

STUDIES OF RECRITICALITY TRANSIENTS IN BWRS DURING REFLOODING: SIMULATE-3K DEVELOPMENT AND ANALYSES

Lars Nilsson
Studsvik Eco & Safety AB
SE-611 82 Nykoeping, Sweden.
larsnil@ecosafe.se

David Kropaczek*
Studsvik ScandPower, Inc.
1087 Beacon Street, Suite 301, Newton, MA 02159, USA.
krop@soa.com

Wiktor Frid
Royal Institute of Technology, Dept. of Nuclear Reactor Engineering
SE-100 44 Stockholm, Sweden.
wiktor@egi.kth.se

* Present address: GE Nuclear Energy, Fuel Engineering
P.O. Box 780, Wilmington, NC 28401
e-mail: dave.kropaczek@gene.ge.com

ABSTRACT

Recriticality in a BWR has been studied for a total loss of electric power accident scenario. In a BWR, the B₄C control rods may melt and relocate from the core before the fuel during core uncover and heat-up. If electric power returns during this time-window, unborated water from ECCS systems will start to reflood the partly control rod free core. Recriticality might take place for which the only mitigating mechanisms are the Doppler effect and void formation. Of particular interest are global effects of hydraulic feedback between the coupled reactor core and peripherals system, i.e. non-core components. A study was made using the core kinetics code SIMULATE-3K (S-3K), specially adapted to model the reflooding and recriticality problem. S-3K is a transient version of the advanced 3-D core analysis code SIMULATE-3. S-3K models each fuel channel uniquely, with transient hydraulic and radial fuel pin conduction solutions providing local nuclear feedback for the 3-D neutron spatial kinetics solution. The S-3K peripheral system models provide a representation of such non-core components as the downcomer, lower and upper plenum, and steam separator. The core model couples to the peripherals system model by communicating integral core conditions such as enthalpy rise, exit flow, and core pressure drop. These models and the results of applications of S-3K to reflooding transients in the Swedish advanced BWR, Oskarshamn 3, are the subjects of this paper.

1. INTRODUCTION

1.1 BACKGROUND

It is well known from studies of hypothetical severe accidents, e. g. initiated by total loss of external electrical power, that in BWRs melting and relocation of the control rods is likely to start already at about 1500 K, before melting and relocation of the fuel (Ref. 1). The reason is an eutectic reaction between the absorber material of boron-carbide and its stainless steel sheath. Although the fuel claddings of Zircaloy might rupture locally in contact with Inconel spacers at about the same temperature, fuel damage and relocation takes place much later. Metallic Zircaloy fuel cladding starts to melt at about 2100 K, but oxidised Zr can withstand melting up to more than 2900 K, i. e. the same temperature level as for early melting of UO₂ fuel interacting with Zr.

If the electrical power supply is restored, the emergency core cooling systems, and possibly also the feed water, would be activated and begin to inject unborated water into a core which might be more or less without control rods, but with still intact fuel geometry. (In Swedish BWRs there are also systems with a limited amount of borated water, but these must be activated manually). The increasing water level will cause recriticality in the control rod free part of the core, if that part is large enough. The only mitigation mechanisms are the Doppler effect and void formation.

Recriticality could have significant impact on progression and consequences of an accident. One concern is the possibility that the reactor achieves power well above the decay power thus resulting in steam production and containment loads different from those foreseen in accident management strategies. (A related problem connected with reflooding of an overheated core is the possibility of significantly increased hydrogen production). Another concern is the possibility of the core reaching a state above prompt critical, which could result in very rapid, and large power excursion. The worst possible consequence of this scenario could be melting and disintegration of the fuel, leading to fuel-coolant interaction and dynamic loads capable of failing the reactor pressure vessel and containment.

Scott, et al. (Ref. 2) concluded, based on a bounding analysis, that the energy deposition in the fuel due to power excursion is probably not sufficient to cause melting and disintegration of the fuel. It was predicted that recriticality is likely to produce core power levels less than about 20% of nominal power. The steady-state analyses for a unit fuel cell of the Peach Bottom Unit 2 BWR performed by Shamoun and Witt (Ref. 3) and Mosteller and Rahn (Ref. 4) show the effects of void fractions, temperatures and distribution of the control rod material on recriticality. It was concluded that recriticality is possible but that retention of even a small fraction of the control rod material in the fuel cell may be sufficient to prevent recriticality, however, 3-D effects of core degradation may make the results uncertain.

Bandurski, et al. (Ref. 5) performed one-dimensional, dynamic analysis on a simplified reactor model (typical BWR-4 of GE design) using the TRAC/BF1 and ONEDANT codes. They found that a super prompt-critical excursion is possible but of no safety concern for credible reflood rates and that following the power excursion a steady state fission power level of at most about 10% of nominal power is achieved for realistic reflood rates. They pointed

out the strong influence of the fuel cooling conditions during the reflooding process on recriticality (e.g. decreasing of Doppler efficiency with increasing reflood rate).

The importance of the two-phase flow and heat transfer regimes for recriticality has been discussed by Sandervåg (Ref. 6). Okkonen, et al. (Ref. 7) suggested that a BWR core can become critical if at least 1 m of the core is without absorber and if the void fraction is less than 60 %.

These earlier studies were either made by means of separate, or loose coupled, thermal-hydraulics and reactor kinetics models, or without a more detailed three-dimensional treatment of the problem. The analyses presented in this paper for the Swedish advanced BWR, Oskarshamn 3 (O-3), were made using the 3-D core kinetics code SIMULATE-3K (S-3K), specially adapted to model the reflooding / recriticality problem. S-3K explicitly models each fuel channel, with hydraulic and radial fuel pin conduction solutions providing local nuclear feedback for the neutron spatial kinetics solution.

Present work is based on the SARA project (Ref. 8), which was carried out as an EU project within the Fourth Framework Programme (1995 – 1998) of the European Commission on Nuclear Fission Safety. The SARA project comprised parallel studies on recriticality using three different codes, in addition to S-3K by Studsvik, also APROS by VTT in Finland and RECRIT by Risoe in Denmark.

1.2 OBJECTIVES AND SCOPE

The objectives of the present work were to:

- Develop and adapt the S-3K code to the special application for reflooding and recriticality calculations in BWRs during a severe accident, including simulation of initial conditions with core uncover and heat-up.
- Carry out recriticality calculations for Oskarshamn 3 BWR, for postulated severe accident sequences including reflooding of an overheated core, based on boundary conditions calculated with the SCDAP/RELAP5 code.
- Evaluate the effects of recriticality with respect to initial prompt power peak and enduring elevated power level during continued reflooding.
- Assess the effects of the recriticality transient on the integrity of fuel, reactor system and containment.

The recriticality analysis for O-3 comprised conversion and transfer of the SCDAP/RELAP5 results into initial and boundary conditions for S-3K. Since the originally available version of S-3K was not able to model the interaction with systems outside the reactor core in a reflooding transient, the SCDAP/RELAP5 conditions had to be specified at the core boundaries for S-3K. Some initial, scoping calculations were made in this way.

Next step was to develop S-3K to include modelling of in-vessel components outside the core and implement the thermal-hydraulic coupling between core and peripheral parts of the

reactor primary system of importance for reflooding. The final calculations were made with this model.

The recriticality calculations were made with a model of the O-3 plant based on data for a real fuel loading and actual operating conditions. Plant data for some early fuel cycles were made available by courtesy of the utility, OKG AB.

This paper describes the development and adaptation of S-3K for the reflooding/recriticality problem, the applications of the code for selected scenarios in Oskarshamn 3 BWR and the results of the S-3K calculations.

2. DESCRIPTION OF SIMULATE-3K

2.1 GENERAL ABOUT SIMULATE-3K

SIMULATE-3K (Ref. 9) is a transient version of the advanced 3-D core analysis code SIMULATE-3, which, along with the lattice physics code CASMO-4, comprises the Core Management System (CMS) code package of Studsvik ScandPower, Inc. S-3K explicitly solves for each fuel channel in a nodalized manner, with hydraulic and radial fuel pin conduction solutions providing local nuclear feedback for the neutron spatial kinetics solution. The S-3K approach of modelling the thermal-hydraulic behaviour of each fuel assembly on a mesh consistent with the neutronics solution is important in preserving the accuracy of the three-dimensional core model. This is in contrast to conventional approaches that employ a few-channel representation of the core thermal-hydraulics, evaluating local feedback conditions which must then be mapped back to the geometry of the detailed neutron kinetics calculation.

2.2 SIMULATE-3K MODEL DESCRIPTION

The spatial neutronics models in SIMULATE-3K solves the two-group, three-dimensional, transverse-integrated, neutron diffusion equations using fourth-order flux expansions in the fast group and either fourth-order (QPANDA) (Ref. 10) or analytic (SANM) (Ref. 11) flux expansions in the thermal group. Delayed neutron precursor equations are solved analytically assuming a linear temporal variation of the nodal fluxes at each time step. Neutron cross sections as a function of instantaneous and historical fuel temperature, moderator density, void and control rod position are provided by data from the standard SIMULATE neutronics data library. Pin power reconstruction is active in the transient mode for use in both thermal limit and detector response calculations.

Fuel pin temperatures and heat fluxes are calculated using a finite-difference model of the non-linear cylindrical heat conduction equation. An explicit fuel pin conduction calculation is performed for the average fuel pin in each axial plane of each fuel assembly (i.e., each node), and, optionally, for the hot pin in each node (as determined from pin power reconstruction).

Fuel, gap, and clad thermal properties are treated as functions of node-averaged fuel pin exposure (burnup) and local temperature. Convective heat transfer coefficients are computed using flow regime dependent correlations.

The channel hydraulics solution in S-3K is based on the one-dimensional, area-averaged form of the phasic mass, phasic energy, and mixture momentum conservation equations (Ref. 12). The model includes the interfacial heat transfer between phases and the direct heat transfer from the fuel clad to each phase (direct phasic heat and wall heat flux). A general drift flux formulation based on phasic superficial velocities is used for void closure.

Features of the SIMULATE-3K hydraulics model include:

1. Five equation hydraulics (phasic mass, phasic energy, and mixture momentum conservation equations)
2. Consistent, non-staggered spatial discretization
3. Numerically stable, fully implicit time discretization
4. Computationally efficient, non-linear solution scheme
5. Consistency with existing SIMULATE-3 spatial neutron kinetics and pin conduction solutions

The discretization of the conservation equations is obtained by performing a volume integration from lower to upper mesh edge, thereby preserving node integral quantities appearing in the temporal derivative and (non-gradient) source terms. Thus, the order of spatial truncation error is determined directly by the order of spatial approximation used in representing the functions which are being integrated (i.e. a linear approximation produces a first order method). In addition, the use of an edge-centred mesh formulation avoids the need for donoring, which is the process of evaluating products of edge and cell centred quantities, such as mass flux, based on the flow direction. The temporal discretization is fully implicit, with all source and gradient terms evaluated at the new time step. This is different from most thermal-hydraulic system codes which employ a staggered mesh spatial discretization and a semi-implicit temporal discretization.

It is stressed that no linearization of terms appears anywhere in the solution of the conservation equations. The complete non-linear solution is resolved at each time step on a node by node basis via a globally convergent Newton line search iteration. For a full core BWR problem of 700 channels, nodalized in 25 axial mesh (like in the O-3 case), this involves the non-linear solution of greater than 17 500 hydraulic nodes at each time step.

2.3 SIMULATE-3K BOUNDARY CONDITIONS

S-3K achieves its coupling to external peripheral systems (non-core components) by communicating plena boundary conditions. At the channel level, all phasic primitive variables are considered known at the inlet while the upper plenum provides a known pressure boundary condition common to all channels. An alternative boundary condition replaces the inlet phasic mass fluxes with a known lower plenum pressure and inlet flow quality. In the latter case, the pressure drop across each channel is matched to the total core pressure drop through adjustment of the inlet flow within each channel via an outer iteration. Within the context of linking to an external peripheral systems model, both boundary conditions have been successfully demonstrated to have specific advantages. The inlet pressure / exit pressure boundary condition provides the benefit of balancing channel flows such that the pressure drop in each fuel channel is matched to the total core pressure drop. The inlet flow / exit pressure boundary condition allows the user the option of maldistributing the inlet flow as a function of channel location.

For the reflood transient, an external BWR peripheral systems model was constructed for use with the S-3K core model in order to properly model the S-3K transient boundary conditions. This was necessary since core inlet flow depends directly on core pressure drop, which is dictated by integral loop momentum, energy and mass balance over the core, upper plenum, separator, downcomer, and lower plenum. In addition, saturated liquid recirculated through the separator will affect the enthalpy mixing in the downcomer and, ultimately, the core inlet enthalpy.

2.4 REFLOOD PERIPHERAL SYSTEMS MODEL

The assumptions utilized in the peripheral system models for the reflood scenario are as follows:

1. The coupled lower plenum and downcomer region is comprised of incompressible liquid and is perfectly mixed.
2. Core exit liquid and vapour flows are saturated.
3. The homogeneous equilibrium mixture model (HEM) is used for the fluid in the coupled upper plenum / separator region.
4. Recirculated liquid from separator is saturated with zero carryover to the steam dome.
5. Steam dome pressure versus time is input (no modelling of the steamline).
6. All state properties are evaluated at the steam dome pressure (no modelling of sonic waves).
7. The S-3K core model boundary is known inlet flow / exit pressure.

The governing equations utilized in the peripherals systems model are as follows:

Mass Conservation (combined lower plenum and downcomer)

$$\frac{d}{dt}M_{dc} = W_r + W_{fw} - W_{cin} \quad (1)$$

Mass Conservation (core):

$$\frac{d}{dt}M_c = W_{cin} - W_{cout} \quad (2)$$

Energy Conservation (combined lower plenum and downcomer):

$$\frac{d}{dt}(M_{dc}h_{dc}) = W_r h_f + W_{fw} h_{fw} - W_{cin} h_{dc} \quad (3)$$

Integral Momentum Balance:

$$\Delta P_c + \Delta P_{sep} - \Delta P_{dc} = 0 \quad (4)$$

where,

$$\Delta P_{dc} = \rho_{dc} \Delta z_{dc} g \quad (5)$$

$$\Delta P_{sep} = \rho_{sep} \Delta z_{sep} g + K_{sep} \frac{W_{cout}^2}{2\rho_f A_{sep}^2} \Phi^2 \quad (6)$$

Momentum Balance (core):

$$\Delta P_c = \left(\frac{M_c}{A_c} \right) g + K_c W_{cin} \quad (7)$$

Equation (7) relates the core pressure drop to the core static head and flow loss (as a function of inlet flow). The constant, K_c , is an effective flow loss coefficient for the core obtained from a linearization of the frictional core pressure drop as a function of inlet flow within the S-3K core model.

2.5 COUPLED SYSTEMS SOLUTION ALGORITHM

The boundary conditions for the peripheral systems are the feedwater flow rate (W_{fw}) and enthalpy (h_{fw}). These variables are specified through user input as a function of time. The initial conditions are the combined lower plenum and downcomer mass (M_{dc}) and enthalpy (h_{dc}). The initial mass, (M_{dc}), is assumed to be equal to the density of the lower plenum multiplied by the volume of the lower plenum. This defines an initial level, (Δz_{dc}), of zero for the downcomer at just prior to the start of the reflood event. The initial enthalpy, (h_{dc}), is the initial enthalpy of the lower plenum as specified through user input. A schematic showing the

various calculated quantities within the coupled peripheral systems and S-3K core model is shown in Figure 1.

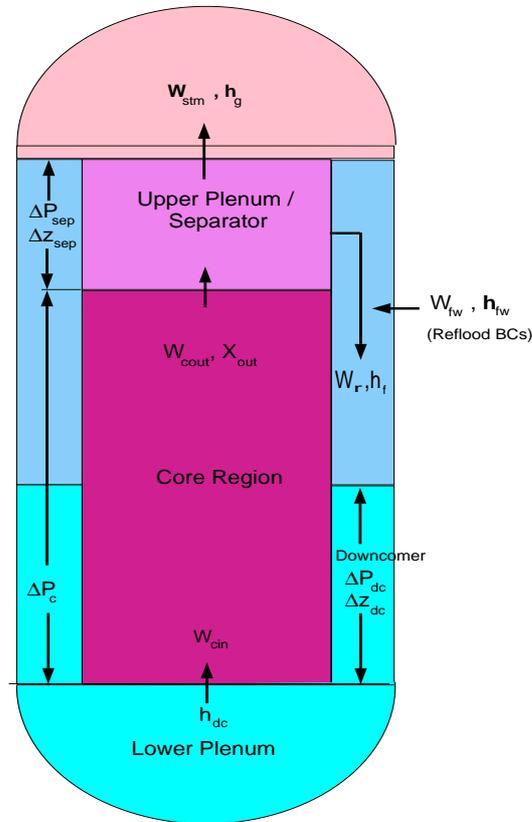


Figure 1. Reflood Peripheral Systems Model.

The temporal derivatives of equations (1), (2), and (3) are discretized as a forward difference in time. The variables W_{cin} , and W_{cout} , which appear in equations (1), (2), (3) and (6), correspond to the core inlet and core exit flows, respectively. These flow rates are evaluated explicitly in time and are obtained directly from the S-3K core model. The recirculation flow of equation (1), W_r , is likewise modeled explicitly with values obtained from the S-3K core model. The recirculation enthalpy (h_f) is simply the saturated liquid enthalpy at the user input dome pressure as a function of time.

With W_{cin} , W_{cout} , and W_r known, equations (1) and (2) may be solved for M_{dc} and h_{dc} at the new time step. From the enthalpy and dome pressure, the single phase density, (ρ_{dc}), is evaluated from state properties. The lower plenum mass is then equal to ρ_{dc} multiplied by lower plenum volume. The downcomer mass is calculated by subtracting the lower plenum mass from M_{dc} . Finally, the static head (ΔP_{dc}) is calculated as downcomer mass divided by area. Equation (5) then allows calculation of the new time step downcomer level, (ΔZ_{dc}).

The pressure drop of the combined plenum and separator (ΔP_{sep}), is calculated using previous time step values for core exit flow from the S-3K core model. The value of ΔP_{sep} is a geometrical height above the top of the core for the combined upper plenum and separator. The density (ρ_{sep}) is calculated using a HEM based void model and saturation properties for

the liquid and vapour. The loss coefficient (K_{sep}), is input by the user. Φ^2 is the homogeneous two-phase multiplier as a function of flow quality.

Once ΔP_{sep} and ΔP_{dc} are known, the core pressure drop (ΔP_c) is calculated from equation (4). Equation (7) is then used to calculate the new time step core inlet flow (W_{cin}) utilizing the linearized core loss coefficient (K_c) of the previous time step S-3K result. The coefficient, K_c , is calculated by taking the core pressure drop of the three-dimensional neutronics calculation (minus the core static head) divided by the core inlet flow. In this way, the peripheral systems model implicitly captures the effect of the changing core flow on core pressure drop.

The approximations made in the thermal-hydraulic modelling of recirculation loop can be justified as giving minor deviations in results considering the relatively large uncertainties in boundary conditions at start of reflooding. The performed parameter study gives some estimation of these uncertainties. The error introduced by taking all state property values at the steam dome pressure, instead of accounting for the pressure gradient around the circulation loop, was estimated and found to be negligible. The combined relative error was as largest for density, and evaluated to be maximum 0.4% in the worst case.

3. INITIAL CONDITIONS FOR RECRITICALITY ANALYSES

Preparatory reflooding calculations for Oskarshamn 3 (O-3) were made with the severe accident analysis code SCDAP/RELAP5 (Ref. 13). The aim was to investigate the conditions which can lead to recriticality, and to produce initial and boundary condition data as a basis for the S-3K recriticality calculations. A summary of main results is presented here. SCDAP/RELAP5 models the thermal-hydraulics for the whole primary system in greater detail than S-3K. SCDAP/RELAP5 calculates core heat-up from decay power and, in addition, even core damage progression and oxidation which are not taken into account in S-3K. The SCDAP/RELAP5 results were used as model for simulation of core heat-up with S-3K. Reactivity effects were not calculated with SCDAP/RELAP5, since this code has only a point kinetics model, which is not detailed enough for recriticality studies.

The reactor model in SCDAP/RELAP5 comprised 140 so-called hydrodynamic volumes connected by flow junctions. The core was divided into five concentric rings each with ten axial nodes. The power distribution and other operating conditions were taken from a SIMULATE-3 output for O-3 for the middle of an early fuel cycle, at which the thermal power was 3020 MW. The axial power distributions for three of the five radial rings (Ring 1, 3 and 5 from the core centre) are shown in Figure 2.

Station blackout, i.e. loss of power to all cooling systems, was postulated as initiating event in the studied accident scenarios. Steam venting through safety valves then makes the water level in the reactor vessel decrease. After about 24 minutes the Automatic Depressurization System (ADS) is activated at low downcomer water level (0.5 m above core exit). The ADS valves stay open for the rest of the transient, assuming a constant containment backpressure of 0.5 MPa. Returning power to emergency core cooling systems was then simulated to take place, at different times, when the fuel was heated up to various maximum temperatures between 1700 K and 2000 K.

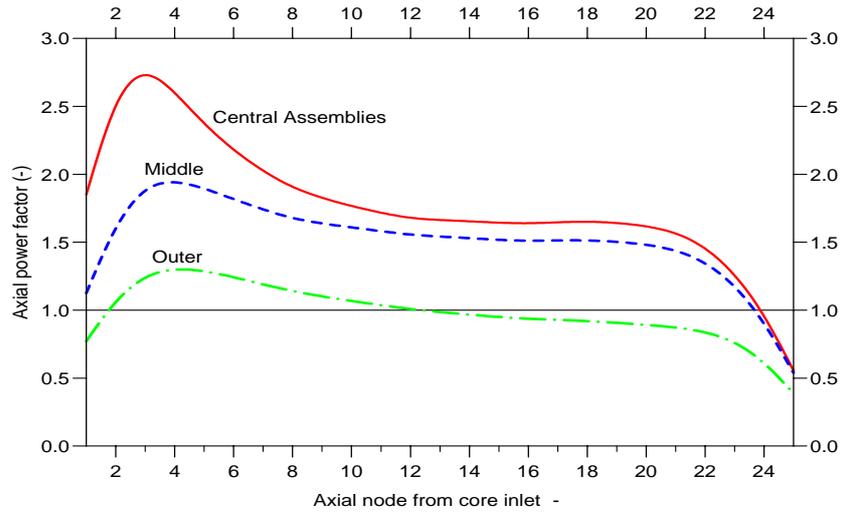


Figure 2. Axial power distribution in Oskarshamn 3 BWR for analyzed fuel cycle.

In addition to a base case without reflooding, calculated up to 2 hours after the total loss of AC power, a number of 13 reflooding cases were performed within the following parameter range:

- Eleven bottom flooding cases with injection of 20 °C water into the downcomer (DC), with a constant mass flow of 45, 90, 200, 500, 1000, 1500 and 2000 kg/s.
- Two top spray cases, i.e. injection into upper plenum with mass flow rates 45 and 90 kg/s, started at a core maximum temperature of about 1800 K.

The core uncover and heat-up predicted by SCDAP/RELAP5 is shown in Figure 3

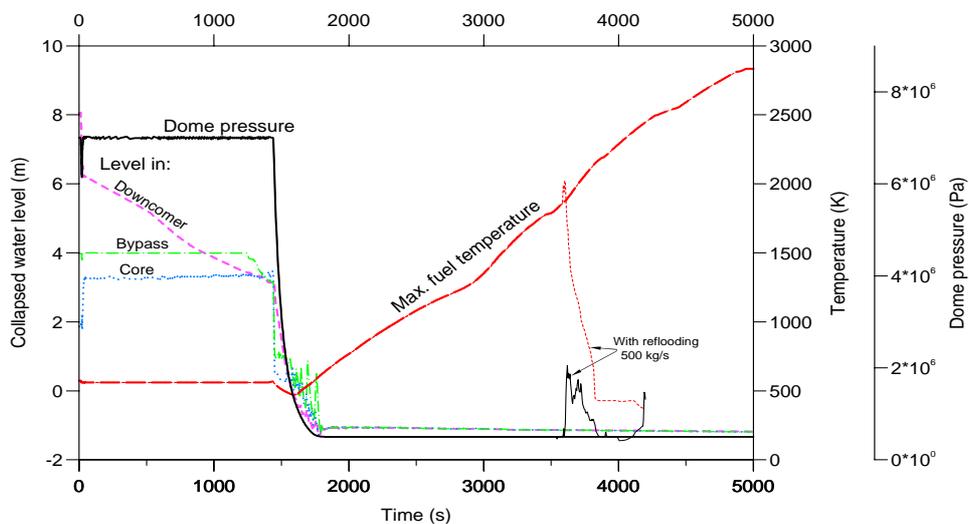


Figure 3. Water levels in vessel, dome pressure and core temperatures.

The major results of importance for the recriticality calculations are as follows:

- Timing of events, such as for automatic depressurisation (ADS), core uncover, start of core-heat-up, beginning of control rod melting and fuel rod damage (the time period between the latter two constitutes the "time-window" crucial for recriticality calculations).
- Core heat-up and temperature distribution in core. Figure 4 illustrates the temperature distribution for the five core zones according to SCDAP/RELAP5.
- Control rod status before recriticality, i.e. of absorber material mass and distribution in core prior to recriticality.
- Reflooding conditions as function of water mass flow injected into downcomer, i.e. core inlet flow rate and water level as function of time.

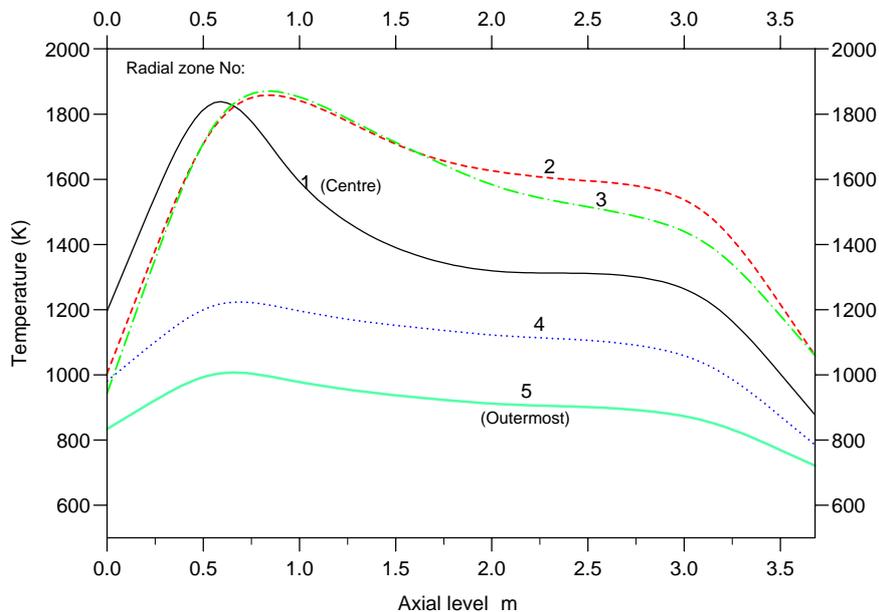


Figure 4. Fuel temperature distributions for the core zones before reflooding.

The additional melting of control rods that was obtained during reflood due to increase in power from oxidation processes when water was added to the dry, overheated core is taken into account for the initial conditions in the S-3K calculations.

The state of control rods in the core before recriticality, shown in Figure 5, including the additional melting obtained due to oxidation during reflooding. In most cases melting took place in the three innermost core zones from axial level No. 2 (of totally 10 axial nodes) and above. Melted absorber material was accumulated in the lowermost axial node No. 1. It is assumed that control rod material in upper nodes which did not undergo melting, according to SCDAP/RELAP5, could not be supported by lower, empty nodes but were relocated into the bottom nodes.

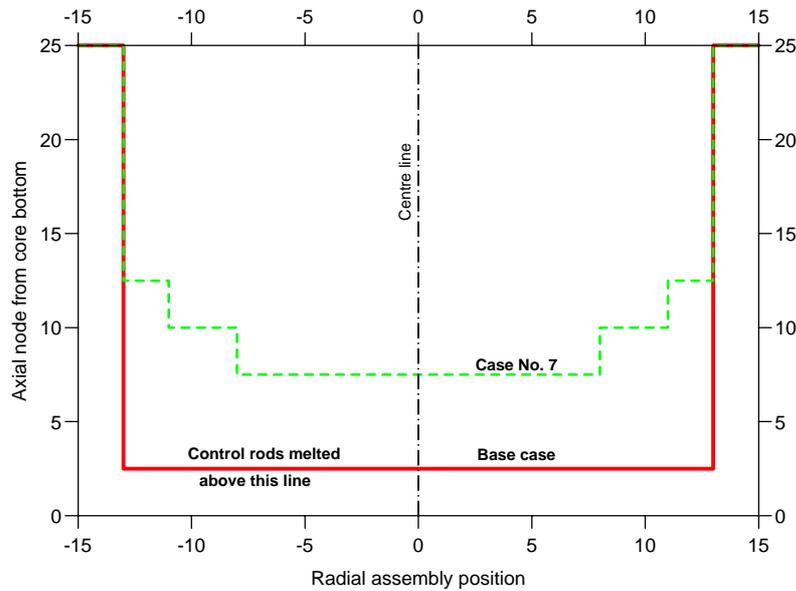


Figure 5. Control rod status from SCDAP/RELAP5 applied in the recriticality calculations.

The water level in the vessel was more than 1 m below the core inlet after blowdown according to SCDAP/RELAP5. Different times were then needed to reach the core lower boundary for different flow rates. The resulting reflooding velocity, i.e. the speed with which the water level increases in the core, is a function of the injection mass flow rate and the boiling rate in the core. A substantial fraction of the water is boiled off in the core which reduces the net reflooding velocity. The additional pressure drop in the core from increased two-phase flow counteracts the reflooding as well. Varying pressure drops in the parallel core channels makes the water surfaces oscillate between different channels.

4. SIMULATE-3K RECRITICALITY CALCULATIONS

4.1 ASSUMPTIONS AND CASES STUDIED

In order to simulate realistic conditions in the transient S-3K calculations, operating data for O-3 were taken from a SIMULATE-3 steady-state core follow calculation provided by the utility. An early fuel cycle, same as for SCDAP/RELAP5, was chosen with a cycle burn-up of 3.59 MWd/kgU. At this point the reactivity is quite high since much of the burnable poison is gone. The power was 3020 MW_{th}, i.e. 100%, with a recirculation flow reduced to 79% of the nominal value. Axial power distributions were shown in Figure 2.

The plant boundary conditions were the same as in the preparatory SCDAP/RELAP5 reflooding calculations, but due to modelling differences the initial conditions before

reflooding, after the heat-up phase, differ. Among other things, the core model is more detailed in S-3K with each fuel assembly as a separate flow channel, while in SCDAP/RELAP5 many assemblies were lumped into five parallel radial rings. In S-3K 25 axial nodes were used, but in SCDAP/RELAP5 only 10 nodes. On the other hand S-3K did not include any oxidation heat generation, only decay power after scram.

Due to differences in core modelling it was not possible to reproduce the preparatory SCDAP/RELAP5 results completely for the initial conditions with S-3K. The temperature distribution calculated by S-3K was a function of the individual assembly power factors, since all assemblies are modelled separately, and not symmetric around the core centre like in the SCDAP/RELAP5 model. S-3K showed also a higher heat-up for the central assemblies and lower temperatures at the periphery. The maximum axial temperatures, at which reflooding was initiated, are compared in Figure 6 below.

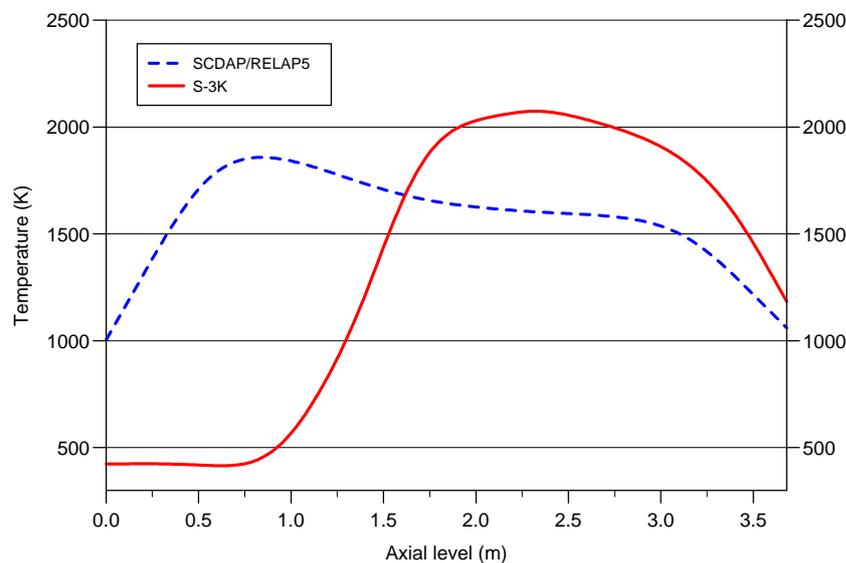


Figure 6. Maximum fuel temperatures after heat-up phase, at start of reflooding.

One case was selected as a base case (Case No. 1) with the following conditions:

- ECCS water mass flow rate to downcomer = 500 kg/s
- Initial core maximum temperature = 2093 K
- Initial water level = 0.0 m (core inlet level)
- System pressure = 0.5 MPa, constant
- Control rod status: 133 innermost rods withdrawn to 90% in rings 1-3, outer 36 fully inserted, according to SCDAP/RELAP5 predictions (see Fig. 5).
- Temperature of ECCs water at injection point = 293 K
- Flow restriction in RCP loop: $D=0.2$ m, $L=1.0$ m, $\xi =10.0$ (Loss coefficient in pumps, velocity heads). No. of RCPs = 8
- Hydraulic time step at recriticality point = 0.01 s.

The following parameter study, listed in Table 1, was carried out:

Table 1 Case Matrix for S-3K Calculations

Case No	Parameter	Value (Variation from base case)
1		(Base case)
2	ECCS flow rate to DC	90 "
3	"	200 "
4	"	1000 "
5	"	1500 "
6	"	2000 "
7	Control rod melt down	Less melt down, 70, 60 & 50% in group 1, 2 & 3
8	Initial max. core temperature	Lower (1800 K)
9	ECCS water temperature	Increased to 353 K
10	System pressure	From SCDAP/RELAP5, ramp to 1.75 MPa
11	RC loop pressure loss	Reduced, D=0.6, L=0.0 m, K =10.0
12	"	Increased, D=0.1, L=1.0 m, K =10.0
13	Calculation time step	Reduced to 0.001 s

4.2 RESULTS

4.2.1 BASE CASE CALCULATION

The relation between some crucial parameters calculated by S-3K for the base case is shown in Figure 7 below.

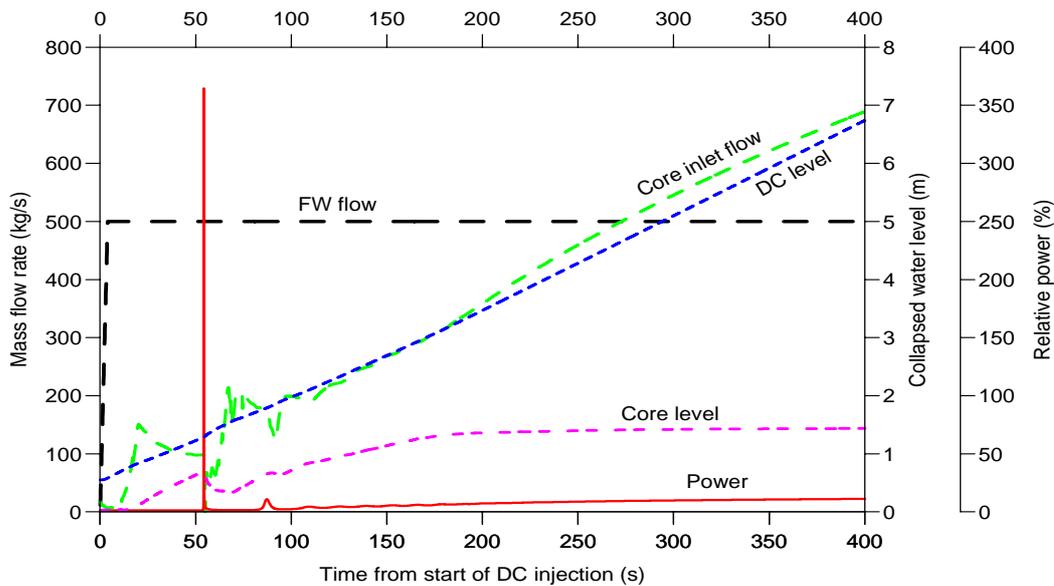


Figure 7. Flow rates, water levels and core power versus time in base case.

After start of water injection into the downcomer, the core inlet flow starts from zero, with some delay needed to fill the downcomer to a certain level and create a driving pressure head. Since the injection flow rate is constant the DC level increases and so the inlet flow rate. At a certain water level in the core critical conditions are reached which leads to the first prompt recriticality. The first power peak is rapidly terminated by Doppler feed back and following recriticality is lessened by void formation. The added power increases boiling and thus the two-phase flow pressure drop in the core so it counteracts the core inflow of water. This kinetic - hydraulic coupling leads to flow - power oscillations, the amplitude of which is a function of the DC injection flow rate and the hydraulic damping. Since the water level in the core continues to increase after quenching and recooling of the hot fuel rods, the fission power increases again and seems to reach a balance with the core inlet flow. The downcomer is now completely filled and the hydraulic driving head no longer increases. At this state the calculations came into an unstable phase and were then ended.

The predicted recriticality was very local to its nature and the fission power was developed in a few nodes in the core centre and in the lowermost part which became reflooded. This is illustrated in Figure 8 which shows the nodal power factors for a longitudinal section of the core at the first recriticality peak in the base case. The power distribution was, on the large, rotational symmetric in the cross section plane.

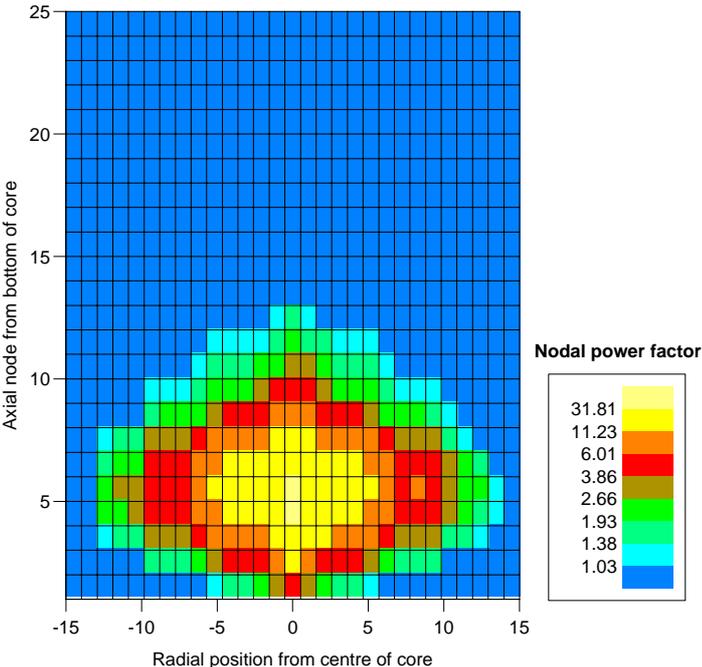


Figure 8. Nodal power factors at first recriticality in base case in a core axial plane through core centre.

The maximum power factors were obtained at axial level 5, i. e. about 0.7 m above core inlet. The distribution of nodal power factors in axial plane 5 is depicted in Figure 9 on following page.

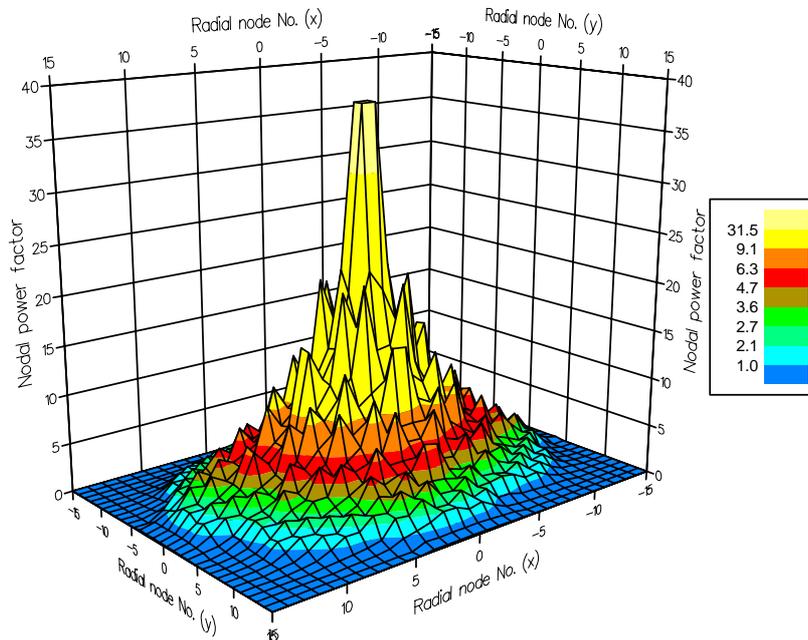


Figure 9. Nodal Power factors at first recriticality in base case in the cross sectional plane at axial level 5

4.2.2 EFFECT OF INJECTION MASS FLOW RATE ON PEAK POWER

Prompt recriticality was calculated to occur in all cases when the water level at reflooding had increased into a certain height in the control rod free part of the core. The amplitude of the peak increased with feed water flow rate, but the duration of the first recriticality became short, a few tenths of a second, due to Doppler feedback. Increased void formation kept the power at a low level until the continued increase in water level gave rise to new power peaks, but with lower amplitudes than the first one. The power continued to increase as long as the effective reactivity was slightly above unity. It is reasonable to assume that, at the end, the core power balanced the ECCS water flow, since the water level in the core seemed to reach an asymptotic upper value. The calculations were stopped when the downcomer was completely filled. The core inlet flow had then reached its maximum value and after that the calculations became unstable.

The recriticality power as a function of ECCS mass flow rate is illustrated in Figure 10, showing the first prompt criticality, and in Figure 11 with enlarged scale, showing the increased long-term recriticality. The total power reached more than 11 times nominal power with 2000 kg/s. The peak arrived earlier with increasing flow rate due to the shorter time needed to reach the critical water level. The peak for 90 kg/s was small and is visible only with the blown up scale, see Figure 11.

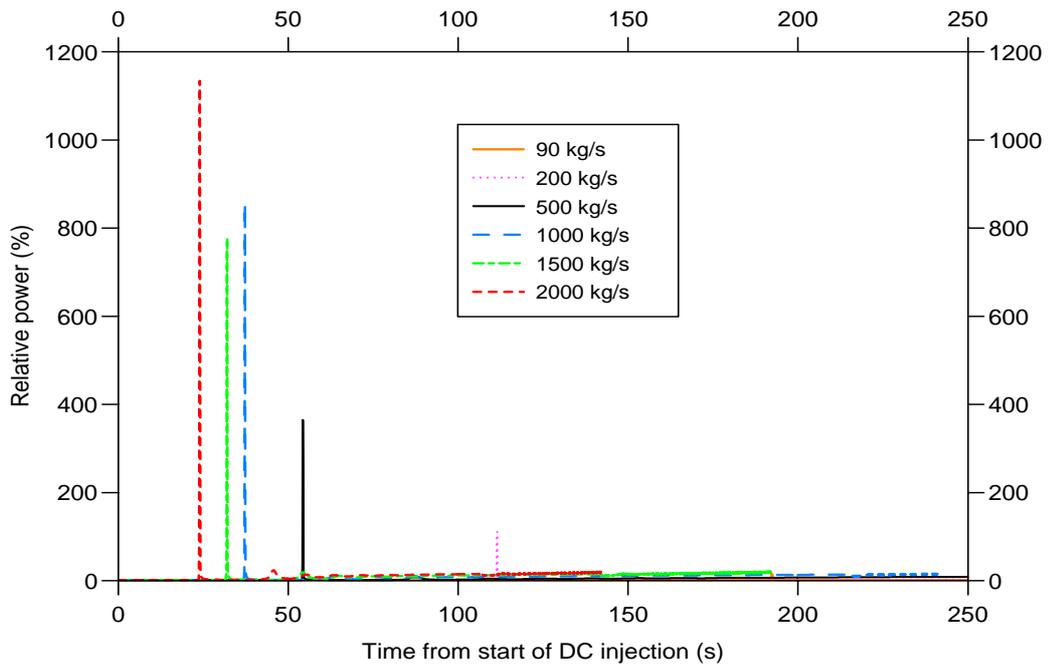


Figure 10. Total core power versus time after start of ECCS flow for various injection mass flow rates to downcomer. Cases 1 to 6.

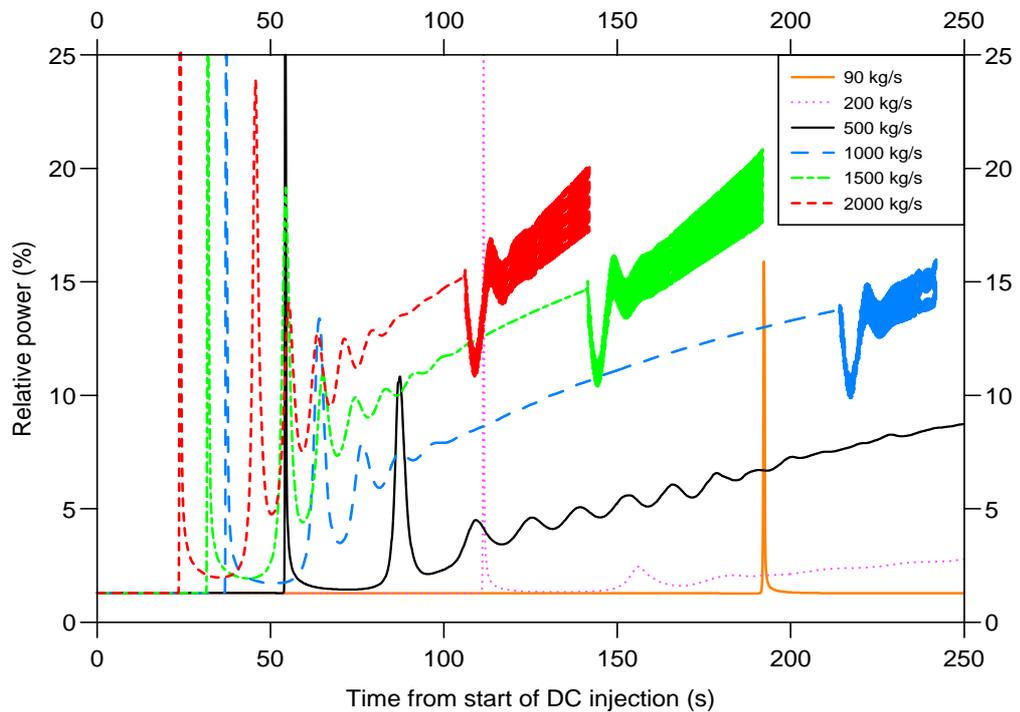


Figure 11. Total reactor power in the long term after first prompt recriticality for different ECCS flow rates. Cases 1 to 6.

The power in the long term after the first recriticality peaks increased slowly and, as mentioned above, it seemed to approach some asymptotic value. Also here the power level became higher with higher reflooding flow rate and reached 15% of nominal power for the

2000 kg/s case. All power values corresponds to total power, i.e. includes power from decay of fission products. The decay power, which before recriticality amounts to about 1.3% of nominal power, is slightly increased to about 1.7% as new short-lived isotopes are created at restarted fission.

The shape of the prompt recriticality peak is shown in Figure 12. The reason why the peak is lower in Case 5 with 1500 kg/s than in Case 4 with 1000 kg/s (Figure 10) are missing data points. In order to improve the resolution, short time steps had to be used in the calculations around the peak. The reduced maximum hydraulic time step used in Case 13, 0.001 s instead of 0.01 s in the other cases, had the effect of giving a narrower but higher power peak.

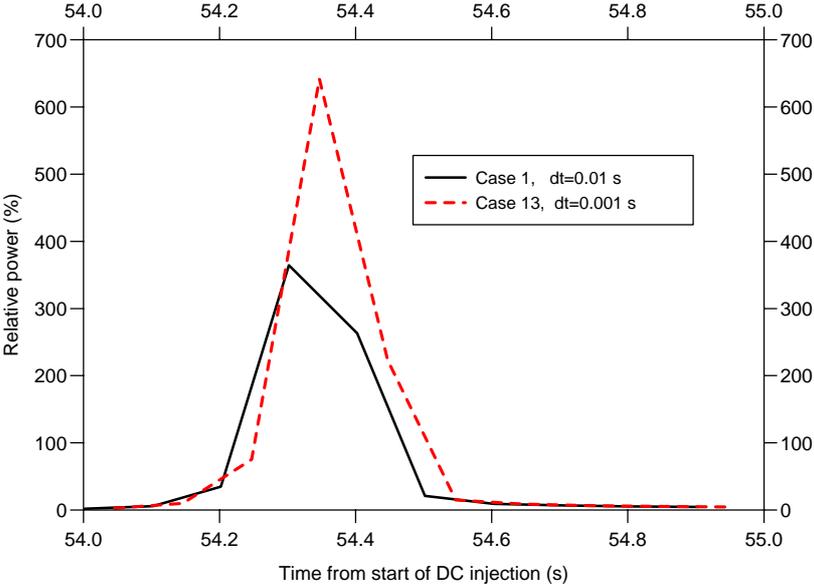


Figure 12. Shape of first recriticality peak in case 1 and 13.

4.2.3 TEMPERATURE AND HEAT-UP DURING REFLOODING

S-3K predicted rewetting and recooling by the reflooding water in all cases. Only for feedwater flowrates above 500 kg/s did the recriticality peak lead to increase of the initial maximum fuel temperature, as shown in Figure 13. However, in the nodes with the highest nodal power factor, which did not have to coincide with the location of the maximum core temperature, the heat-up could be more noticeable.

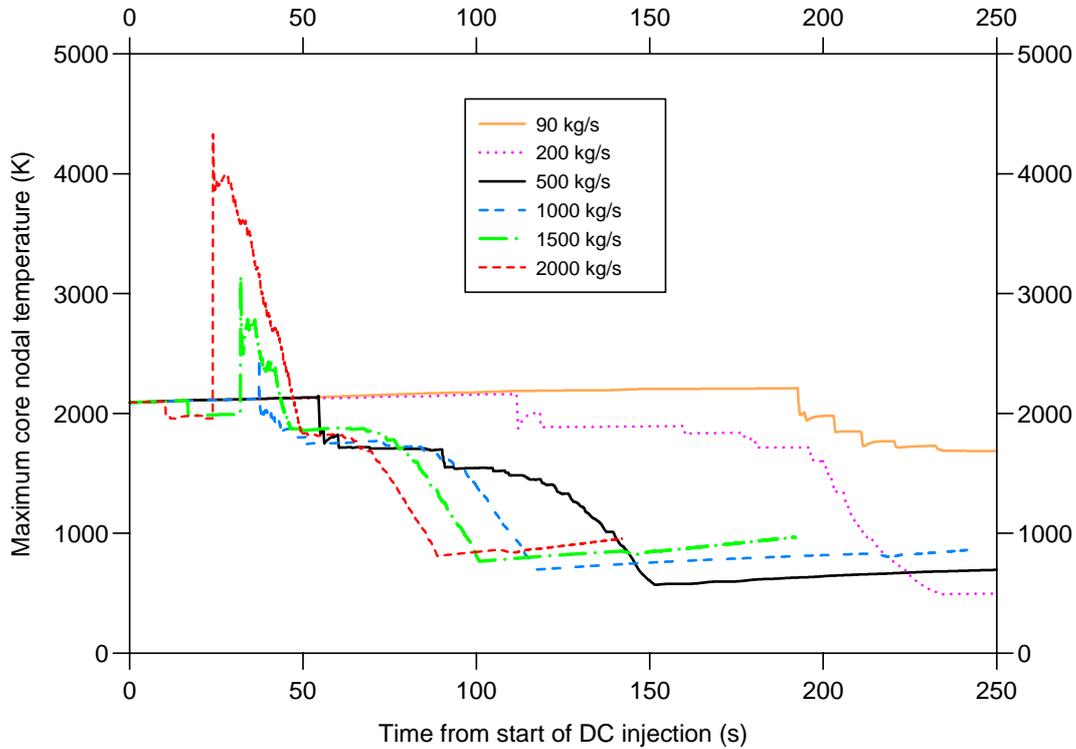


Figure 13. Maximum nodal fuel temperatures for various ECCs water flow rates.

4.2.4. ENERGY DEPOSITION IN THE FUEL DURING RECRITICALITY PEAK

Since the first, prompt recriticality was developed very locally in the core, the power factors in some nodes became high. This implies that the energy deposited during the first power peak, and within a relatively short period of time, could be significant with regard to the threshold for fuel damage. A criterion for cladding failure can be as low as 140 cal/gUO₂, but the threshold for fragmentation and dispersion of the fuel with moderate burnup lies in the range 200 – 280 cal/gUO₂. Numerous investigations have been made to determine this limit, which is of importance for assessing the safety against fuel damage at so called RIAs, Reactivity Initiated Accidents. In this context it is important to consider that these threshold values have been obtained in tests with “normal” fuel rods, and are therefore likely to be lower for strongly overheated fuel rods under severe accident conditions. Some very low values have been cited, down at 60 to 70 cal/g, but they have been obtained with high burnups, above 40 to 50 MWd/kgUO₂ and possible with high degree of hydration (Refs. 14 and 15).

Estimation of maximum energy deposition was made in a simple manner, based on the maximum nodal power factor and a rough integration of the plotted power curve. However,

only the largest values of energy deposition, calculated by S-3K, are of the same magnitude as the fragmentation limits for normal burnup reactor fuel. Fuel damage due to energy deposition from recriticality is thus not likely in most of the analysed reflooding cases. The additional energy deposition is reflected in the calculated maximum fuel temperature. Only in the three most extreme cases (Case 5, 6 and 11) was there a substantial increase as a result of super-prompt power excursion, however, in those cases the fuel melting temperature was exceeded..

The energy deposition during the first power peak and some other crucial results of the S-3K calculations for O-3 are summarized in Table 2 below.

Table 2. Summary of main results of S-3K calculations for O-3

Case No:	1	2	3	4	5	6	7	8	9	10	11	12	13
Time* at first power peak (s)	54.3	192	111	37.3	32.0	23.9	153	82.1	53.0	47.2	52.6	90.6	54.3
Peak amplitude, relative (Times nominal power)	3.65	0.16	1.11	8.56	7.78	11.3	0.47	5.35	3.26	11.8	12.7	3.30	6.42
Max. nodal power factor (-)	37.2	41.8	42.1	36.5	36.2	36.9	30.9	38.5	37.5	23.4	39.2	39.1	37.6
Duration of 1:st peak (s)	0.45	1.13	0.49	0.38	0.38	0.31	1.45	0.35	0.46	0.39	0.36	0.42	0.35
Energy deposition in fuel during first peak (cal/g)	134	14	59	237	354	418	44	176	126	222	397	130	192
Energy deposition during 100 ms of peak (cal/g)	36	2	17	104	110	136	5	59	37	80	140	38	69
Maximum fuel temperature (K)	2147	2212	2167	2438	3148	4328	2138	2432	2145	2065	4430	2181	2698
Power at end of simulation, % of nominal	11.4	4.6	7.5	13.8	14.6	15.5	11.4	11.8	7.6	11.4	17.4	10.0	11.4
Time at end of simulation (s) **	423	2592	1079	214	141	106	499	450	399	453	550	466	432

*) The time is counted from start of injection to downcomer. **) Time to fill the whole downcomer.

All cases above were calculated with an average cycle burnup of 3.59 MWd/kgU (mid-cycle). The maximum burnup for fuel assemblies retained from the two previous fuel cycles were about 19 MWd/kgU. In order to see the effect of cycle burnup, Case 1 was also calculated with restart from a low burnup of 0.4 MWd/kgU, i.e. at beginning of cycle. The results indicate only minor difference in peak recriticality power. The only noticeable effect was that the first power peak arrived somewhat earlier with the shorter burnup. No run was made for higher burnup for the end of cycle, but it is assumed that this would result in smaller recriticality power, since the fuel then has less excess reactivity.

6. CONCLUSIONS

Use of the standard version of the SIMULATE-3K code for severe accident simulation including core uncover and heat-up to core nodal temperatures around 2000 K is out of the normal application of this code. S-3K is primarily aimed for analysis of relatively mild operating transients, like ATWS, control rod drop or ejection, etc. Therefore some special modifications were made in order to adapt S-3K for analysis of the reflooding / recriticality

transients. Despite difficulties to reproduce the heat-up phase and lack of quench heat transfer models to give complete agreement with the results from the severe accident codes like SCDAP/ RELAP5, S-3K performed well in simulation of the very fast recriticality transients. Uncertainties in the modelling of the hydraulic coupling to peripheral systems and inability to calculate feedback to steam dome pressure are shortcomings of the present version of the code. However, the parameter studies which were made for crucial variables facilitate estimation of the sensitivity to most of these parameters.

It is clear that the most crucial parameter which control the magnitude of the recriticality power is the reflooding flow rate, or ECC injection rate, provided that the control rod free zone of the core is large enough. Since the inlet flow is gravity driven by the static pressure difference between downcomer and core, the flow resistances in the flow paths are important as well as the water mass distribution in the core. Low hydraulic damping seem to give earlier and higher initial recriticality power peak, but has less effect on the long term power level.

Although the first super-prompt recriticality power peaks reached high amplitudes, the total energy contributions were quite moderate in most cases. However, the power density is locally very high, and the energy is generated in a very short time period, during which little heat is lost to the coolant. At reflooding rates higher than about 500 kg/s the energy deposition in the fuel therefore became considerable and approached, or even exceeded, the threshold values for fuel fragmentation and dispersion. These results are different from other studies, which found that the energy deposition in the fuel due to super-prompt power excursion would be below the threshold values.

Strong oxidation of the fuel claddings takes place in the heat-up phase and especially during the rewetting and quenching in the reflooding phase. The exothermic metal-water reaction can then temporarily generate power of the same magnitude as the decay power. Oxidation is not taken into account in S-3K. The oxidation phenomena will probably lower the threshold values for fragmentation, and thus increase the risk for fuel damage at recriticality.

The long term power predicted by S-3K seems to almost balance the gross inflow of water to the downcomer. In the case with the lowest flow rate of 90 kg/s at 20 °C, the power at the end of simulation was 4.6 % of nominal power, i. e. 139 MW. The power needed to evaporate all the injected water, corresponding to this flow rate, is larger, 240 MW. However, it should be expected that the power in the long term continues to increase, and if no large power oscillations take place, it seems to approach an upper limit corresponding to the boil-off power for the injected water. Until then the water level in the core will increase.

There is an uncertainty about this long-term behaviour which depends on the magnitude of the hydraulic damping in the recirculation loop. With lower damping factors, than those employed in the base case, the core flow rates will probably continue to oscillate after the first power peaks. With lower damping an oscillatory, more violent boiling will take place throwing water plugs out of the core exit, and the water level in the core will also fluctuate. This will generate repeated power peaks. The average long-term power was, however, predicted to be only slightly higher than in the base case with larger damping. Therefore, lowering the loss coefficients will not substantially affect the results of the analysis.

Since S-3K was not able to calculate the dome pressure, the resulting back-pressure dependent ECCS injection flow rate could not be determined. A parameter study was therefore done for

the injection flow rate. Earlier SCDAP/RELAP5 calculations indicate that the low pressure ECCS flow rate during the reflood phase in O-3 would be limited to about 300 to 400 kg/s. This sets then an upper limit also for the recriticality power, provided that the normal feedwater is not activated, which would increase the reflooding flow rate.

The steam production at long term recriticality power is blown off to the containment. Even the power at lowermost injection rate will then be too large to be cooled off by the containment cooling systems. The water in the containment pool will be heated to saturation and the steam production can not be taken care of by the filtered venting system (such systems have been installed at all Swedish nuclear reactor plants). This will eventually lead to overheating and overpressurization and containment failure.

In a new version of S-3K the capabilities to simulate the integrated reactor system with feedback on reactivity has been enhanced. This includes a BWR steam dome and steam line model which facilitates simulation of power - pressure interaction.

NOMENCLATURE

A	Flow area (m ²)
D	Pipe diameter (m)
H	Enthalpy of coolant (J/kg)
HEM	Homogeneous Equilibrium Mixture
K	Pressure loss coefficient, velocity heads (Pa·m·s ² /kg)
L	Pipe length (m)
M	Mass (kg)
P	Pressure (Pa)
W	Mass flow rate (kg/s)

Greek

Δ	Difference, differential
Φ^2	Homogeneous two-phase multiplier as a function of flow quality.
ρ	Density (kg/m ³)

Subscripts

<i>c</i>	core
<i>cin</i>	core inlet
<i>cout</i>	core outlet
<i>dc</i>	downcomer
<i>fw</i>	feed water
<i>sep</i>	separator
<i>stm</i>	steam
<i>out</i>	outlet

ACKNOWLEDGMENTS

This work, which is a contribution to the European Commission project "SARA", was funded by the European Commission (EC) and the Swedish Nuclear Power Inspectorate (SKI).

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