such as absence of depressurization faults, large heat sink of primary coolant, easy establishment of natural circulation and large margin to coolant boiling in normal operations. An additional freedom is the choice of fuel: oxide, metal, carbide or nitride. On the other hand, there are two areas where LMRs could be less intrinsically safe than LWRs: Use of sodium coolant has the potential for exothermic sodium-air and sodium-water reactions and the use of Plutonium fuel in a fast spectrum yields a much reduced fraction of delayed neutrons compared to LWRs. However, the SEFOR experiments [4] have successfully demonstrated the efficacy of the Doppler effect in mixed oxide-fuelled fast reactors: they provide excellent stability in spite of the reduced fraction of delayed neutrons. The risk of sodium reactions has led to the adoption of an intermediate sodium heat transport system which poses an economic penalty, but offers also the beneficial effect of increased thermal inertia in the case of a loss of steam generators heat sink. In general, it can be stated that most of the safety considerations are equally applicable to LMRs and LWRs [5].

II. EFR Safety Approach

EFR has like all other fast reactors some remarkable safety features as mentioned above. Its considerable margin to coolant boiling in normal operations are illustrated in Fig.1. The safety approach being taken in the design of EFR is described in [6]. For the purpose of a better understanding of the scope of the present paper, some key principles of this approach are briefly outlined.

The design targets for EFR are set as follows:

- The frequency of core melt is less than 10^{-6}/year.
- Consistent with this core melt frequency, the loss of shutdown function or loss of decay heat removal function is less than 10^{-7}/year.

Without going too much into details, which are described in [6], some features of the reactor shutdown system will be discussed here to show how, in this special case, these targets can be achieved.

In addition to the physical barriers (fuel matrix, fuel pin cladding and primary coolant system) engineered features are incorporated into the system to provide defence in depth. For the reactor shutdown the function is assured by two independent, redundant and diverse systems. Each system is able to shut down the reactor and comprises a trip system and the associated absorber rod group. Each absorber rod group consists of a mixture of two different rod types, the *Control and Shutdown Rods* (CSD) and the *Diverse Shutdown Rods* (DSD):

- first group (RG1): 12 CSD + 5 DSD,
- second group (RG2): 12 CSD + 4 DSD.

The sensors of each trip system (core outlet temperature measurement and neutron flux monitoring) are connected to a logic which commands the gravity drop of one absorber group. A feedback-free link between the two systems ensures that one trip system is sufficient to initiate the drop of both absorber rod groups.

In the safety analyses of fast reactors, a limited number of initiating faults have been identified which, although never expected to occur are, nevertheless, mechanistically possible. They are representative of the most severe accidents of their category. The more important ones are:

- single absorber rod withdrawal,
- primary pipe rupture,
- single subassembly fault.

The design of the reactor is largely based upon an analysis of these faults. The event which results in the highest damage level is commonly labelled the *Design Basis Accident* (DBA). If it appears that the consequences of a particular family of events are beyond the design criteria, then design measures have to be taken to reduce their frequency of occurrence.

Beyond the DBA, there lies the domain of *Hypothetical Accidents*. In this domain, successive failures of multiple barriers are assumed, which normally are provided and maintained. Serious consequences can develop when a major off-normal condition is encountered combined with a postulated failure of the plant protective system. These events are generally classed as *Unprotected Transients* or *Anticipated Transients Without Scram* (ATWS).

Although the occurrence of these circumstances in fast reactors is highly improbable, *Hypothetical Accidents* have been extensively considered in safety analyses. Because LMR cores are not arranged in their most reactive configuration, the consequences of core compaction has to be explored. In this accident path, the ultimate neutronic shutdown could only come about by the development of fuel and/or coolant vapour pressure, which would physically disassemble the core. This has led to the commonly used term *Hypothetical Core Disruptive Accident* (HCDA). There is another conceivable path of *Hypothetical Accidents*, which may lead to permanent shutdown by core melting into a subcritical array, not requiring disruptive vapour pressures. To distinguish both paths, the first is usually referred to as *energetic* HCDA.

In the whole range of unprotected accidents, three specific initiators have emerged to serve as standard events to assess the safety margins of the plant:

1. the *Unprotected Loss of Coolant Flow* (ULOF) by loss of power to the pumps,

2. the *Unprotected Transient Overpower Accident* (UTOP) which is caused by inadvertent withdrawal of one or more control rods and

3. the *Unprotected Loss of Heat Sink* (ULOHS) which implies that the system can no longer remove heat.

The EFR safety approach foresees, in addition to the preventive measures already provided within the design basis, to have further measures of risk minimization. For convenience, for those measures supporting the shutdown function, the name *Third Shutdown Level* is used. With these measures, the preventive line of defence is strengthened and will reach such a degree of reliability, that severe accidents will be relegated far into the residual risk domain. The *Third Shutdown Level* consists of active and passive features, such as control rod stroke limitation or *Control Rod Enhanced Expansion Devices* (CREED) which are intended to exclude core damage even in events of shutdown systems failure. The additional line of defence provided by the *Third Shutdown Level* is located within the grey area of Fig.1 between the defence line of automatic protection and the limits of coolant boiling and fuel melting.

There are a number of plant characteristics which have a major impact on the behaviour of the reactor to an ATWS event. They can be inherent and thus be an integral part of the design (reactivity coefficients, natural circulation, extended pump coast down) or engineered which are specifically introduced to improve the reactor response to transient and accident conditions. They are further distinguished into passive and active. A passive feature is one that is automatically activated through a physical law of nature (gravity, changes in temperature, pressure or neutron flux etc.) once the transient has caused exceeding a trigger threshold. The *Control Rod*

Enhanced Expansion Device, called ATHENa [7], is an example of this category of passive devices. Its performance is described in Sect.IV.

The present note is mainly concerned with the analysis of ULOF and UTOP events in EFR under the assumption that the control rod drive lines are provided with enhanced expansion devices of the type ATHENa.

III. Reactivity Feedbacks

As the temperature changes during a transient, feedbacks are activated according to their associated time constants and their net effect is governing the dynamics of the system. The most important feedbacks which are taken into account in the dynamics code DYANA2 [8] are discussed below. Their coefficients are given in Sect.V.2.

Doppler Effect: The Doppler effect, which is affected by the fuel temperature, is generally the fastest acting feedback mechanism. It removes reactivity from the system as the fuel temperature rises and can thus help to limit the extent of power increases. But in the case of power reductions, when the fuel temperature drops, the reactivity effect is positive and tends to limit the power decrease. The local effect is calculated at each fuel node and weighted over the core region to give the total effect.

Fuel Axial Thermal Expansion: The fuel thermal expansion is a relatively fast acting feedback mechanism. Its radial component is accommodated within the pin and does not affect the reactivity significantly. Axial fuel expansion increases the core height as temperature rises and increases the radial neutron leakage which has a negative effect on the reactivity. Again, as in the case of the Doppler effect, the sign of the reactivity changes if the fuel temperature decreases.

Sodium Density Effect: The coolant density decreasing with temperature affects the reactivity mainly by two effects of opposite sign: (i) spectral hardening and (ii) increased neutron leakage. The former effect is positive and strong in the central core region whereas the latter effect is negative and increases near the edge of the core. The global effect is positive in the EFR. If the sodium temperature rises up to boiling, the sodium density effect is rapidly increasing as the coolant is expelled from the channels (sodium void effect). This condition presents an important safety problem for fast reactors, a problem not present in thermal reactors. The reduction of the core height from 1.4 m to 1.0 m in the new EFR core design was essentially intended to reduce the sodium void reactivity. In the DYANA2 code, the temperature effects of clad and structure (steel), affecting the dimensions of the coolant channels, are included in the sodium density effect.

Core Radial Expansion: The radial expansion of the core is a result of thermal expansion as well as design of the core and restraint system. The core restraint system is designed to limit the motion of the active core zones of fuel assemblies and to displace them outward as the temperature increases. In DYANA2, this effect is separately treated and called *Bowing Effect*. Its efficacy is not easy to demonstrate, therefore this (negative) reactivity effect is neglected in this study. Thermal expansion of the core increases the axial neutron leakage causing a negative feedback. It depends on the axial coolant temperature rise and on the increase of the core inlet temperature which causes an expansion of the grid plate. The *Inlet Temperature Effect* is generally only significant in ULOHSs.

Control Rod Drive Line (CRDL) Expansion: As the core outlet temperature increases during the initial period of a transient, the CRDL, usually supported from the reactor head, becomes hotter and expands down further into the core. This provides an effective means of passively inserting negative reactivity. The reactivity depends on the control rod positions in the core. Later in the transient the reactor vessel has time to heat up, which, in turn, causes a relative movement between core and CRDL with the effect of withdrawing the control rods by some of the previously inserted distance. This is the reason that the CRDL expansion effect does not shut down the reactor permanently, but provides only a prolonged "grace" time. It will be seen, how the ATHENa device changes this situation totally.

IV. The Control Rod Enhanced Expansion Device ATHENa

This device has been developed by KfK in cooperation with SIEMENS to increase the thermal expansion effect of the EFR CRDL. The basic design features are as follows, more details can be found in [7]. ATHENa is a hydraulic expansion module consisting of a sodium-filled container with expansible metal bellows. With increasing temperature the expanding sodium volume elongates the bellows and increases the length of the device. By adjusting the cross section of the bellows, the expansion can be increased by about a factor of 10 compared to the normal, thermal CRDL expansion. The device is designed to attain a thermal expansion coefficient of about 1 mm/K. This is also the value which has been used in the dynamics calculations.

Dynamics calculations [7] had shown that in a ULOF accident ATHENa is very efficient in reducing the initial coolant outlet temperature rise and preventing coolant boiling, but the ensuing decrease of coolant temperature causes a reduction of the length of the CRDL resulting in a withdrawal of the control rods from the core. The coolant temperature starts to rise again, thus initiating a new cycle. Under certain conditions, this feedback may lead to system instability.

A solution to this problem was to use the elongation of ATHENa to separate the absorber mechanically from the CRDL, such that a successive reduction of its length can no longer withdraw the absorber from the core. In order to realize this idea, CRDL and absorber are connected through a ball release mechanism, which delatches if the elongation of the device reaches a threshold value, which can be chosen by adjusting the quantity of sodium in the container. Normally, after delatching the absorbers drop by gravity and terminate the transient by a shutdown of the reactor. Even in the extremely unrealistic case that an absorber control rod is delatched, but cannot drop due to increased friction in the absorber channel, the enhanced thermal expansion of the device is forcing the absorber rod further into the core, thus providing sufficient negative reactivity to terminate the transient.

In the EFR the ATHENa devices are mounted on the CRDLs in the lower part of the *Above Core Structure*(ACS) [9]. The drive lines move in shroud tubes and are immersed in flowing hot sodium. The temperature response of the device depends on the coolant temperature in the shroud tubes which is influenced by the mixing of sodium entering into the ACS with the sodium already present. The mixing time constant is flow dependent and its value has been determined by thermal hydraulic calculations. The fluid dynamics code FLUTAN [10], a vectorized and improved version of the code COMMIX, has been used to calculate the temperature response of a 3-dimensional model of ATHENa, housed in the EFR control rod shroud tubes of the ACS, during different types of transients.

The results showed that the time-dependent expansion of the device can be well described by two subsequent first-order low-pass filters applied to the temperature of the coolant entering the shroud tube. This model has been implemented into the dynamics code DYANA2 (see Sect.V.1) which is applied for the present analysis and the following values have been used in the calculations:

- a first low-pass filter with a time constant $\tau_1 = 8/q$ s, representing the mixing of the sodium in the shroud tubes with a relative flow rate of q (q = 1.0 at nominal conditions, following the flow reduction in the core until q = 0.5 and remaining constant for the rest of the LOF),
- a second low-pass filter with a time constant $\tau_2 = 6$ s, representing the heat conduction from the sodium of the shroud tubes to the sodium in the ATHENa container.

The delatching mechanism is activated as soon as the threshold length of ATHENa is reached. This corresponds to a delatching temperature T_{del} of the container sodium.

In order to model the absorber rod movements relative to the core, the following effects have to be included in the dynamic code:

- CRDL expansion including ATHENa,
- the thermal expansion of the core support plate and the vessel,
- the absorber rod movements.

In the case of a control rod withdrawal in a UTOP, only the net effect of withdrawal and expansion is considered. If the absorber did not drop after delatching, the CRDL either rises alone leaving the absorber rod behind in its fixed position in the core or the absorber rod is forced further into the core depending on the net effect of thermal expansion rate of ATHENa and speed of CRDL withdrawal.

V. Dynamics Calculations

The efficiency of ATHENa devices to prevent sodium boiling or fuel melting in ATWS events has been investigated for the EFR with the dynamics code DYANA2. In the following, a short description of some of the principal features of the code are given, followed by an outline of the specific data of EFR and conditions of the calculations. More details about DYANA2 can be found in [8].

V.1. The Dynamics Code System DYANA2

The dynamics code system DYANA2 contains separate modules for network fluid dynamics and component thermal hydraulics and has a great flexibility to simulate different design features (pool or loop, branched or unbranched secondary system, etc.) with a choice of model sophistication (simplified or detailed core model, simplified 1-dimensional DYANA model or 2-dimensional code ATTICA for the hot plenum, etc.).

The core is subdivided into a number of parallel channels consisting of a fuel pin, surrounded by coolant and structure. Usually, a channel represents an average pin in a fuel subassembly or a group of subassemblies, but it can also represent blanket assemblies or control rod channels or the hot channel for safety analyses. A channel includes the whole length of the subassembly, from coolant inlet to coolant outlet. Different axial zones represent subassembly sections (fuel and axial blankets, gas plenum, upper and lower reflectors, etc.).

The fuel section of the pin is treated in more detail than the other sections. Each axial level contains radial nodes for fuel, coolant and structure (cladding and duct walls). Several radial nodes can be used in the fuel region to describe porosity distribution and restructured zones with fuel properties depending on temperature. The dependence of gap conductance on fuel and cladding temperature is described by using a relationship that was calibrated with a fuel performance code. The model allows fuel melting between a solidus and liquidus point. Coolant boiling, however, is not modelled.

Reactivity includes contributions from the control and safety systems and different types of feedback reactivity as described in Sect.III such as local contributions from Doppler, fuel expansion, sodium and steel density as well as global contributions from radial core expansion, bowing and control rod drive line thermal expansion effects.

Time-dependent fission power is calculated by point kinetics including delayed neutrons. Decay heat power can be chosen for each core channel and total power (fission plus decay heat) is assumed to be liberated in the fuel.

DYANA2 provides thermodynamic models for the following components: core, hot and cold plena, pipe, in-vessel pipe, intermediate heat exchanger, steam generator, immersed cooler and air cooler. They are linked together to simulate the primary, secondary and the decay heat removal systems. The mass flows used in thermodynamic component models are determined in fluid dynamics network models. The plena models can be replaced in the programme system DYANA2 by the more sophisticated 2-dimensional code ATTICA.

V.2. EFR Reactor Data and Conditions for Calculations

The EFR design CD 9/90 with a core height of 1 m has been adapted to the DYANA2 code and the data set together with the code system were made available for use on the computer system at KfK [11]. The EFR core is represented by 6 channels which include 3 fuel regions at different burn-up stages (500, 1000 and 1420 d burn-up), 1 breeder and 1 reflector region as well as fuel subassemblies stored in the vessel. An additional channel is used to represent the peak-rated fuel pin ($\chi = 410$ W/cm) at its end of life. Its coolant temperature rise of 196 K corresponds to the conditions in the hottest subassembly. The major characteristics of the channels are summarized in Tab.1. Each channel is vertically divided into 7 meshes and the fuel region has 4 radial concentric annuli. Nominal power of the EFR core is 3600 MW_{th}. Its distribution to different channels is also given in Tab.1. Nominal coolant inlet/outlet temperatures are 395/545 °C. The reactivity coefficients for the feedbacks which are considered in the DYANA2 code are compiled in Tab.2. The design and performance of the EFR fuel pin has been determined by using the code IAMBUS [12]. The results yielded values for the fuel structure depending on burn-up such as stoichiometry, porosities and boundaries of equiaxed and columnar grains zones as well as the dimensions of the central channel.

Channel no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Group of S/As	**Fuel 500 d BU**	**Fuel 1000 d BU**	**Fuel 1420 d BU**	**Breed-er**	**Inter-nal Stor-age**	**Reflec-tors, Shield-ing, Leak-age**	**Fuel, max. loaded**
Number of S/As	126	126	124	78	78	188	-
Number of Pins per S/A	331	331	331	169	331	19	331
S/A Flow (kg/s)	45.8	45.8	45.4	15.7	3.26	1.49	48.9
Total Flow (kg/s)	5774	5774	5635	1223	254	280	-
S/A Power (MW)	9.95	9.00	8.77	1.42	0.02	0.06	12.16
Temperature Rise (K)	171.4	155.0	152.3	71.6	5.3	31.8	196.0
Max. Linear Rating (W/cm)	336	304	298	94	0.7	35	410

Table 1. Core representation in DYANA2: Group of channels with power and flow distribution

A simplified parametric gap conductance model is included in the code DYANA2, the parameters of which are obtained from IAMBUS calculations at different power levels. It is a good aproximation for power levels $\leq$ 100 % including transients with power reductions (ULOF and ULOHS). In the case of overpower transients, the actual evolution of gap conductance is not well described by the parametric model, therefore this model is replaced by pessimistic assumptions limiting the value of gap conductance to 0.1 W/(cm K). This gives for the power-to-melt value only 570 W/cm. The peak fuel temperature at nominal power is 2200 °C and is attained in the hot channel with a peak linear heat rating of $\chi = 410$ W/cm at the central fuel node. Fuel melting is thus reached at about 140 % of nominal power which causes a strong limitation for ramp rates in the case of UTOPs (see Sect.VI.2).

The ATHENa time constant τ_1 (see Sect.IV) depends on the flow rate through the ACS, it is therefore important to model this effect correctly, especially in flow transients like ULOFs. The hot plenum model for the flow description has been improved for this case by using results of 2-dimensional calculations with the DYANA/ATTICA code [11].

Reactivity Feedback Coefficients	
Doppler fuel incl. axial breeder	-726 pcm
Doppler radial breeder	-85 pcm
Sodium density	0.413 pcm/K
Clad expansion	0.200 pcm/K
Wrapper expansion	0.141 pcm/K
Fuel axial expansion	-0.400 pcm/K
Bowing	0.0 pcm/K (conservative)
Diagrid expansion, fast (5s)	-0.330 pcm/K
Diagrid expansion, slow (200s)	-0.600 pcm/K

Table 2. Reactivity Feedback Coefficients: The reactivity is in units of 1 pcm = 10^{-5}.

VI. Results of Calculations and Discussion

VI.1. Unprotected Loss of Flow Accident (ULOF)

A ULOF event starts with the loss of power to the coolant pumps of the main and intermediate circuits. The pump coast down is determined by the rotational inertia of the motors and flywheels connected to the pumps. Fig.2a shows the relative coolant flow rate through the EFR core which decreases rapidly with a halving time of 10 s until it reaches about 4 % of its nominal operating value after about 120 s. The power reduction, also shown in Fig.2a, is much slower and the subsequent mismatch in power and flow causes the coolant temperature to rise (Fig.2b).

Two reactivity effects are directly associated with the increase in coolant temperature (Fig.3a): (i) the positive reactivity feedback of the coolant density reduction and (ii) the smaller and somewhat delayed negative effect of the CRDL expansion. In addition, there are two effects indirectly associated with the coolant temperature rise: The Doppler effect and the axial thermal fuel elongation. Their signs depend on the fuel temperature change relative to the initial values.

The reactivity feedback effects are depicted in Fig.3a together with the net reactivity. The initial phase of the transient, which lasts about 20 s, is determined by a slight decrease of the power to about 85% of the nominal value (Fig.2a). This is due to the negative value of the net reactivity as illustrated in Fig.3a. During this phase, the biggest feedback is the coolant density effect. Doppler and axial expansion feedbacks are both negative and increasing in value with time, even during a phase of decreasing power. This, somewhat surprising phenomenon is the result of the superposition of two opposite effects affecting the fuel temperature: (i) a flattening of the radial temperature profile due to the power density decrease in the fuel pin and (ii) a temperature rise caused by an increase of the coolant temperature in the channel. The net effect, as shown in Fig.3b, is a rise of fuel temperature, the value of which increases going from the center to the surface of the fuel.

During this time, the CRDL effect is not yet affected by the ATHENa device and is still small. The inlet temperature effect is negligible because of the long time for the returning sodium. Doppler, axial expansion and CRDL expansion effects are sufficiently large to overcompensate the positive coolant effect and to reduce the power, but the reduction is not fast enough to stop the coolant temperature to rise (Fig.2b).

However, the sodium temperature in the ATHENa container rises with some delay caused by the time constants τ_1 and τ_2, as seen in Fig.4, and reaches the delatching temperature of 590 °C at 20 s. The ball release mechanism then separates CRDLs from the absorber rods which drop by gravity into the core and shut down the reactor. In the first calculation it is assumed that only 3 $, i.e. 10 % of the shutdown reactivity, can be inserted into the reactor by rod drop. The coolant outlet temperature decreases rapidly before reaching the sodium boiling temperature of 938 °C in the hot channel.

In a second calculation, it is assumed that all absorbers fail to drop. In this case the enhanced expansion of the ATHENa devices is forcing the absorbers further into the core. The sodium temperature, however, continues to rise and reaches the boiling temperature in the hot channel at 24 s. The enhanced power reduction, caused by the enhanced CRDL expansion effect, finally leads to a decrease of the sodium temperature (Fig.2b). In all other channels the peak sodium temperature remains below 800 °C with a large margin to boiling.

A look at reactivity (Fig.3a) shows that in the case where the rods fail to drop, the enhanced expansion of the ATHENa devices forces the absorber rods further into the core, finally providing about -1.5 $ of reactivity. The rapid power decrease which follows leads to a further flattening of the radial fuel temperature profile. According to Fig.3b, the fuel temperature drops in the inner pin region below the initial values, but near the fuel surface it remains higher than before the ULOF. This explains that the Doppler reactivity changes its sign, whereas the axial expansion effect, mainly determined by the surface temperature, remains negative for a much longer time. With decreasing power, the Doppler effect is becoming the dominant positive feedback, but the CRDL reactivity is strong enough to overcompensate the positive effects and to finally shut down the reactor.

In order to avoid sodium boiling also in the hot channel, two measures can be envisaged: (i) lowering the delatching temperature or (ii) extension of flow coast down by increase of the rotational inertia of sodium pump motor and flywheel in the primary circuit. Both methods have been investigated with DYANA2 calculations. Fig.5 shows sodium outlet temperature of the hot channel for 3 different values of the delatching temperature. By decreasing its value to 580 or 570 °C, respectively, the peak temperature remains below the boiling point. This can also be achieved by increasing the pump coast down halving time from 10 to 12 or 14 s, respectively, as seen in Fig.6. In the latter case, the reduction of the first temperature peak leads to a smaller absorber insertion and thus to a slower power reduction and a higher subsequent second temperature peak.

It has to be emphasized that for all ULOF calculations the most pessimistic conditions have been assumed concerning the control rod positions which are near the upper edge of the core, i.e. only 5 cm inserted. This corresponds to a core at the end of a cycle. In cores at lower burn-up stages, the rods are farther inserted and their efficiency is higher. The same CRDL expansion yields in this case a faster and more negative feedback reactivity.

VI.2. Unprotected Transient Overpower Accident (UTOP)

General Case

A UTOP accident is initiated by an uncontrolled withdrawal of a control rod, the reactor being at nominal conditions. The flow rate remains constant. Results of calculations are shown in Figs.7 to 9 for the case with a ramp rate of 1 ¢/s and an initial control rod position of 10 cm, which corresponds to almost end of core cycle conditions. The power rises as the control rod is withdrawn (Fig.7a) and the fuel temperature increases, especially in the inner parts of the fuel pellets as can be seen in Fig.7b. Therefore the Doppler effect is the dominant source of negative feedback and much stronger than the axial fuel thermal expansion effect which is based on fuel surface temperature (cf. Fig.8a). On the other hand, the coolant temperature rise is moderate, as indicated in Fig.9, and thus the CRDL effect is small. The overall effect is a positive net reactivity. After an initial transition phase of several seconds, the ramp rate, introduced by control rod withdrawal, and the coolant reactivity as positive contributions, are practically compensated by the negative contributors to the feedback. As a consequence, there is only a slight additional increase of the net reactivity.

The resulting power rise would finally lead to incipient fuel melting in the central part of the fuel in the hot channel. Whether this can be avoided, depends on the delatching of the ATHENa devices. The further course of the transient is therefore entirely determined by the assumptions made about the efficacy of the ATHENa devices. After the ATHENa devices have reached their delatching temperature, two different, pessimistic assumption are made: (i) a single rod drops, providing a minimum of -0.6 $ of reactivity or (ii) all rods are jammed.

Single Rod Drop

In the first case, i.e. drop of a single rod, there is a steplike reactivity change which brings the reactor to subcriticality (Fig.8a). However, the net reactivity starts rising again rapidly, essentially due to the Doppler effect which becomes now positive as a consequence of the drop of fuel temperature (Fig.7b). The power is reduced in a prompt jump to 80 % of its nominal value and it decreases in the further course of the transient until it reaches its asymptotic value at about 50 % of its nominal value (Fig.7a). Fuel and coolant temperature are reduced to values corresponding to the lower power level and nominal flow rate. The net reactivity approaches zero (Fig.8a) and the power is stabilized, since the reactivity of -0.6 $ is not sufficient to shut down the reactor. A complete shut down would need at least -1 $ of reactivity or the drop of 2 control rods.

All Rods Jammed

In the case where all rods are jammed, the results of calculations are also shown in Figs.7, 8b and 9. The power rise is terminated by delatching of the absorbers, but the fuel in the hot channel starts to melt (Fig.7b) and may finally lead to pin failure with a possibility of severe consequences for the plant safety. The reactor remains delayed supercritical but the reactivity approaches the value of zero (Fig.8b), stabilizing the power at about 140% of its nominal value (Fig.7a). Due to the high fuel temperature, Doppler effect and axial expansion are sufficiently high to compensate together with the small CRDL effect the inserted reactivity and the coolant effect. It is evident that in this case the efficacy of the ATHENa device is not sufficient to stabilize the reactor at a low enough power level to avoid fuel melting in the hot channel.

Reduction of Ramp Rate and/or Delatching Temperature

This is, however, the case if either the delatching temperature or the ramp rate are reduced. The effect of ramp rate or delatching temperature reduction on hot channel peak fuel temperature for transients from nominal conditions and initial control rod positions of 10 cm is shown in Fig.10a. The power rise is terminated before fuel melting is reached, however, the asymptotic power level is still rather high (Fig.10b), because only a small amount of reactivity could be inserted by the ATHENa devices.

Influence of Initial Rod Position

The influence of the initial rod positions has also been investigated by DYANA2 calculations. The efficiency of the absorbers increases if the rods are more inserted into the core, therefore the ATHENa devices are more effective for the same amount of CRDL expansion. This can be clearly seen in Fig.11, which shows the CRDL effect and the net reactivity for 3 different values of initial control rod insertion. A consequence of the increased absorber reactivity is, that the reactor is intermediately subcritical and the power is reduced to a level (Fig.12a) which is sufficiently low to avoid fuel melting (Fig.12b). The asymptotic power, however, is always above the nominal power level, since the CRDL reactivity does not completely compensate the reactivity inserted by control rod withdrawal.

Stroke Limitation

A control rod stroke limitation is considered as a countermeasure against excessive reactivity insertion in the frame of the *Third Shutdown Level* (see Sect.II). In order to investigate the efficiency of this measure, calculations have been made by insertion of reactivity ramps which are terminated after a given reactivity value is attained. The ATHENa device is not active in these calculations. The results in Fig.13 show that the stroke has to be limited to about 0.35 $ to avoid fuel melting. The peak fuel temperature depends only slightly on the ramp rate. Again, the reactor is stabilized at a rather elevated power level.

A problem with this measure is, that the reactivity range between nominal critical and stroke limit decreases rather rapidly at operation with core burn-up and the stroke limit has to be re-adjusted periodically. This is not only inconvenient for reactor operation, but it bears the possibility of inadvertent misadjustment, i.e. setting of excessive limits, with severe consequences for the safety in the extremely improbable case of the occurrence of a UTOP accident. It is preferable to rely on the passive action of the ATHENa devices which limit the stroke by delatching the absorbers from the CRDLs.

UTOPs from Part Load Conditions

So far only transients starting from nominal conditions or full-load have been considered. According to Fig.1, the margin to fuel melting is smallest for these transients. It is, however, of interest to study also cases which lie inside the region of power operation. Since at least the power is below the nominal value, the term part-load is used for these conditions. In order to stay below the nominal value of coolant outlet temperature, the operational points are confined by the condition $p \leq q$. In the case of $p=q$, the coolant temperature rise between core inlet and outlet is the same as in nominal conditions. If the reactor is operated at part-load but 100% coolant flow rate, the temperature rise along the core channels is smaller than at nominal conditions. This is disadvantageous for the efficacy of the ATHENa devices, because the margin to delatching temperature is increased.

Therefore two cases have been investigated where the transient starts from 20% of full power but with nominal coolant flow rate. The ramp rates which are applied are 0.5 and 1.0 ¢/s, respectively, with delatching temperatures of 580 and 570 °C, respectively. Results are shown in Figs.14a to 14b and compared with transients from nominal conditions. The power rise is terminated by the action of the ATHENa devices at about the same power level (130 to 135% full power) as the reference cases (Fig.14a), the peak fuel temperature is only slightly higher (10 to 20 °C) than in the reference cases (Fig.14b).

The other two transients which again start from 20% full power, but with only 50% of nominal flow rate, are also studied by insertion of ramp rates of 0.5 and 1.0 ¢/s, respectively. The results, as illustrated in Figs.15 and 16, show that in both cases the power rise is terminated at levels well below full power with the consequence of big margins to fuel melting and sodium boiling in the hot channel. This is due to the reduced flow rate which results in faster rises of coolant outlet temperature with power. As a consequence, the delatching temperature is attained at a lower power level and lower fuel temperatures. The results confirm, what is already suggested by Fig.1, that transients which start from conditions with full flow rate have the smallest margin to fuel melting.

VII. Conclusions

In the safety analysis of fast reactors, ATWS events have to be considered and the safety margins and eventual consequences have to be assessed, even when their frequency of occurrence lies far beyond the design basis accident. In the case of the EFR, the safety approach foresees, in addition to preventive measures already provided within the design basis, further measures of risk minimization in the frame of the so-called *Third Shutdown Level*. One of these measures is a control rod enhanced expansion device, called ATHENa, which has been especially developed by KfK together with SIEMENS as a passive device to practically exclude core damage, even in events with shutdown system failures.

The efficiency of the ATHENa device to prevent sodium boiling and fuel melting in ATWS events in EFR has been investigated by calculations with the dynamics code DYANA2.

In the case of ULOF accidents, sodium boiling can be prevented even in the hot channel, if at least one out the 24 rods equipped with ATHENa devices drops into the core after delatching of the absorbers. The probability that all rods remain jammed after delatching is so extremely low that this event can be placed far into the hypothetical category. But even then, sodium boiling could be prevented by extending the pump coast down halving time from 10 to 12 s or by a reduction of the delatching temperature to 580 °C or less.

In UTOP accidents caused by an uncontrolled withdrawal of a control rod, the main concern is incipient fuel melting. The results of the calculations have shown that if the ramp rate is limited to values not exceeding 1 ¢/s, the power rise can be terminated by delatching the absorbers before fuel melting occurs. Again, assuming the extremely hypothetical case that all rods remain jammed after delatching, fuel melting in the hot channel could only be prevented by reduction of the delatching temperature. The ATHENa devices can reliably terminate the insertion of reactivity by delatching the absorbers from the drive lines and are thus preferable to control rod stroke limitations.

The relatively high linear heat rating of the EFR hot channel is the cause of the rather early incipient fuel melting. A core optimization in the sense of reducing the hot channel heat rating is a very efficient measure to reduce the risk of fuel melting. Therefore, all efforts should be put in the design of a well flattened power distribution. In this case, there is more freedom of choice for pump coast down halving time, ramp rate and delatching temperature.

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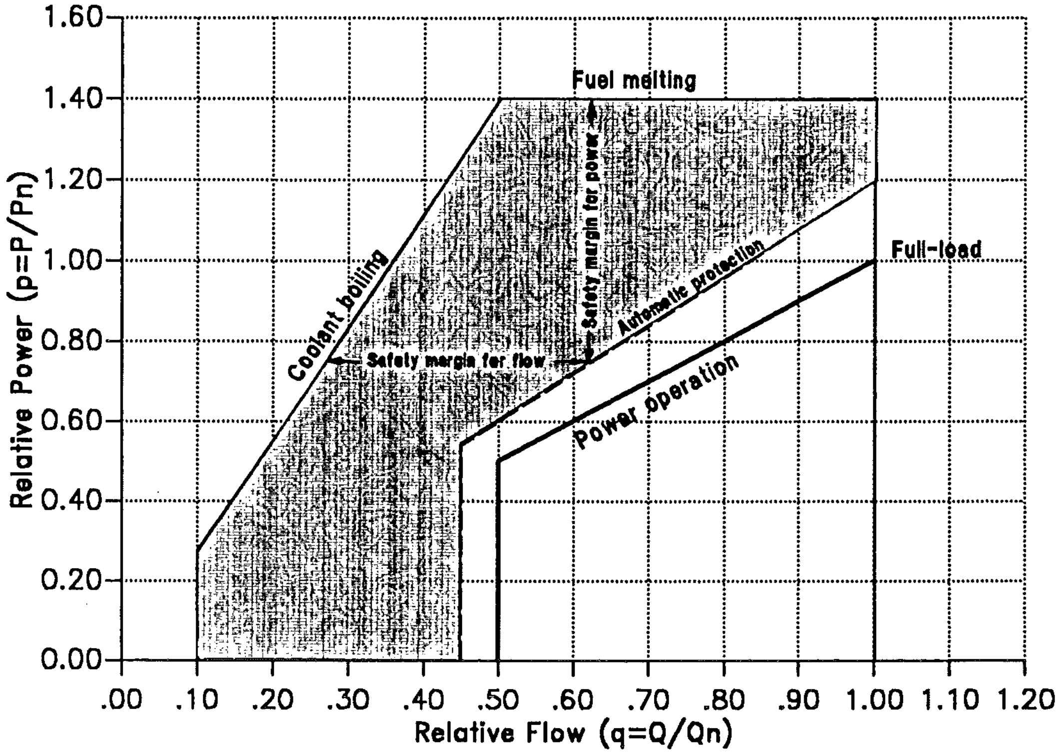


Fig.1. EFR margins to coolant boiling and fuel melting.

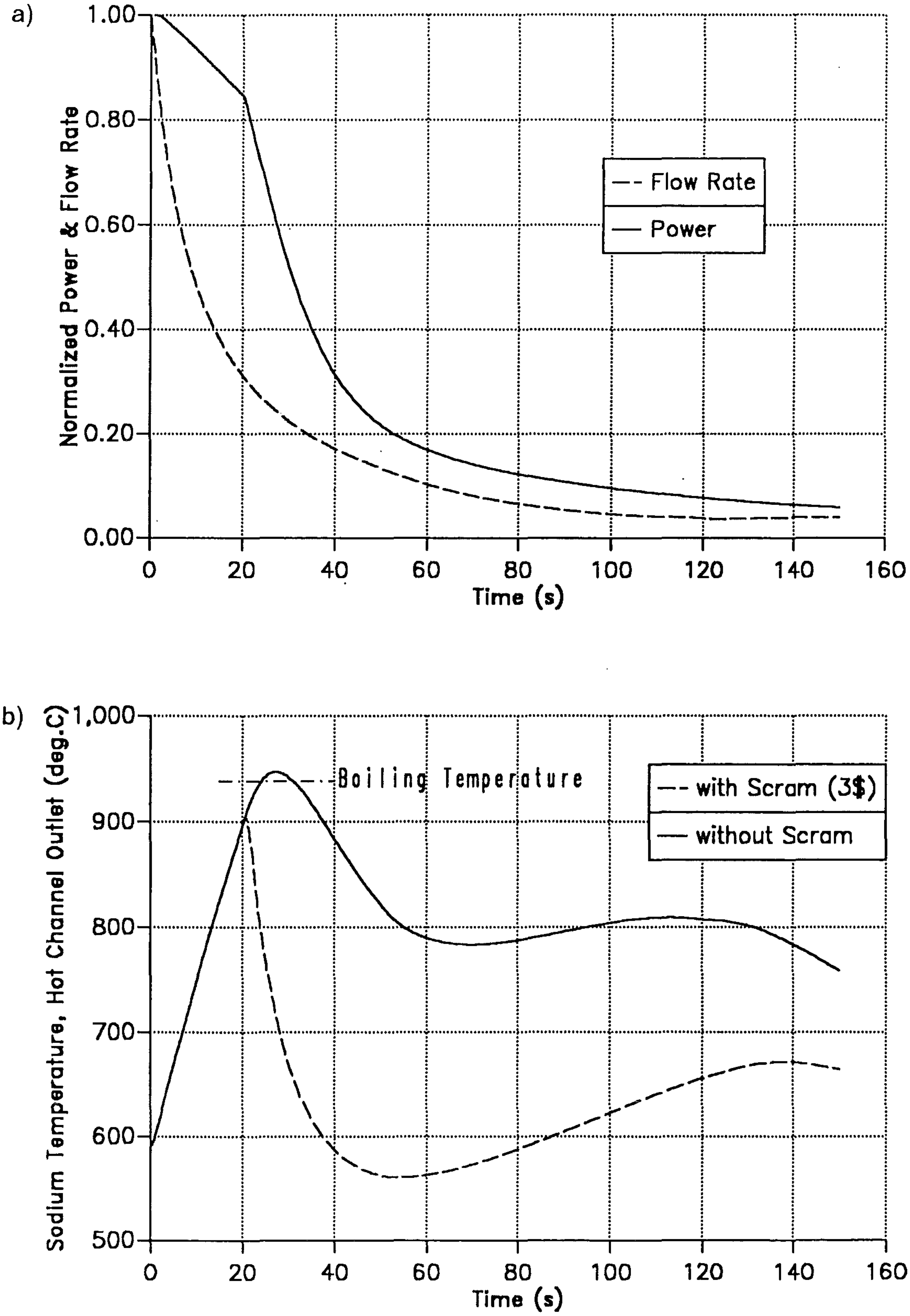
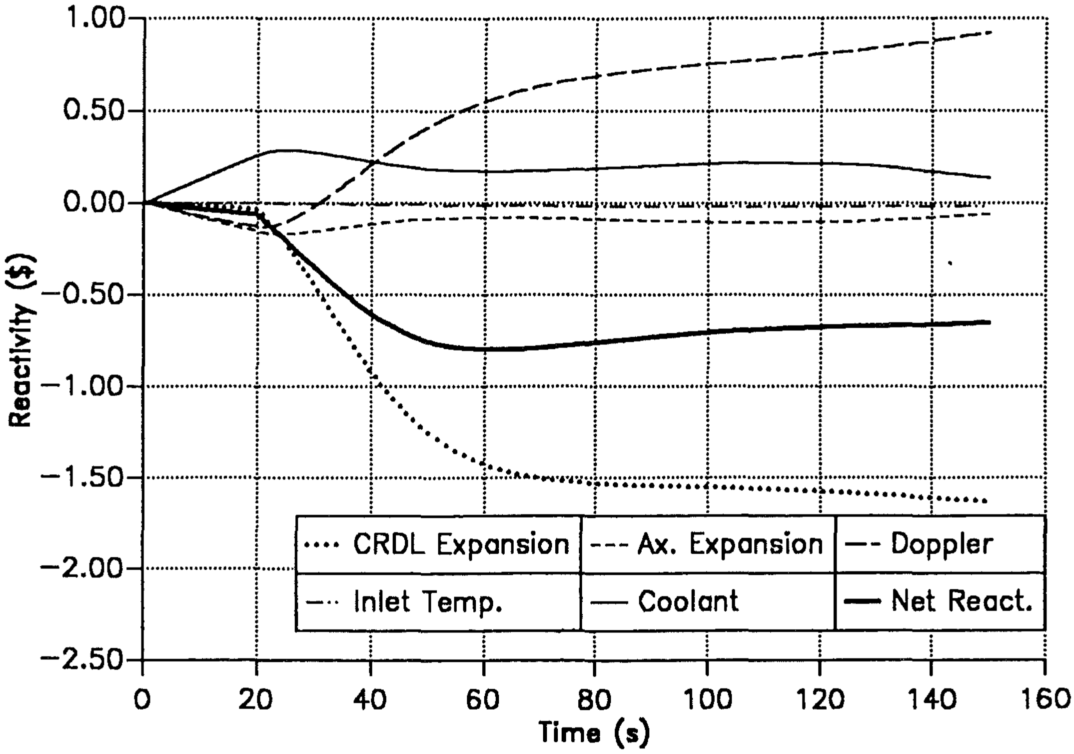


Fig.2. ULOF from nominal conditions and delatching temperature of 590 °*C*:

a) Normalized power and flow rate, case without scram.

b) Hot channel coolant outlet temperature. Absorber rods either drop (with scram) or are forced into the core after delatching of the ATHENa devices (without scram).

a)



b)

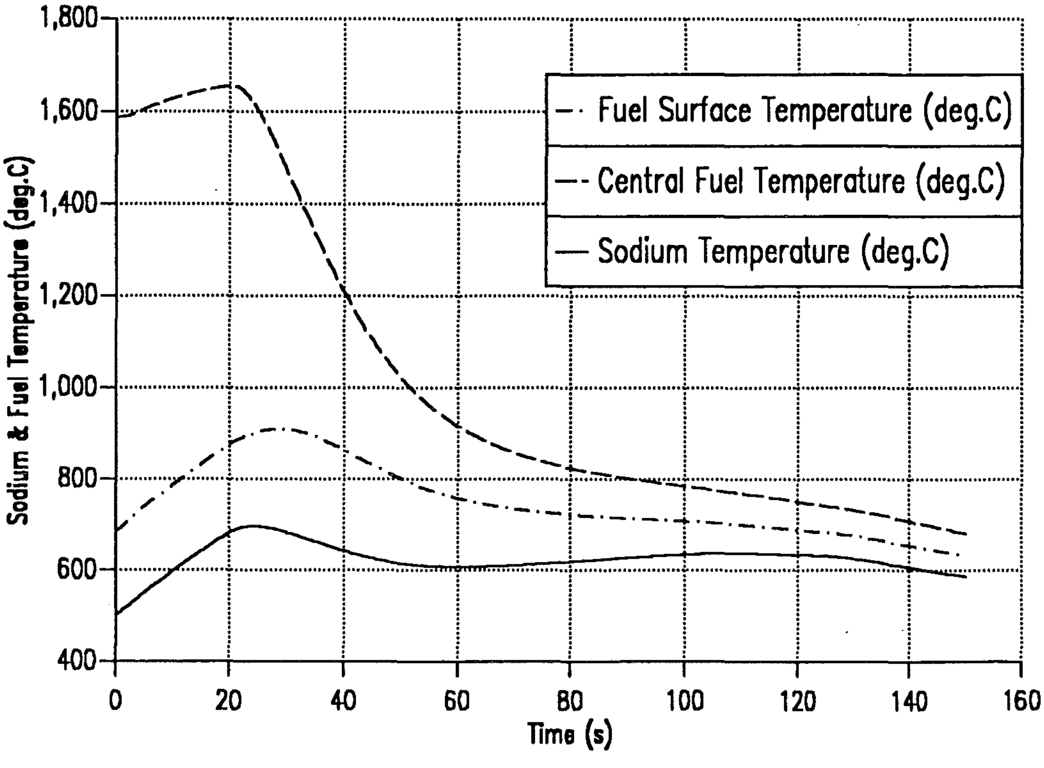


Fig.3. ULOF from nominal conditions and delatching temperature of 590 °*C*:

a) Net reactivity and feedbacks.

b) Coolant, fuel surface and central temperature at peak node of average channel.

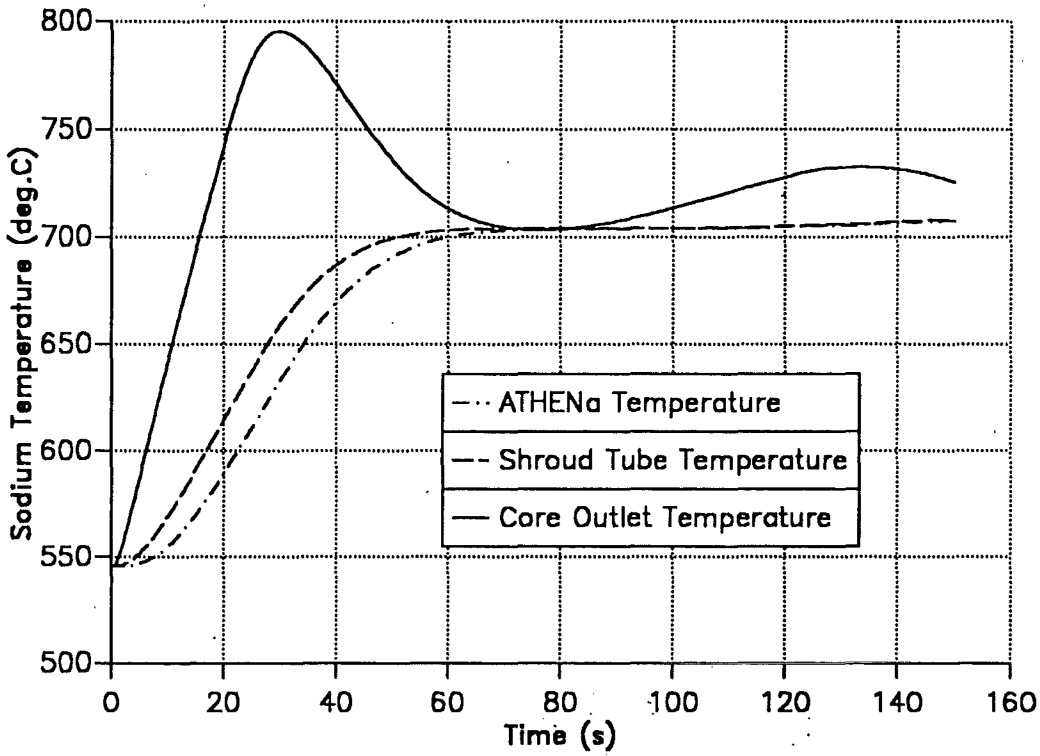


Fig.4. ULOF from nominal conditions and delatching temperature of 590 °*C*: Coolant temperature at core outlet, in shroud tube and container of ATHE-Na device.

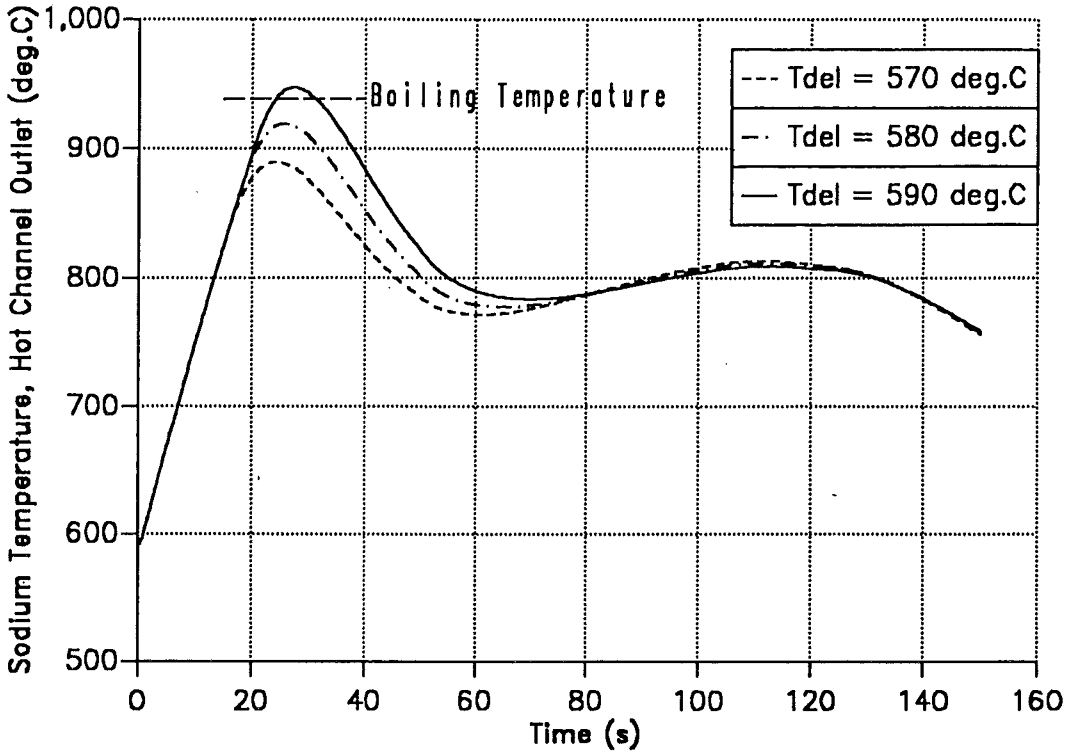


Fig.5. ULOF from nominal conditions with different delatching temperatures: Hot channel coolant outlet temperature.

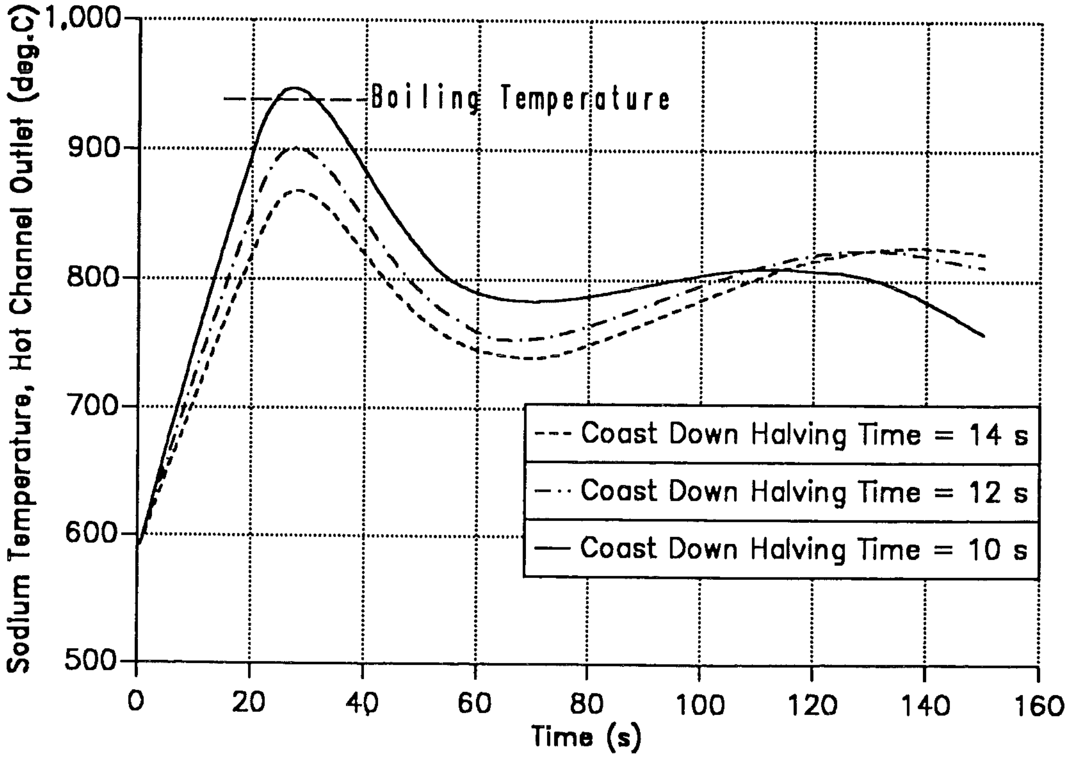
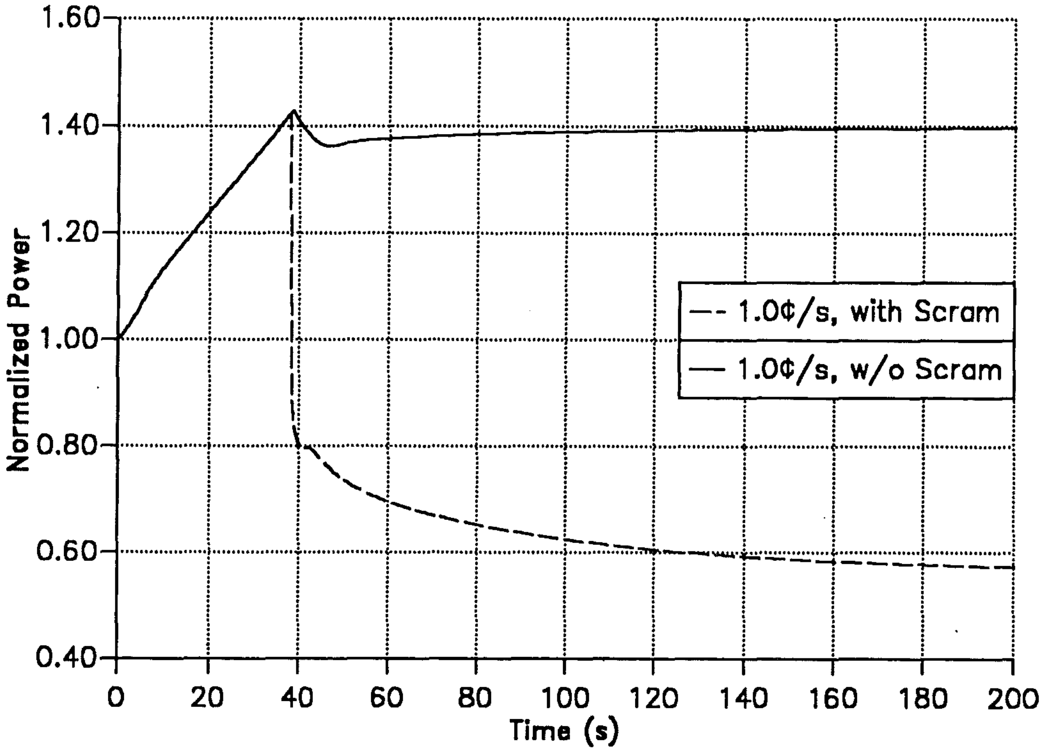


Fig.6. ULOF from nominal conditions for different values of pump coast down halving time. Delatching temperature is 590 °C: Hot channel coolant outlet temperature.

a)



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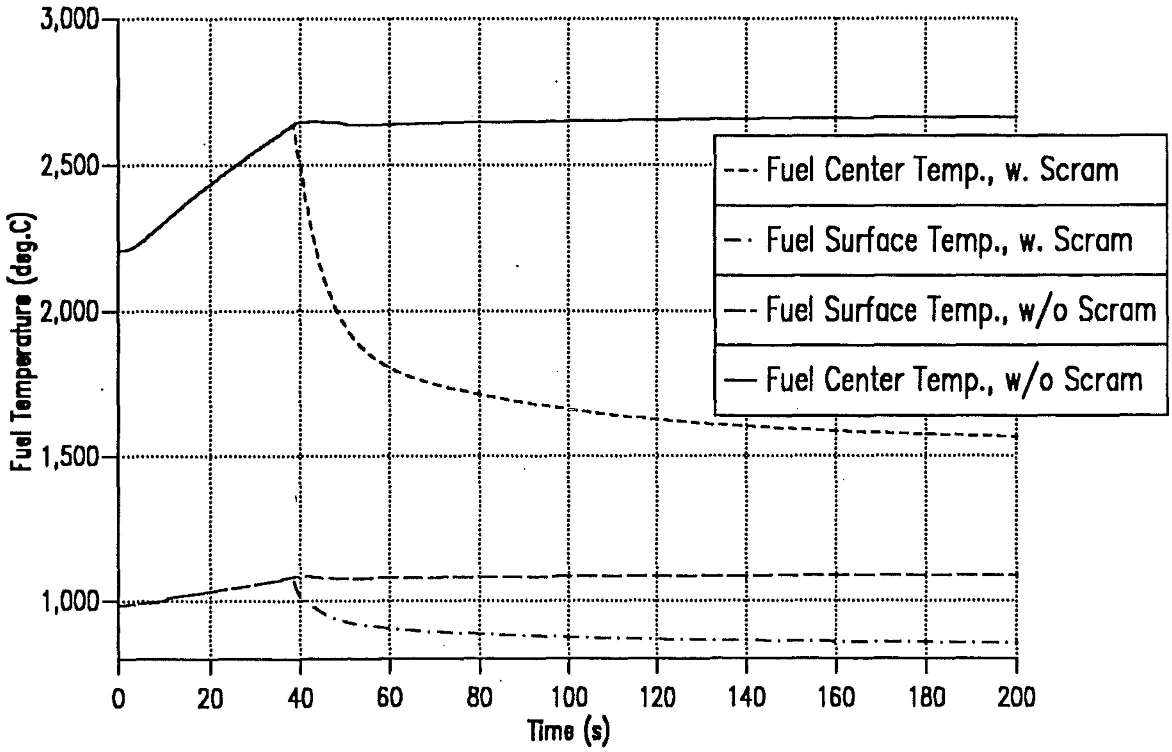
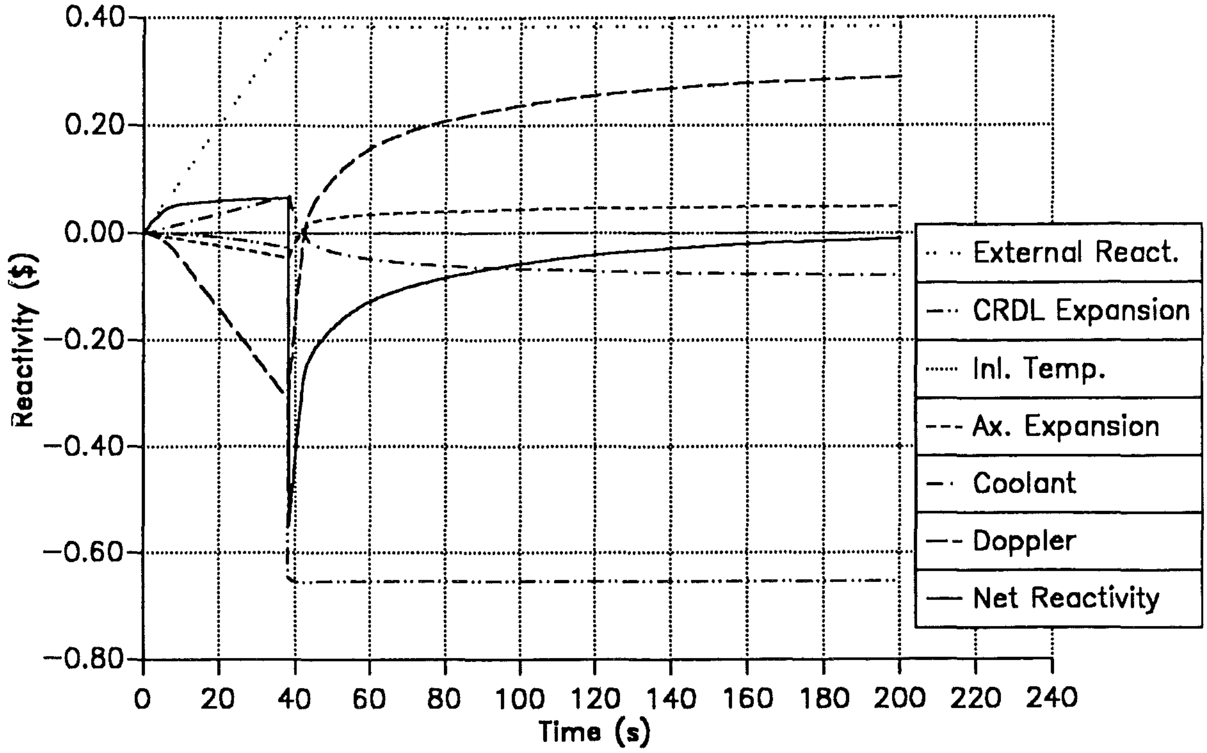


Fig.7. UTOP from nominal conditions with a ramp rate of 1¢/s with and without scram (-0.6 $). Delatching temperature is 580 °C and control rod position 10 cm:

a) Normalized power.

b) Hot channel peak fuel surface and central temperature.

a)



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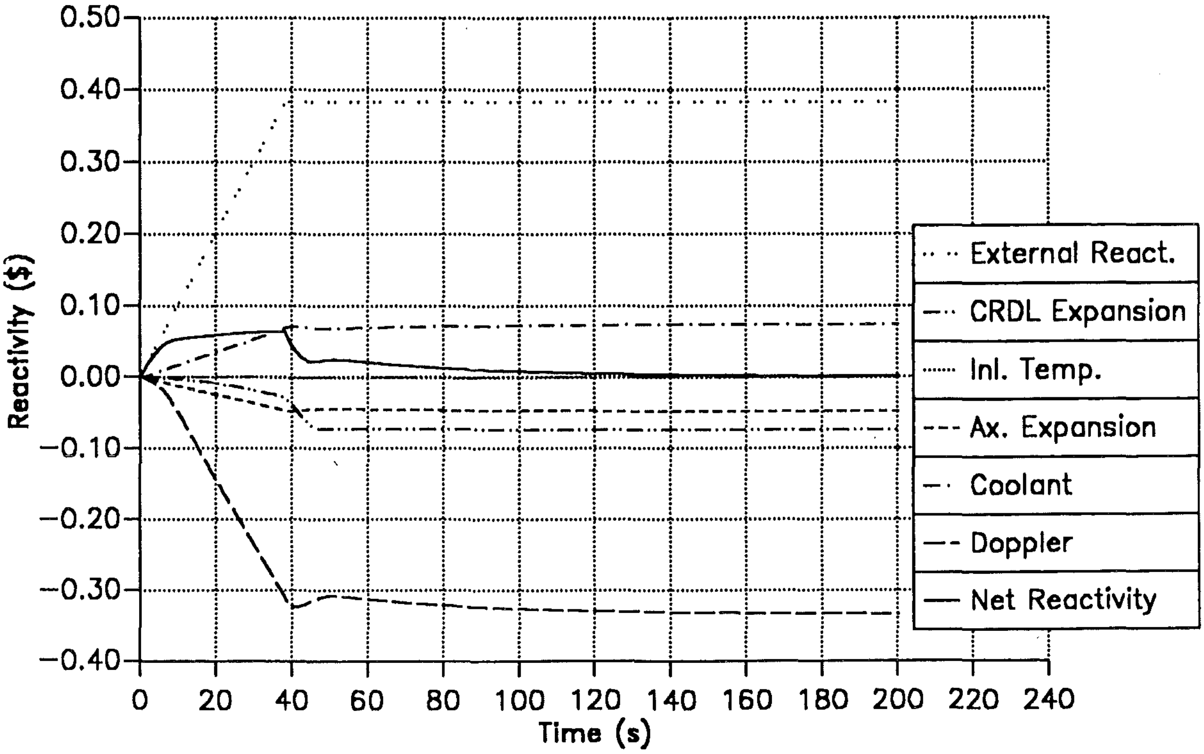


Fig.8. UTOP from nominal conditions with a ramp rate of 1¢/s with and without scram (-0.6 $). Delatching temperature is 580 °C and control rod position 10 cm:

a) Net reactivity and feedbacks for case with scram.

b) Net reactivity and feedbacks for case without scram.

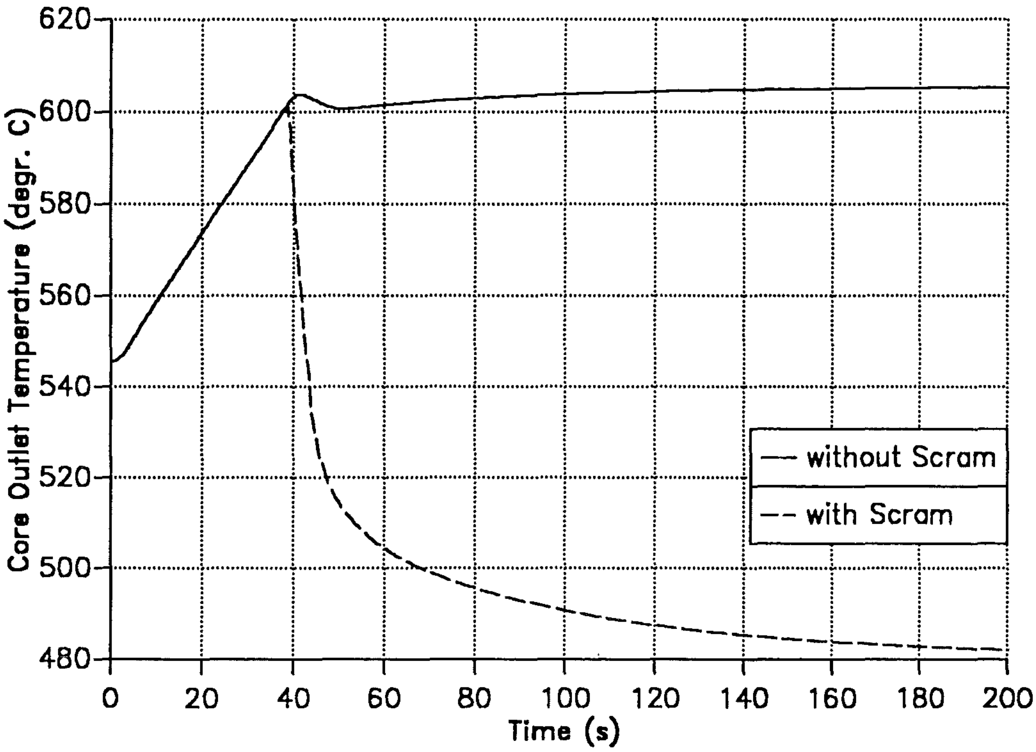
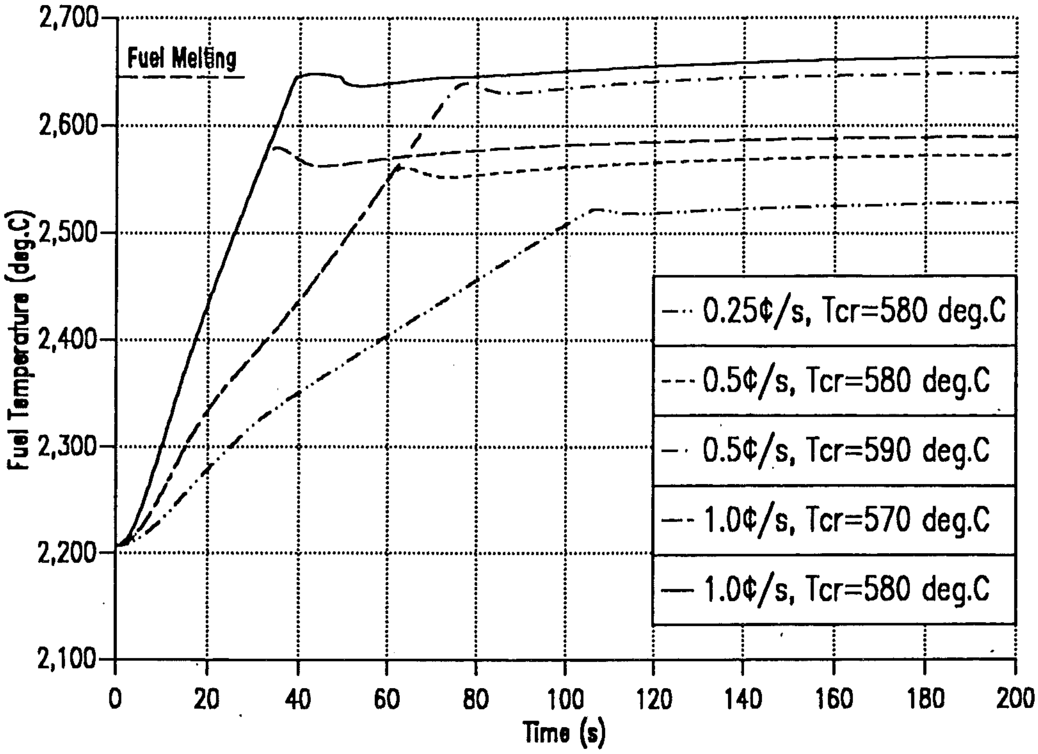


Fig.9. UTOP from nominal conditions with a ramp rate of 1¢/s with and without scram (-0.6 $). Delatching temperature is 580 °C and control rod position 10 cm: Core outlet temperature.

a)



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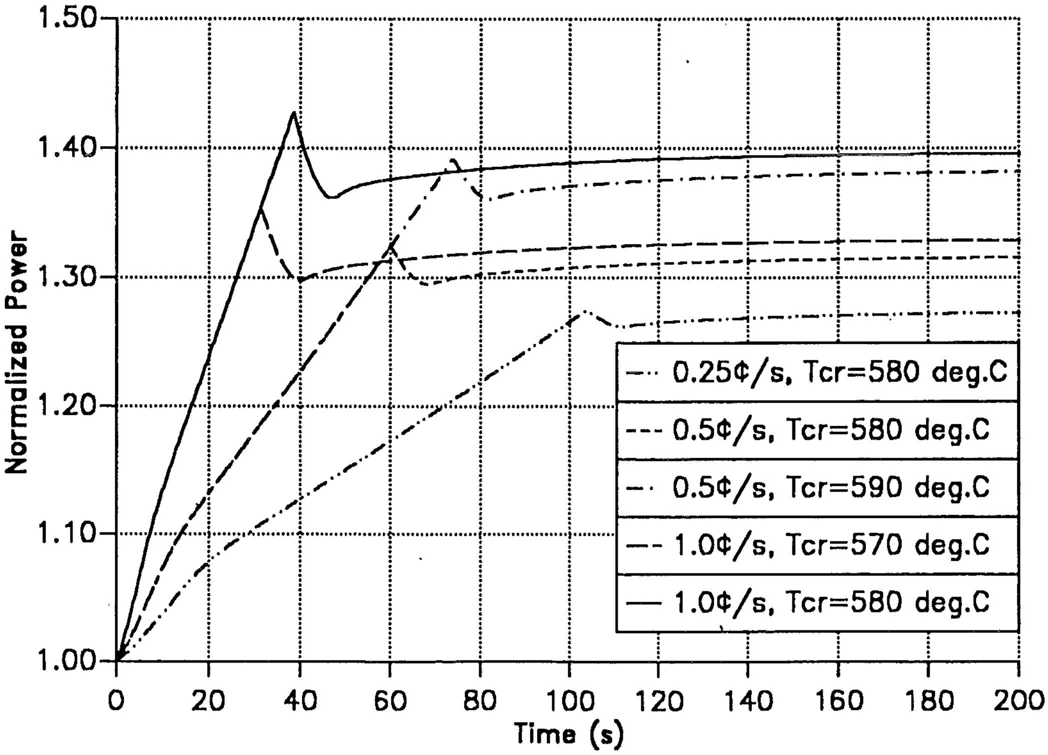


Fig.10. UTOPs from nominal conditions with different ramp rates and delatching temperatures. Control rod position 10 cm:

a) Hot channel central peak fuel temperature.

b) Normalized power.

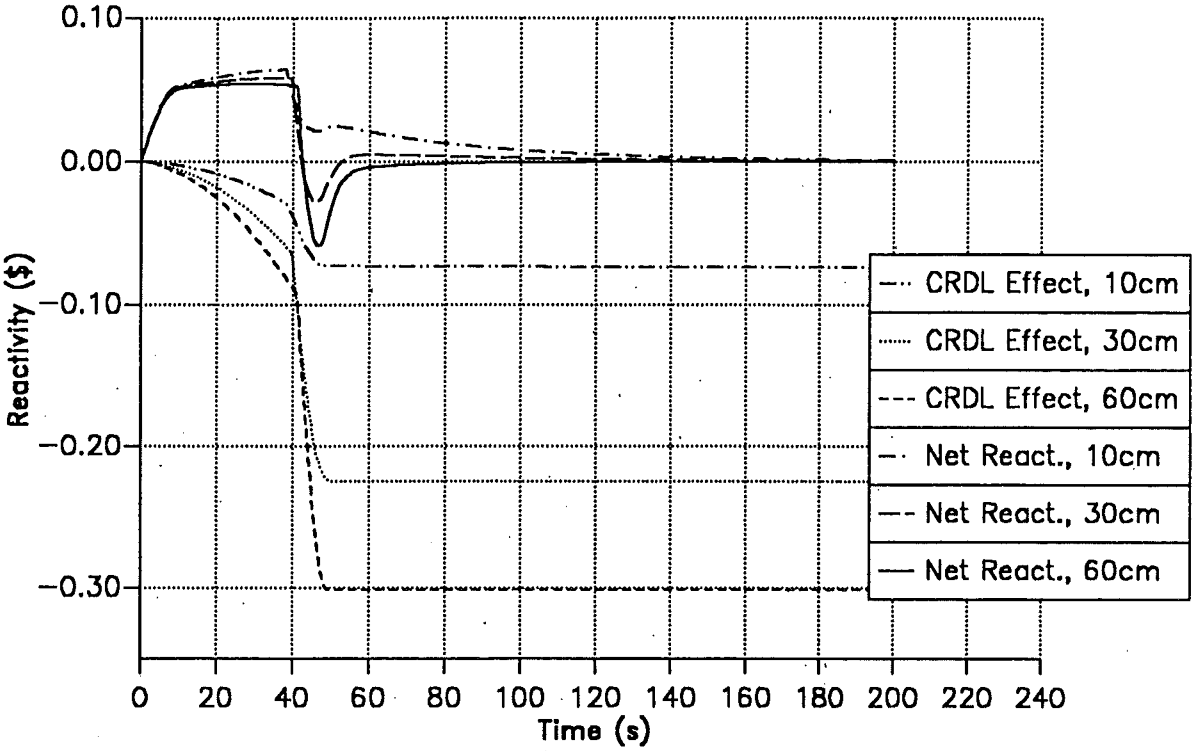
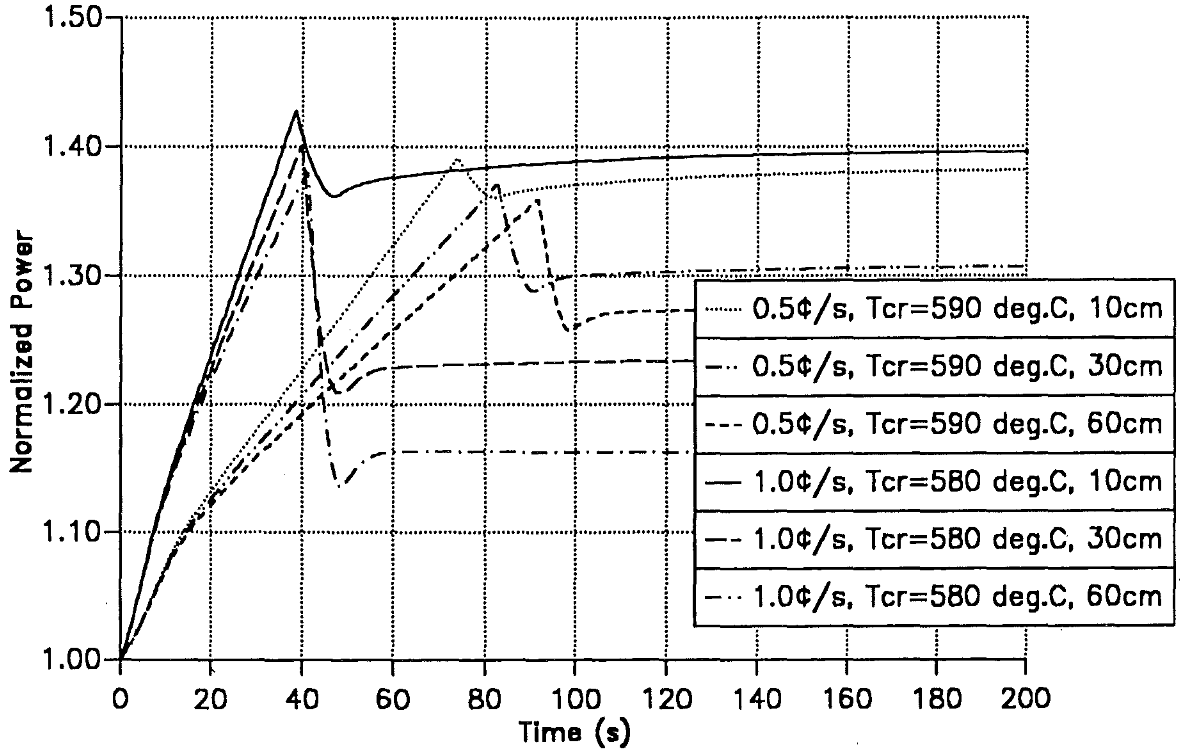


Fig.11. UTOPs from nominal conditions with a ramp rate of 1 ¢/s and different control rod positions. Delatching temperature is 580 °C: Net and CRDL reactivity.

a)



b)

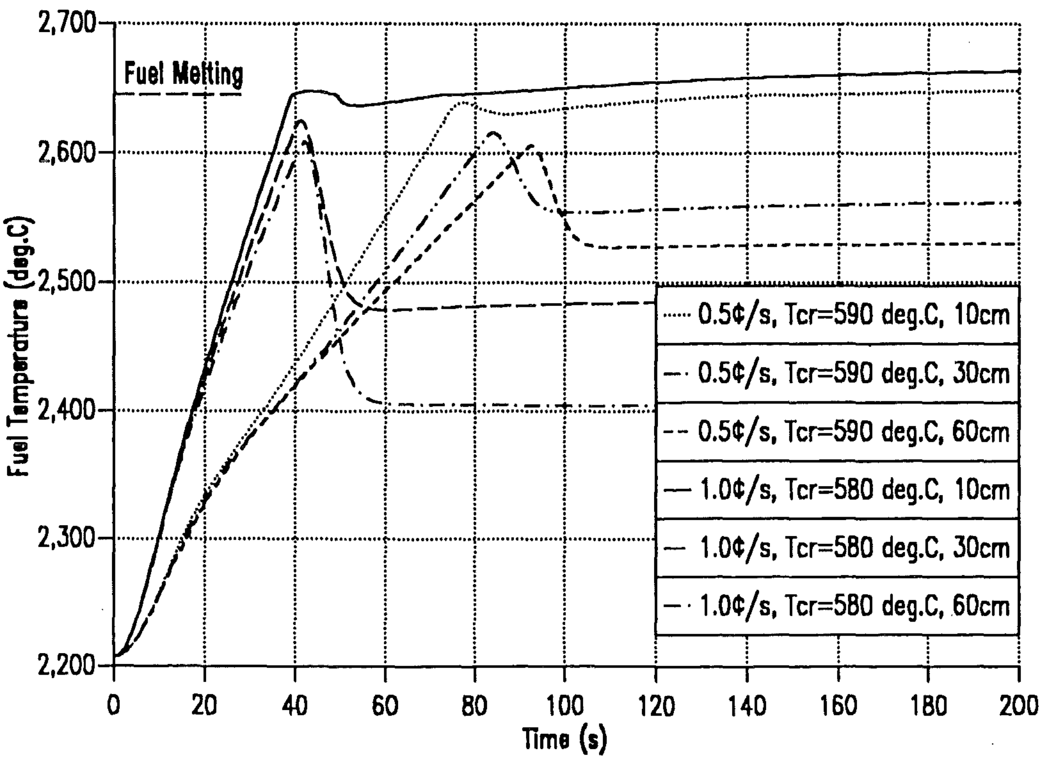


Fig.12. UTOPs from nominal conditions with different ramp rates and control rod positions:

a) Normalized power.

b) Hot channel fuel central temperatures.

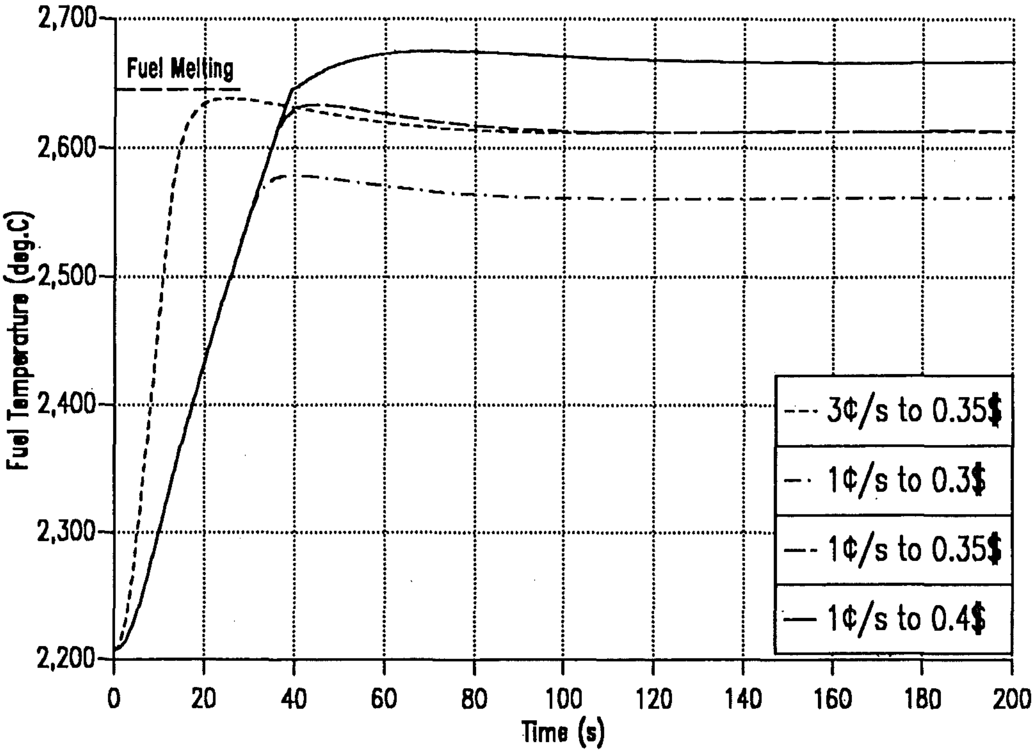
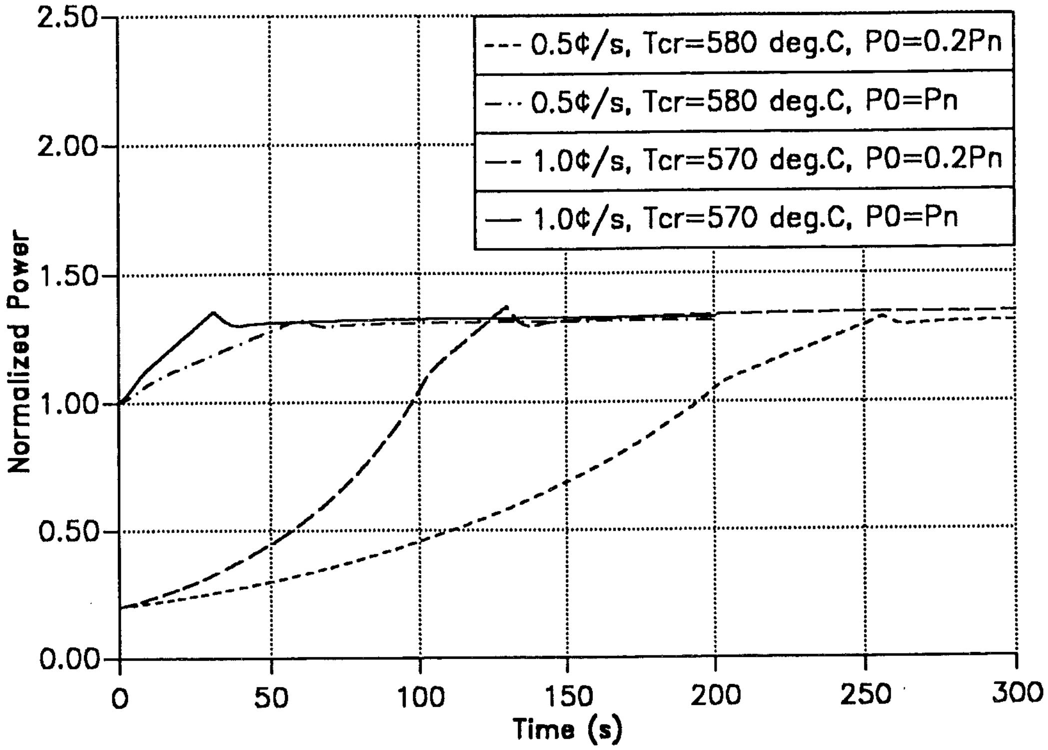


Fig.13. Hot channel fuel temperatures for stroke limited UTOPs from nominal conditions. Initial control rod position 10 cm.

a)



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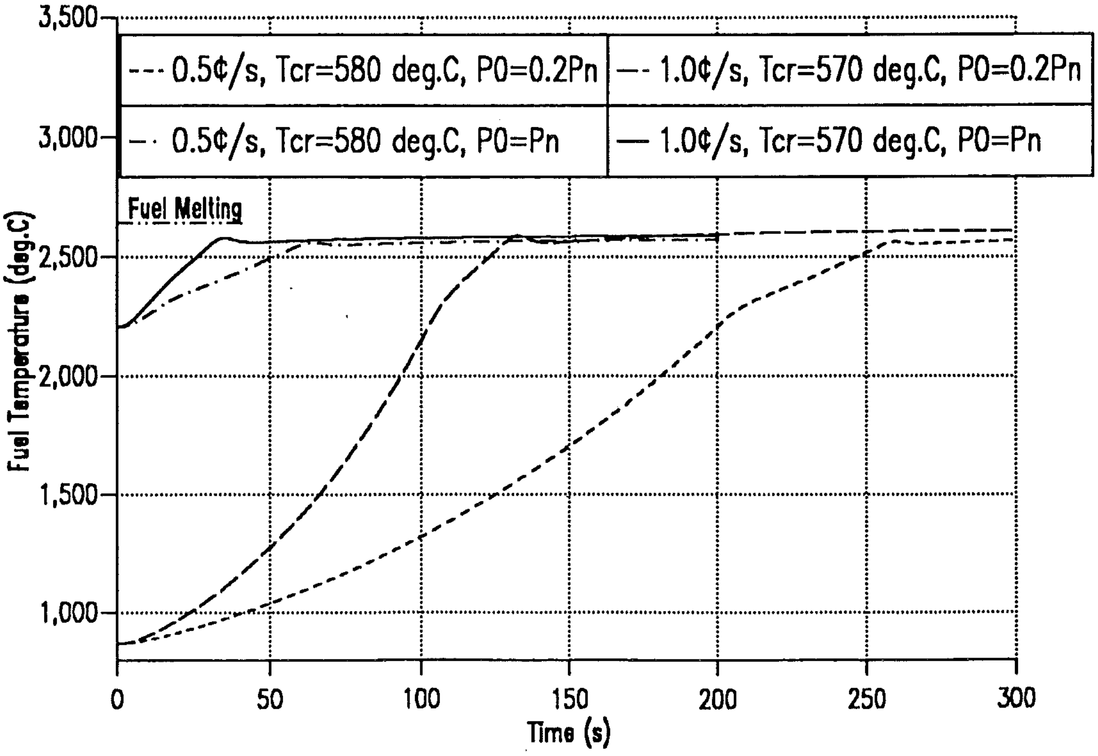
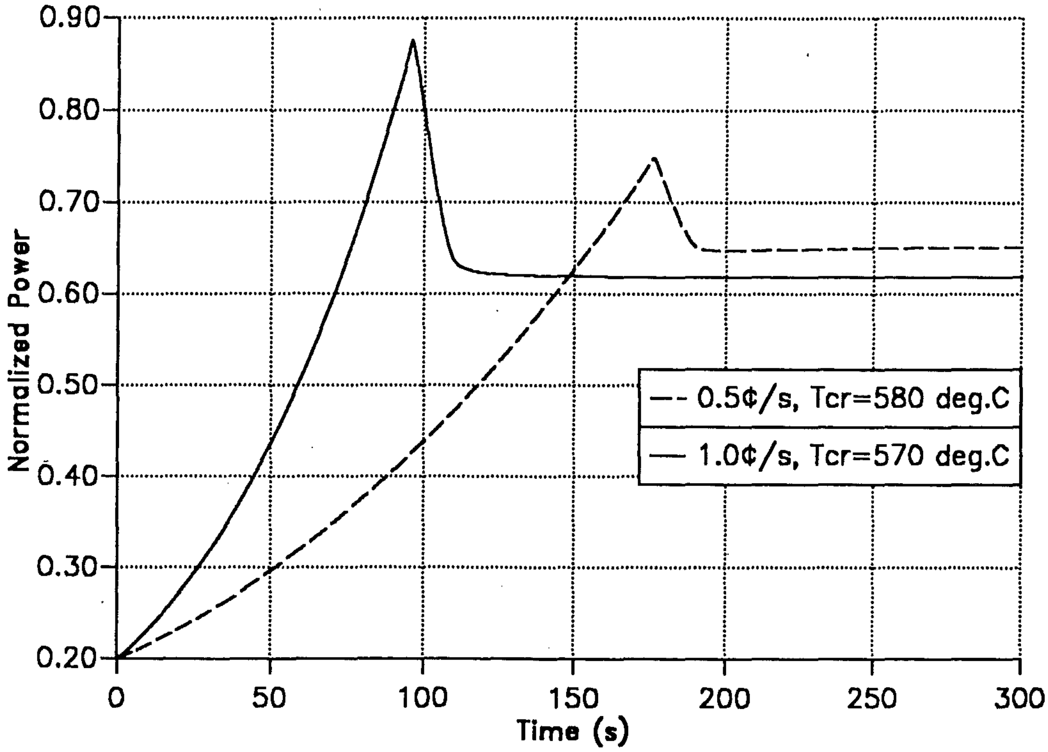


Fig.14. UTOPs from different power levels with nominal coolant flow rate. Control rod position 10 cm:

a) Normalized power.

b) Hot channel peak fuel temperatures.

a)



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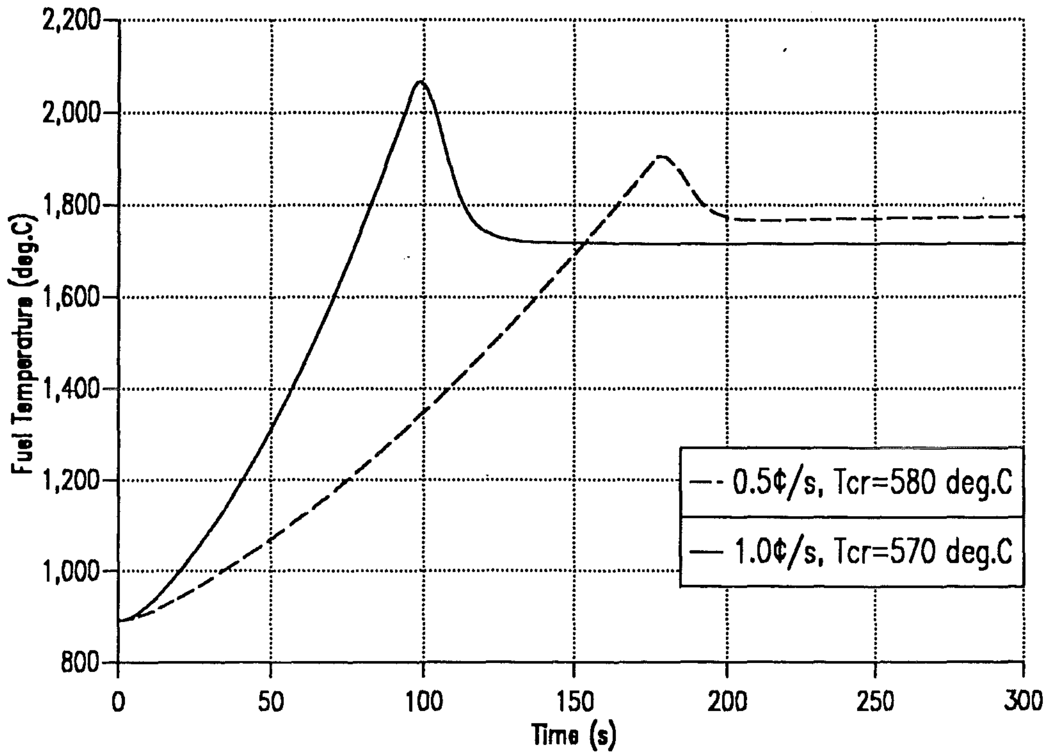

Fig.15. UTOPs from 20% of full power with 50% of nominal flow rate. Control rod position 10 cm:

a) Normalized power.

b) Hot channel peak fuel temperatures.

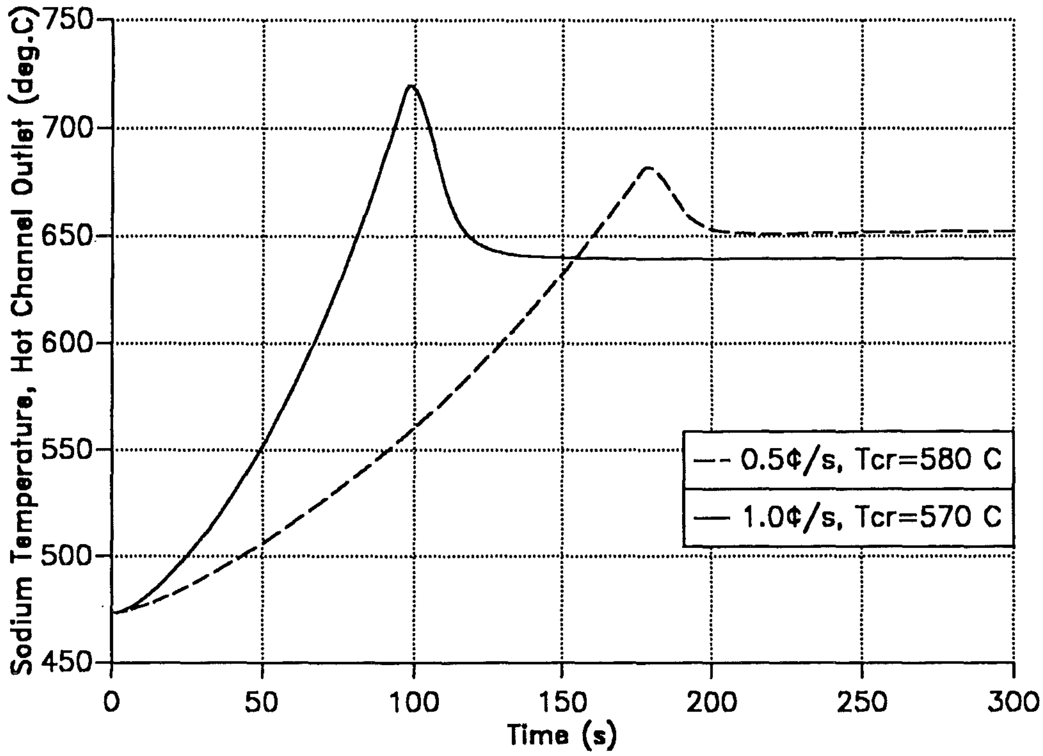

Fig.16. UTOPs from 20% of full power with 50% of nominal flow rate. Control rod position 10 cm: Hot channel coolant outlet temperatures.