COUPLING OF REACTOR POWER WITH ACCELERATOR CURRENT IN ADS SYSTEMS

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ABSTRACT

In ADS systems it is generally assumed that the electrical current feeding the accelerator proton beam originates from the grid. On the other hand, in an accidental event, the safety of these systems is largely based on current interruption, it being generally assumed for ADS that the required reactivity compensations during reactor operation and burnup should be regulated through a current reserve, rather than through a control rod adjustment (this avoiding inadvertent control rod removal accidents). In the case of a serious accident, if the current interruption fails, the consequences may be severe. In this work we consider an approach by which the probability of such an event is drastically reduced. Its principle is based on the coupling of the accelerator proton current, rather than with the external grid, to the electricity produced by the same reactor, except at startup conditions, for which an external electrical current of a relatively low intensity would be used. A self-regulating mechanism, introducing an extra negative power feedback, for contributing to limiting temperature rise during transients, is also considered. The "balance of reactivity" method proposed by Wade is finally proposed for the analysis of accidental events. In an intercomparison analysis, the advantages of this approach with respect to ADS systems so far considered are discussed.

1. INTRODUCTION

In ADS systems it is generally assumed that the electrical current feeding the accelerator proton beam originates from the grid. On the other hand, in an accidental event, the safety of these systems is largely based on current interruption, it being generally assumed for ADS that the required reactivity compensations during reactor operation and burnup should be regulated through a current reserve, rather than through a control rod adjustment. In the case of a serious accident, if the current interruption device fails, the consequences may be severe. Various feedback mechanisms have been considered to alleviate
this difficulty, such as the flooding of the proton beam target due to the expansion of the coolant following its increased temperature. However, even if small, a marginal probability of serious consequences from such an event cannot be excluded.

In this work we consider an approach by which the probability of such an event is drastically reduced. Its principle is based on the coupling of the accelerator proton current, rather than to the external grid, to the electricity produced by the same reactor, except at startup conditions, for which an external electrical current of a relatively low intensity would be used.

There are a number of ways for realizing a full coupling by which channeling to the accelerator a fraction of reactor power, fixed at a given time and slowly adjusted during burn-up to follow the subcriticality level evolution. A simple model would consist in the splitting of the secondary coolant loop into a production one, generating the electricity feeding the external grid, and a coupling one, generating the electricity feeding the accelerator. So, as a result, the smaller the overall power, the smaller the neutron source, and, vice versa, the larger the overall power, the larger the neutron source. This last circumstance is not desirable. So, it would be appropriate to introduce an additional device reducing the coolant flow into the coupling loop in case of power (and, then, coolant temperature) increase, and vice versa. Such device should be temperature controlled, the temperature increase being the main effect of a power rise. To make it intrinsically safe, rather than via an electronically based mechanism, a direct one exploiting the natural thermal expansion properties of metals should be adopted. Such additional device would play the role of an extra negative feedback, intrinsically associated with the power-accelerator current coupling.

It is implicit with the above model that a transient of overpower incident would consist in an inadvertent full opening of the coupling loop inlet. Such opening should be limited by design, not to surpass that corresponding to maximum available current (at and of life).

The subcritical systems equipped with such a current coupling device are identified as ACS, to distinguish them from subcritical ones driven by an independent external source, identified as ADS.

The equations governing the neutron density of ACS systems in a simple point model are defined. The analytical solutions obtained evidence the merits of the proposed power-current coupling.

The Wade's "balance of reactivity" method (Wade, 1986) has been extended to events relevant to ACS systems. A comparison between ACS and the corresponding ADS systems is made. The advantages of the proposed power-current coupling are evidenced.

2. ADS WITH POWER- CURRENT COUPLING (ACS)

The general, simplified point kinetics equations relevant to a subcritical system, assuming one group of delayed neutrons, may be written in the form:

\[
\frac{dn(t)}{dt} = -\frac{\bar{\rho}}{\ell} n(t) + \beta c(t) + q(t) \\
\]

\[
\frac{dc(t)}{dt} = \frac{\beta}{\ell} n(t) - \lambda c(t)
\]

where \(\ell\) is the prompt neutron lifetime while \(\bar{\rho}\) the subcriticality level, i.e.

\[
\bar{\rho} = 1 - K_{\text{eff}}.
\]
may be generally considered a function of (integrated and instant) power, i.e., accounting for burnup material changes (affecting the subcriticality) and power (prompt and delayed) feedbacks during transients.

In an ADS system the source \( q \) corresponds to the amount

\[
q = \xi n_o \eta P_o
\]  

(4)

where \( P_o \) is the power at nominal conditions (corresponding to neutron density \( n_o \)), \( \eta \) is the fraction of this power needed to feed the accelerator proton current \( i \), while \( \xi \) is the amount of source neutrons (in \( n_o \) units) produced per feed energy unit (quantity \( \xi \) is then independent of power changes). To compensate reactivity during operation and burnup, fraction \( \eta \) is (independently) adjusted by the operator to the power level requested.

Since the neutron source is proportional to the proton current, we may then write

\[
\delta q = \frac{\delta n}{\eta} = \frac{\delta i}{i}.
\]  

(5)

Let us consider an ADS system in which the neutron source is coupled with the power level. We shall identify it as ACS (Accelerator Coupled System). To minimize deviations from nominal power level, a self-regulating mechanisms is also considered. We then assume a neutron source given by the expression

\[
q(t) = n_o \xi \eta [1 - \gamma_o (P(t - t_{SP}) - P_o)] P(t - t_{SP})
\]  

(6)

where \( \gamma_o \) is an assigned positive coefficient, while \( t_{SP} \) is the time delay needed for the transformation of fission energy into proton current.

During the system life, also in this case there will be an (independent) regulation of the power fraction \( \eta \) for maintaining the prescribed power level.

At steady state conditions we may write

\[
-\frac{\rho}{\ell} n_o + n_o \xi \eta P_o = 0
\]  

(7)

which gives, normalizing the power so that \( P_o = 1 \),

\[
\eta = \frac{1}{\xi} \frac{\rho}{\ell},
\]  

(8)

which may be viewed as a "critical condition" for an ACS system. It gives, in fact, the (critical) value of the power fraction \( \eta \) such that the neutron generation chain at nominal level conditions is sustained.

Looking at ATWS (Accidental Transient Without Scram), there are several initiating events leading directly to power variations, for example, consequent on a change of control rod positions (if control rods are used for compensation of reactivity), or on an inadvertent change of the proton current, or on different accidental reactivity insertions.
2.1. TOC Event

First, let us consider a transient of power incident (TOC) consequent to an inadvertent insertion of the reserve current. We assume here for simplicity that the (subcriticality) level (\(\bar{\rho}\)) is not affected by power feedbacks.

For an ACS a TOC event (analogous to the TOP event of the IFR) may be defined as a current increase at nominal operation level, consequent to an erroneous regulation of the feed power fraction \(\eta\). This change may correspond, for instance, to the margin reserve \(\Delta \eta_{\text{TOC}}\) for compensating reactivity loss with burn-up.

At full reactivity compensation condition (end of life, hot operating reactor at nominal level conditions), the source term can be rewritten as

\[
\xi \eta \left(1 + \frac{\Delta \eta_{\text{TOC}}}{\eta}\right) \equiv \bar{\rho} \left(1 + \frac{\Delta \bar{\rho}_{\text{TOC}}}{\bar{\rho}}\right),
\]

(9)

\(\Delta \bar{\rho}_{\text{TOC}}\) being the increase of the subcriticality level to which the compensation margin \(\Delta \eta_{\text{TOC}}\) corresponds.

So, an incident affecting the current regulation may be viewed as corresponding "reactivity" insertion \(\Delta \rho_{\text{TOC}}\) (this quantity corresponds numerically to \(\Delta \bar{\rho}_{\text{TOC}}\), but is now viewed not as a subcriticality level increase, but rather as an increment of the multiplication coefficient).

In case of a TOC event, the neutron source may then be written, recalling Eq.(6),

\[
q(t) = n_o \bar{\rho} \left(1 + \frac{\Delta \rho_{\text{TOC}}}{\bar{\rho}}\right) \left\{1 - \gamma_o\left[P(t - t_{\text{SP}}) - 1\right]\right\} P(t - t_{\text{SP}}).
\]

(10)

Eqs. (1) and (2) are relevant to the neutron density \(n(t)\). We can easily transform them into corresponding equations relevant to the system power \(P(t)\) defined as

\[
P(t) = \kappa \nu \Sigma_{\text{fiss}} V_{\text{core}} C(t),
\]

(11)

\(\kappa\) being the number of energy units per fission, \(\nu\) the neutron velocity, \(V_{\text{core}}\) the core volume, and \(\Sigma_{\text{fiss}}\) the average fission macroscopic cross section.

If we assume a power normalization such that at nominal conditions (corresponding to neutron density \(n_o\)) it is \(P_o=1\), and having defined the quantity

\[
C(t) = \kappa \nu \Sigma_{\text{fiss}} V_{\text{core}} C(t),
\]

(12)

multiplying both sides of Eq. (1) and (2), with the source term given by Eq.(12), by \(\kappa \nu \Sigma_{\text{fiss}} V_{\text{core}}\), they may be rewritten as

\[
\frac{dP(t)}{dt} = -\frac{\bar{\rho} + \beta}{\ell} P(t) + \lambda C(t) + \frac{\bar{\rho}}{\ell} \left(1 + \frac{\Delta \rho_{\text{TOC}}}{\bar{\rho}}\right) \left\{1 - \gamma_o\left[P(t - t_{\text{SP}}) - 1\right]\right\} P(t - t_{\text{SP}})
\]

(13)
\[ \frac{dC(t)}{dt} = \frac{B}{\ell} P(t) - \lambda C(t) . \]  

(14)

If we assume here for simplicity that the reactivity is not affected by power feedbacks, the analytical solution can be found by the Laplace transformation only if \( \gamma=0 \). So, we analyze this case first.

ACS without Self-regulating Mechanism

Having set \( \gamma=0 \) and defined the transforms

\[ N(s) = \int_0^\infty P(t)e^{-st}dt \quad \Gamma(s) = \int_0^\infty C(t)e^{-st}dt , \]  

(15)

multiplying Eqs. (13) and (14) by \( e^{-st} \) and integrating, we find the algebraic equation system

\[ sN - 1 = -\frac{\bar{\rho} + \beta}{\ell} N + \lambda \Gamma + \frac{\bar{\rho}}{\ell} (1 + \frac{\Delta \rho_{TOC}}{\bar{\rho}})Ne^{-stSP} \]  

(16)

\[ s\Gamma - C_o = \frac{\beta}{\ell} N(t) - \lambda \Gamma \]  

(17)

Then

\[ N(s) = \frac{\ell \left\{ 1 + \frac{\lambda C_o}{s + \lambda} \right\}}{s\ell + \bar{\rho} - (\bar{\rho} + \Delta \rho_{TOC})e^{-stSP} + \frac{s\beta}{s + \lambda}} \]  

(18)

After the inverse Laplace-transformation, the solution can be written in the form

\[ n(t) = \sum_i A_i e^{\omega_i t} \]  

(19)

where \( \omega_i \) are roots of the characteristic equation (equalizing the denominator of Eq. (19) to zero), i.e.,

\[ (\omega + \lambda)\left\{ \omega + \bar{\rho} - (\bar{\rho} + \Delta \rho_{TOC})e^{-\omega t_{SP}} \right\} + \omega \beta = 0 \]  

(20)

Let us assume slow transitions for which \( |\omega| << \lambda \). To allow further approximations, let us also consider \( t_{SP} \sim 10 \text{ s} \) (which seems to be a reasonable value). Then \( \omega t_{SP} \ll 1 \), considering that the decay constant \( \lambda \sim 0.08 \text{ sec}^{-1} \). With a reasonable accuracy, we can use the following approximation:

\[ e^{-\omega t_{SP}} \approx 1 - \omega t_{SP} \]  

(21)

Finally, we obtain
The corresponding expression for a TOP event in a critical reactor is

\[ \omega = \frac{\Delta \rho_{\text{TOP}}}{\ell + \frac{\beta}{\lambda} + t_{\text{SP}}(\rho + \Delta \rho_{\text{TOP}})} \]  

(22)

The corresponding expression for a TOP event in a critical reactor is

\[ \omega = \frac{\Delta \rho_{\text{TOP}}}{1 + \frac{\beta}{\lambda}} \]  

(23)

Comparing Eqs. (22) and (23), we may conclude that spallation neutrons can be considered as a "supplementary" group of delayed neutrons, which could be created "artificially" in accordance to deterministic safety requirements, taking into account that

- \( \rho_0 \) plays the role of a delayed neutron (like \( \beta \))
- \( t_{\text{SP}} \left(1 + \frac{\Delta \rho_{\text{TOP}}}{\rho}\right) \equiv t_{\text{SP}} \left(1 + \frac{\delta_1}{i}\right) \) plays a role similar to \( 1/\lambda \)
- \( t_{\text{SP}}(\beta + \Delta \rho_{\text{TOP}}) \) plays a role similar to \( \beta/\lambda \) and may be called "effective spallation neutron lifetime", as well as \( \beta/\lambda \) may be called the "effective delayed neutron lifetime"

The appearance of a relatively large "effective spallation neutron lifetime", makes all dangerous transitions slower, increasing with relatively large reactivity insertions.

For example, if \( \Delta \rho_{\text{TOP}} = 2\beta \approx 700 \text{ pcm} \) (BREST-type core (Orlov and Slessarev, 1988)) and \( K_{\text{eff}} = 0.95 \) then the "effective spallation neutron lifetime" can be assessed as 0.06 \( t_{\text{SP}} \) (that is 0.6 sec if \( t_{\text{SP}} = 10 \text{ sec} \)). It is of the order, or larger than the "effective delayed neutron lifetime" (\( \beta/\lambda \approx 0.03 \text{ sec} \) for Pu239-fuel and 0.08 sec for U235-fuel) and, of course, much larger than the prompt neutron lifetime (\( \ell \sim 10^{-7} \text{ sec} \)).

In an ACS rapid transients, for which \( \omega >> 1/t_{\text{SP}} \), may not occur. To show this, let us consider Eq. (22) and make \( \Delta \rho_{\text{TOP}} \to \infty \) (a mathematical exercise). It results \( \omega \to 1/t_{\text{SP}} \).

ACS with Self-regulating Mechanism

For \( \gamma_0 \), i.e., if we now assume the system operates with a self-regulating mechanism, Eqs.(13) and (14) have no simple solution, due to the nonlinearity introduced.

To get some insight into the system behavior due to this mechanism, we shall make a few simplifying assumptions, without detracting from the general conclusion of this qualitative analysis.

Let us first consider that all neutrons are prompt and set \( \beta = 0 \). Then, rather than the model represented by Eqs. (13) and (14), in which the effect of feed power changes are felt after of delay \( t_{\text{SP}} \), we shall consider a fictitious one in which the energy for the feed current is stored in a pool of reserve energy (of amount \( G \)), and released with a time constant \( \mu = \frac{1}{t_{\text{SP}}} \). The following governing equations can then be written
\[ \frac{dP}{dt} = -\frac{\bar{p} + \beta}{\ell} \rho P + \mu G + \lambda C \quad (24) \]
\[ \frac{dC}{dt} = \frac{\beta}{\ell} P - \lambda G \quad (25) \]
\[ \frac{dG}{dt} = \frac{\bar{p}}{\ell} \left(1 + \frac{\Delta \rho_{\text{TOC}}}{\bar{p}}\right) \left\{1 - \gamma_o [P - 1]\right\} P - \mu G \equiv \frac{\bar{p}}{\ell} \left(1 + \frac{\Delta \rho_{\text{TOC}}}{\bar{p}}\right) \left\{(1 + \gamma_o) P - \gamma_o P^2\right\} - \mu G. \quad (26) \]

We can easily transform these equations into the second order one

\[ \ell \frac{d^2P}{dt^2} + \left[\bar{p} + \ell (\mu + \beta)\right] \frac{dP}{dt} = \bar{\mu} \rho \left[\frac{\Delta \rho_{\text{TOC}}}{\bar{p}} - \gamma_o \left(1 + \frac{\Delta \rho_{\text{TOC}}}{\bar{p}}\right)(P - 1)\right] P, \quad (27) \]

where, denoting by \( G_o \) and \( C_o \) the values of \( G \) and \( C \) at \( t=0 \),

\[ \bar{\mu} = \frac{\lambda G + \lambda C}{G + C} \equiv \frac{\mu G_o + \lambda C_o}{G_o + C_o} = \frac{\lambda (\bar{p} + \beta)}{\lambda \bar{p} + \mu \beta} \]

There isn't a simple analytical solution also for Eq.(27), for the nonlinear term at its right hand side. Since \( \ell \ll 1 \), we may assume that the terms containing \( \ell \) can be neglected. We obtain

\[ \frac{dP}{dt} = \frac{\bar{p}}{\bar{p} + \beta} \bar{\mu} \left[\frac{\Delta \rho_{\text{TOC}}}{\bar{p}} - \gamma_o \left(1 + \frac{\Delta \rho_{\text{TOC}}}{\bar{p}}\right)(P - 1)\right] P, \quad (28) \]

which has the solution (recalling that \( P=1 \) at \( t=0 \))

\[
\Delta \rho_{\text{TOC}} \left(\frac{\lambda \mu}{\lambda \Delta \rho + \mu \beta} \left[e^{\frac{\lambda \mu}{\lambda \Delta \rho + \mu \beta} \left[\Delta \rho_{\text{TOC}} + \gamma_o (\bar{p} + \Delta \rho_{\text{TOC}})\right]^t} - 1\right] \right) \\
\frac{P - 1}{\Delta \rho_{\text{TOC}} + \gamma_o (\bar{p} + \Delta \rho_{\text{TOC}}) e^{\frac{\lambda \mu}{\lambda \Delta \rho + \mu \beta} \left[\Delta \rho_{\text{TOC}} + \gamma_o (\bar{p} + \Delta \rho_{\text{TOC}})\right]^t}} \quad (29)
\]

For \( t \to \infty \), this solution converges to

\[ P_{\text{AS}} = 1 + \frac{\Delta \rho_{\text{TOC}}}{\gamma_o (\bar{p} + \Delta \rho_{\text{TOC}})} \quad (30) \]
which corresponds also to its maximum value. In fact at the value $P_{AS}$ the first order derivative vanishes, as may be easily seen from Eq.(28). So, from this simplified example, we may generally say that the introduction of a self-regulating mechanism may, to a certain extent, help slowing the power increase rate, as well as to limit its asymptotic value.

We note that if in Eq. (29) we set $\gamma_o=0$, we obtain an exponential solution with a time constant consistent (apart a second order effect) with that expressed by Eq. (22) for an ACS without self-regulating mechanism, and with the same assumptions ($\beta=0$ and $\ell$ negligible).

Instant Insertion of Proton Margin Current

Consider a TOC event in an ACS, or in an ADS system. This insertion would cause a rapid power growth which can be estimated by means of Eq. (13). If we takes $P$ as the power after the rapid transition (before it is $P_o=1$), (no feed-back effects being here taken into account) and set all derivatives equal to zero ("prompt power jump approximation", i.e., at times at which no delayed effects have yet occurred), we easily find,

$$\Delta P = \Delta \rho_{TOC} \frac{\beta + \beta}{\bar{\rho} + \beta}. \quad (31)$$

For a corresponding TOP event in a critical reactor, if we assume that the reactivity $\Delta \rho_{TOP} < \beta$, we obtain the following expression

$$\Delta P = \Delta \rho_{TOP} \frac{\beta}{\beta - \Delta \rho_{TOP}}. \quad (32)$$

We may note in this case a much higher power growth than in a corresponding ADS, assuming similar margin reactivity values.

Reactivity Insertions into ADS

Let us now consider the possibility of an accidental reactivity insertion in an ADS. This might occur, for instance, if we assume to use control rods to compensate reactivity changes during operation and/or burnup. An inadvertent control rod extraction could produce a fast TOP event.

For an ACS, as well as for an ADS, we easily find

$$\omega_1 = \frac{\Delta \rho_{TOP} - \bar{\rho}}{\ell + \frac{\beta}{\lambda}} \quad \text{(if } \omega<<\lambda, \text{ far from criticality)} \quad (33)$$

$$\omega_2 = \frac{\Delta \rho_{TOP} - \bar{\rho} - \beta}{\ell} \quad \text{(if } \omega>>\lambda, \text{ approaching, or exceeding criticality)} \quad (34)$$

The power rise corresponding to the prompt-jump approximation results
\[
\Delta P = \frac{\Delta \rho_{\text{TOP}}}{\bar{\rho} + \beta - \Delta \rho_{\text{TOP}}} \quad (35)
\]

Confronting with Eqs. (32), one can see a much smaller neutron density jump in a ADS system than in a critical reactor. However, confronting with Eq. (31), we may see that this jump is significantly higher than that relevant to a corresponding \( \Delta \rho_{\text{TOC}} \) accident.

One can conclude that a power adjustment procedure by changing the proton current is less dangerous than a reactivity compensation by control rod movements regarding TOP accidents. Hence, regarding deterministic safety criterion, it would seem safer to avoid for an ADS the utilisation of control rods for operation and core life reactivity compensations.

2.1. TOC. Choice of Initial ADS Subcriticality Level

Economic parameters as well as technical constraints for accelerators demand to reduce as much as possible the subcritical level of ADS systems. On the other hand, an adequate low subcriticality level in many circumstances can be a key factor in meeting adequate safety requirements.

For the proper choice of an initial subcriticality level capable to effectively limiting the consequences of a TOC event, we can use Eq. (31). Considering an ACS (in which no control rods exist), having assumed a permissible power jump (\( \Delta P \)) limit, and the \( \Delta \rho_{\text{TOC}} \) value corresponding to the design, we obtain

\[
\bar{\rho} = \frac{\Delta \rho_{\text{TOC}}}{\Delta P} - \beta \quad (36)
\]

As we may see, the smaller the \( \beta \) value, the larger the subcriticality level (\( \bar{\rho} \)) required for the same admissible \( \Delta P \) level.

In the case for ADS transmuters, or incinerators of TRU, fed with solid fuel, the subcriticality level (and then the current intensity requirement) is relatively high, on one side for the large reactivity swing during the core life (with the consequent large value of \( \Delta \rho_{\text{TOC}} \)) associated with these systems, and, on the other side, by the decreasing of the \( \beta \) value due to the significant presence of minor actinides. Frequent reloadings would help, but, they are economically "expensive".

For preventing the occurrence of overcritical states, the initial subcriticality level (\( \bar{\rho} \)) should in any case be larger than the value (\( \Delta \rho_{\text{TOC}} - \beta_{\text{eff}} \)). The well known \( \beta_{\text{eff}} \) quantity has been here considered, since it is this "weighted" quantity which indicates the "reactivity" associated with the delayed neutrons.

Always looking at Eq. (36), it appears that ADS systems fuelled with liquid (molten salt) fuel have the significant advantage of working safely in the vicinity of \( \rho_0 \sim \beta_{\text{eff}} \) (that is \( K_{\text{eff}} \) (BOL) \( \sim K_{\text{eff}} \) (EOL) \( \sim 0.995 \)) without threat of important TOC-events. The requirements for a proton current can be reduced by a factor of 10-100 with respect to the corresponding systems with solid fuel.

3. BALANCE OF REACTIVITY

Extensive safety analyses of critical systems was made since the late 80's at the Argonne National Laboratory, specifically with respect to the Integrated Fast Reactor (IFR), using a synthetic, quite effective deterministic method based on a "balance of reactivity" asymptotic approach (Wade, 1986). In
the present paper an attempt is made to extend this methodology so to include also the ACS systems. A previous work (Gandini, Salvatores and Slessarev, 1999) has been done using this methodology in relation to ADS ones. This would allow to estimate the peculiarities of the ACS, with respect to a corresponding ADS and critical systems.

Wade's approach, proposed for fast critical reactors, consists in writing a balance of reactivity ($\rho$), i.e.,

$$\rho = (P - 1)A + \left(\frac{P}{F} - 1\right)B + \delta T_{in}C + \delta \rho_{ext} = 0$$

(37)

where:

- $P$ and $F$ are power and coolant flow (normalized to unity at operating conditions)
- $\delta T_{in}$ is the change from normal coolant inlet temperature $T_{in}$
- $C$ is the inlet temperature reactivity coefficient
- $(A+B)$ is the reactivity coefficient experienced in going to full power and flow from zero power isothermal at coolant inlet temperature
- $B$ is the power/flow reactivity coefficient
- $\delta \rho_{ext}$ is an external reactivity insertion.

In Eq. (37) it is assumed that convergence (criticality) has been reached asymptotically. There are circumstances in which this may not be physically possible, as, under certain conditions, in presence of a scram intervention, implying a strong negative reactivity insertion (in this case $\delta \rho_{ext} = -|\Delta \rho_{scram}|$), or a current interruption (for a TOC event, corresponding to a reactivity insertion $-\bar{\rho}$, i.e., equivalent to the subcriticality level). This occurrence may be identified, since in these cases the resulting values $\delta T_{in}$ or $P/F$, in LOHS and LOF events (with scram intervention), respectively, lose physical sense (being negative).

An important quantity to be analyzed is the coolant output temperature $T_{out}$. If by $\Delta T_c$ we denote the coolant temperature rise at nominal full power/flow ratio, the coolant outlet temperature change $\delta T_{out}$ is defined by the expression

$$\delta T_{out} = \delta T_{in} + \left(\frac{P}{F} - 1\right)\Delta T_c .$$

(38)

3.1. Extension to ACS Systems

Let us consider an ACS system at equilibrium condition after a (power limited) transient. From Eq. (13), setting $\frac{\Delta \rho_{TOC}}{\bar{\rho}} = 0$, and recalling that $\frac{\bar{p}}{\ell} = \xi \eta$, at steady state, nominal conditions we may write (recalling that the term containing $\gamma_o$ vanishes since $P_o=1$)

$$-\frac{\bar{p}}{\ell} P_0 + \xi \eta P_0 = 0 .$$

(39)
which corresponds to a power balance homogeneous equation relevant to a "critical" system (with a "delayed" power source term $\xi \eta P_o$).

After a power transient produced by an accidental event, implying generally changes 
$(\rho_{ext} + \rho_{feedback})$ of the reactivity, and/or $\delta \eta$ of the coupling parameter $\eta$ (in case of malfunctioning of the coupling mechanism), an equilibrium conditions is generally reached, at which the new power level $P$ is governed by the equation (recalling that at nominal conditions $P_o = 1$):

$$-\bar{\rho} + \frac{\rho_{feedback}}{\ell} + \rho_{ext} P + \xi(\eta + \delta \eta)\left[1 - \gamma_o(P - 1)\right] P = 0 .$$ (40)

$\bar{\rho}$ being the subcriticality level before the transient.

Recalling [see Eq. (37)] the expression of the power feedbacks, and that $\ell \xi \eta_o = \bar{\rho}$, we may then write the reactivity balance equation for an ACS system (with self regulating mechanism), i.e.,

$$(P - 1)A + \left(\frac{P}{F} - 1\right)B + \delta T_{in} C + \delta \rho_{ext} + \ell \xi \delta \eta - \gamma_o(\bar{\rho} + \ell \xi \delta \eta)(P - 1) = 0$$ (41)

In transients in which $\delta \eta = 0$, as is the case of loss of flow (LOFWS), loss of heat sink (LOHSWS), and reactivity insertion (TOPWS) events without shut off of the proton current, the behavior of an ACS system will be similar to that of a critical one in analogous circumstances (in this case without control rod intervention), with an added (negative) feedback, if $\gamma_o \neq 0$.

Below we give the expressions of $\delta T_{out}$ for different cases, obtained for the ACS from Eq. (41) and (38).

### 3.2. LOHS (Loss of Heat Sink)

In this case the inlet temperature $T_{in}$ increases while the coolant flow remains constant. A dynamic study should be done to analyze the heat balance evolution. However, some qualitative considerations can be made.

- **The current is shut off.**

  The coolant flow remains unchanged, while $P \to 0$. It is found\(^7\), since in this case $\delta \eta = -\eta_o$, and recalling that in this case the outlet temperature $T_{out}$ collapses into $T_{in}$,

  $$\delta T_{out} = \delta T_{in} - \Delta T_c = \left(\frac{A + B + \bar{\rho}}{C \Delta T_c} - 1\right)\Delta T_c$$ (42)

  which correspond to the analogous expression for a corresponding ADS system (Gandini, Salvatores and Slessarev, 1999).

\(^7\) Expression (42) is valid if an equilibrium (critical) condition can be reached. Otherwise, the $\delta T_{in}$ value would result negative, i.e., out of physical sense.
- The current fails to be shut-off (LOHSWS, Loss of Heat Sink Without current Shut-off).

From an ADS it can be shown that in this case the power is sustained down to a lower limit proportional to $\bar{\rho}$. The integrated energy, if not adequately absorbed by the system heat capacity, may lead to unacceptable temperature levels (Gandini, Salvatores and Slessarev, 1999). On the contrary, for an ACS the expressions for $\delta T_{in}$ and $\delta T_{out}$ are given by

$$\delta T_{out} = \delta T_{in} - \Delta T_c = \left(\frac{A + B}{C \Delta T_c} - 1\right) \Delta T_c .$$

(43)

This indicates a clear advantage of an ACS with respect to a corresponding ADS system.

3.3. TOC (Transient of Over-power by Current Insertion)

For an ADS a TOP event (analogous to the TOP-WS event of a critical system, like the IFR) may be defined as a current increase ($\Delta i_{TOC}$ for an ADS and $\Delta \eta_{TOC}$ for an ACS). This change may correspond, for instance, to the current reserve for compensating reactivity loss with burn-up. The coolant flow $F$ remains unchanged.

- Short term ($T_{in}$ unchanged)

For an ADS, assuming that $\left(\frac{\Delta i_{TOC}}{i}\right)$ is a small quantity with respect to unity, we obtain (Gandini, Salvatores and Slessarev, 1999)

$$\delta T_{out} = -\frac{\Delta \rho_{TOC}}{(A + B) - \bar{\rho}} \Delta T_c ,$$

(44)

where we have written $\bar{\rho}$ and $\Delta \rho_{TOC}$ in place of $\xi/\eta$ and $\left(\xi/\eta \frac{\Delta i_{TOC}}{i}\right)$, respectively.

Given a reactivity margin ($\Delta \rho_{TOC}$) to be accommodated as a current reserve, a large value (in absolute terms) of the sum (A+B) would be desirable. The subcriticality condition also significantly helps under this respect.

For an ACS, we obtain, replacing $\ell \xi \Delta \eta_{TOC}$ with $\Delta \rho_{TOC}$,

$$\delta T_{out} = -\frac{\Delta \rho_{TOC}}{A + B - \gamma_0 \bar{\rho}} \Delta T_c ,$$

(45)

i.e., as in a corresponding critical reactor, with the added (negative) term $-\gamma_0 \bar{\rho}$ at the denominator at the right hand side. Since we may well assume that $\gamma_0 \bar{\rho} < \bar{\rho}$, there is some advantage for the ADS under this respect.
- **Long term (P→1)**

\[ \delta T_{\text{in}} \text{ gradually increases until an adequate subcriticality is reached. It is found, as for the ADS case (Gandini, Salvatores and Slessarev, 1999),} \]

\[ \delta T_{\text{out}} (= \delta T_{\text{in}}) = - \frac{\Delta \rho_{\text{TOC}}}{C}. \quad (46) \]

**3.4. LOF (Loss of Flow)**

With this event the inlet temperature \( T_{\text{in}} \) is assumed not to change while the coolant flow will coast down to natural circulation. A dynamic study should also here be done to analyze the heat balance evolution. However, some qualitative consideration can be made.

- **The current is shut off.**

In this case \( P \rightarrow 0 \), and \( \delta \eta = - \eta_0 \). We obtain, at long term*,

\[ \delta T_{\text{out}} = \frac{A + \bar{p}}{B} \Delta T_c, \quad (47) \]

i.e., equal to a corresponding ADS case (Gandini, Salvatores and Slessarev, 1999).

- **The current fails to be shut-off** (LOFWS, Loss of Flow Without current Shut-off).

In this case in an ADS the power is sustained down to a lower limit. As with the LOHSWS case, the integrated energy, if not adequately absorbed via natural circulation, may lead to unacceptable temperature levels. At short range, the problem associated with the pump coast-down time (\( \tau \)), is aggravated for an ADS with respect to an IFR by the presence of the persistent external source which may be viewed as an amplification of the delayed neutron holdback problem (Gandini, Salvatores and Slessarev, 1999). For an ACS, it results,

\[ T_{\text{out}} = \frac{B(F_{\text{NC}} - 1)}{B + F_{\text{NC}}(A - \gamma_0 \bar{p})} \Delta T_c \quad (48) \]

This also indicates a clear advantage of an ACS with respect to a corresponding ADS system.

**3.5 CIT-WS (Chilled Inlet Temperature without Current Shut-off)**

A chilled inlet temperature, or overcooling event (the inverse of a LOHS), inducing a negative change \( \delta T_{\text{in}} \) of the coolant inlet temperature, may occur if a steam-line rupture overcools the secondary coolant which in turn overcools the primary core inlet temperature. At constant pump flow the resulting reactivity increase is compensated by a power increase with resultant core temperature rise increase.

*In this case, in analogy with what said for the LOHS with scram event, if the equilibrium convergence is not attainable, the P/F value would result negative, i.e., out of physical sense.
Since \( C \delta T_{in} \) is a small (positive) quantity with respect to unity, we obtain, assuming that the current is not shut off,

\[
\delta T_{out} = (1 - \frac{C \Delta T_c}{A + B - \gamma_0 \rho}) \delta T_{in} .
\]  

(49)

In this case \( \delta T_{out} \) results to some extent larger than in the ADS system

3.6. IOR-WS (Insertion of Reactivity without Current Shut-off)

The asymptotic power following an accidental reactivity insertion \( \delta \rho_{ext} \), in an ACS during normal operation, is likewise obtained as in the CITWS case. Since \( \delta \rho_{ext} \) may be assumed small with respect to unity, we may write, assuming that the current is not shut off,

\[
\delta T_{out} = \frac{- \delta \rho_{ext} \Delta T_c}{A + B - \gamma_0 \rho} ,
\]  

(50)

which again results to some extent larger than in the ADS system

3.7. Application

As an example of application of the power balance approach described above, the Russian lead cooled fast reactor BREST (Orlov and Slessarev, 1988) and, for a relative comparison, corresponding ADS systems with various degrees of subcriticality have been considered. The reactivity effects and other relevant characteristics are presented in the Table 1.

<table>
<thead>
<tr>
<th>Table 1. Effects and coefficients of reactivity for the BREST reactor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead density variation in the reactor ( \alpha_{Pb} )</td>
</tr>
<tr>
<td>Radial core expansion ( \alpha_R )</td>
</tr>
<tr>
<td>Assembly plate expansion ( \alpha_G = 2 \alpha_R ) (Wade, 1986)</td>
</tr>
<tr>
<td>Axial fuel elements expansion ( \alpha_E )</td>
</tr>
<tr>
<td>Doppler effect at nominal fuel temperature ( \alpha_D )</td>
</tr>
<tr>
<td>Temperature effect of reactivity ( \Delta \rho_{TER} )</td>
</tr>
<tr>
<td>Power effect of reactivity ( \Delta \rho_{PER} )</td>
</tr>
<tr>
<td>Neptunium effect of reactivity ( \Delta \rho_{Np} )</td>
</tr>
<tr>
<td>Change of isotopic composition due to burnup ( \Delta \rho_{FBE} )</td>
</tr>
<tr>
<td>Operational reactivity margin ( \Delta \rho_{OP} )</td>
</tr>
<tr>
<td>Total reactivity margin ( \Delta \rho_{TOP} )</td>
</tr>
<tr>
<td>Effective fraction of delayed neutrons ( \beta_{eff} )</td>
</tr>
<tr>
<td>Prompt neutron lifetime</td>
</tr>
</tbody>
</table>

Coolant (lead) parameters:

- inlet temperature - 420 °C,
• outlet temperature - 540°C,
• coolant normal heating ΔT_C = 120°C.
• difference between average fuel and average coolant temperature T_i = 500°C

One can use the following expressions to calculate coefficients A, B and C (Wade, 1986):

\[
A = (\alpha_D + \alpha_E) T_f = -0.75 \beta_{eff} \\
B = (\alpha_D + \alpha_E + \alpha_{pb} + \alpha_R) \times (\Delta T_C/2) = -0.17 \beta_{eff} \\
C = (\alpha_D + \alpha_E + \alpha_{pb} + \alpha_G) = -0.0049 \beta_{eff}/\text{grad}
\]

where \(\alpha_G\) is the temperature coefficient relevant to the fuel supporting plate.

TOP event

Since one of the possible use of ADS is that of transmutating (incinerating) TRU fuel, systems with solid fuels may be assumed to have a significant burnup reactivity swing, due to the limited breeding available in this case. So, in the example considered, the value \(\Delta \rho_{TOP} = 2 \beta_{eff}\) has been assumed.

In a TOP event scenario relevant to a critical reactor it is assumed that all rods run out, this introducing a positive reactivity instantly, in a TOC event scenario relevant to an ADS the accelerator produces the maximum proton current instantly, the coolant flow inlet temperature remaining fixed in both cases at short/intermediate state. All this causes a rise of power and, then, of outlet temperature. As time goes on, the inlet temperature starts to rise because the plant cannot absorb the amount of heat produced. In the ideal case, the inlet temperature would increase enough to reduce the power back to its initial level. This corresponds to an asymptotic state.

Table 2 and 3 present the results relevant to different levels of subcriticality for ADS, ACS, and for critical

| Table 2. TOP parameters (\(\Delta \rho_{TOC}\) or \(\Delta \rho_{TOP} = 2 \beta_{eff}\)) at short/intermediate |
|-----------------------------------------------|--|--|
| ADS | ACS | Critical reactor |
| \(\bar{\rho} = 10 \beta_{eff}\): | | |
| \(P = 1.18\) | | |
| \(\delta T_{out} = 20^\circ C\) | | |
| \(T_{out} = 560^\circ C\) | | |
| \(\bar{\rho} = 5 \beta_{eff}\): | All values \(\bar{\rho}\): like the critical reactor, if \(\gamma_c = 0\) | |
| \(P = 1.32\) | | |
| \(\delta T_{out} = 40^\circ C\) | | |
| \(T_{out} = 580^\circ C\) | | |
| \(\bar{\rho} = 2 \beta_{eff}\): | | |
| \(P = 1.60\) | | |
| \(\delta T_{out} = 75^\circ C\) | | |
| \(T_{out} = 615^\circ C\) | | |
| | | \(P = 3.2\) |
| | | \(\delta T_{out} = 260^\circ C\) |
| | | \(T_{out} = 800^\circ C\) |
reactors with similar parameters, for TOC and TOP events at short/medium and asymptotic terms, respectively, assuming that F remains unchanged (i.e., equal to unity). We note, in particular, that the rise of the outlet temperature asymptotically does not depend on the level of subcriticality, if the values $\Delta \rho_{\text{TOC}}$ and $\Delta \rho_{\text{TOP}}$ coincide.

At the beginning of a TOC transient (short/intermediate state), the ADS systems considered have an acceptable temperature rise, compared with a corresponding TOP event in a critical reactor. As expected, the outlet temperature is lower for the lowest $K_0$ state.

Considering asymptotic states, one can conclude that all systems (critical reactors or ADS) may be subject to an excessive temperature rise in correspondence with large $\Delta \rho_{\text{TOC}}$, or $\Delta \rho_{\text{TOP}}$ values, of the order of $\beta_{\text{eff}}$ or higher.

Table 3. Asymptotic parameters for TOP

<table>
<thead>
<tr>
<th>ADS and ACS</th>
<th>Critical reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>All values $\bar{\rho}$:</td>
<td>$P \approx 1$</td>
</tr>
<tr>
<td>$P \equiv 1$</td>
<td>$\delta T_{\text{out}} = 405^\circ C$</td>
</tr>
<tr>
<td>$\delta T_{\text{out}} = 405^\circ C$</td>
<td>$T_{\text{out}} = 945^\circ C$</td>
</tr>
<tr>
<td>$T_{\text{out}} = 945^\circ C$</td>
<td>$T_{\text{out}} = 945^\circ C$</td>
</tr>
</tbody>
</table>

LOHS-WS event

If the secondary heat exchange process is arrested, in a critical reactor the inlet temperature starts increasing. The negative reactivity effect induced by the inlet temperature rise is compensated by the positive one relevant to the power level decrease, up near zero-level. Assuming $F = F_0$, then $T_{\text{in}} \rightarrow T_{\text{out}}$.

For an ADS system, there is no equilibrium in the outlet coolant temperature. The outlet temperature is increasing constantly because the ADS power cannot approach zero level, notwithstanding significant feed-backs. The power is sustained down to a lower limit proportional to $\bar{\rho}$. This means that the lower the $K_{\text{eff}}$ value, and then the higher the neutron source (q), has been chosen, the higher will be the rate of the asymptotic outlet temperature increase.

For an ACS system, the behavior is quite similar to the critical reactor, and is maintained within an acceptable level.

In Table 4 the results relevant to the coolant asymptotic temperatures for LOHS-WS accidents are shown.

Table 4. LOHS-WS asymptotic parameters

<table>
<thead>
<tr>
<th>ADS</th>
<th>ACS</th>
<th>Critical reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>All values $\bar{\rho}$:</td>
<td>All values $\bar{\rho}$:</td>
<td>$\delta T_{\text{in}} = 190^\circ C$</td>
</tr>
<tr>
<td>No equilibrium in outlet coolant temperature</td>
<td>Like the critical reactor, if $\gamma_0 = 0$</td>
<td>$\delta T_{\text{out}} = 70^\circ C$</td>
</tr>
<tr>
<td>$T_{\text{out}} &gt; 1000^\circ C$</td>
<td>$T_{\text{out}} = 610^\circ C$</td>
<td>$T_{\text{out}} \rightarrow 0$</td>
</tr>
<tr>
<td>$P \rightarrow P_{\text{res}}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LOF-WS event

With this event the inlet temperature $T_{in}$ is assumed not to change while the coolant flow will coasts down to natural circulation.

The consequent raising power to flow ratio induces an increase of the core average temperature, this in turn inducing a negative reactivity feedback. This negative reactivity is compensated by a positive one induced by the power reduction. Asymptotically, a natural circulation flow $F_{NC}$ will be established.

For preliminary quantitative analysis, one can take $F_{NC} = 0.15 F_0$ at nominal core thermal parameters.

Table 5 presents the evaluation of power change as well as the outlet lead temperature growth for ADS and ACS at different levels of subcriticality, and for a corresponding critical reactor. The results show that the asymptotic temperature level for ADS is unacceptable.

Table 5. LOF-WS asymptotic parameters ($F_{NC} = 0.15F_0, P_0/F_0 = 1$)

<table>
<thead>
<tr>
<th>ADS</th>
<th>ACS</th>
<th>Critical reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho = 10 \beta_{eff}$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P = 0.93, \delta T_{out} = 625^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{out} = 1165^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P = 0.87, \delta T_{out} = 575^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{out} = 1115^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P = 0.78, \delta T_{out} = 505^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{out} = 1044^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All values $\rho$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>like the critical reactor, if $\gamma_o = 0$</td>
<td>$P = 0.48, \delta T_{out} = 260^\circ C$</td>
<td></td>
</tr>
<tr>
<td>$T_{out} = 800^\circ C$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CIT-WS event

With this event an inlet temperature decrease of $100^\circ C$ has been assumed. In Table 6 the results.

Table 6. CIT-WS asymptotic parameters

<table>
<thead>
<tr>
<th>ADS</th>
<th>ACS</th>
<th>Critical reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>All values $\rho$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P = 1.05, \delta T_{out} &lt; 10^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{out} = 550^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All values $\rho$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>like the critical reactor, if $\gamma_o = 0$</td>
<td>$P = 1.5, \delta T_{out} = 35^\circ C$</td>
<td></td>
</tr>
<tr>
<td>$T_{out} = 575^\circ C$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
are given relevant to the outlet coolant temperature. We may see that all systems have comparable behaviors.

## 4. GENERAL CONCLUSIONS

Some general concluding remarks can be made:

1. In ACS systems a large negative power coefficient \((A+B-\gamma_{\text{D}})\) would be required for reducing the consequences of TOC, CIT and IOR accidents, whereas, inversely, small one \((A+B)\) would be needed for limiting the consequences of LOHS-WS events. Besides, a large negative value \((A-\gamma_{\text{D}})\) is useful to limit the consequences of LOF-WS events. A trade-off between these contradictory requirements need to be found. The availability of an extra negative feedback \(-\gamma_{\text{D}}\) might be quite useful under this respect.

2. In case of LOHS-WS and LOF-WS events, the outlet temperature in an ADS may reach unacceptable values, whereas in an ACS system, as in a critical reactor, it can be maintained within safe limits.

3. A small current reserve is desirable (so that \(\delta_{\text{TOC}}\) is small), for reducing the consequences of TOC accidents (at small and long terms) in an ACS, as well as in ADS systems. This may be achieved (in a system assumed without reactor life control elements) by compensating the burn-up criticality swing by an adequate internal conversion ratio and burnable neutron poisoning.

4. For all events considered, the ACS seems to performs like, or better than a corresponding critical reactor (in particular retaining its property of reaching acceptable outlet coolant temperatures values in case of TOP-WS and LOHS-WS events), at the same time maintaining all the advantages of a subcritical system, under the point of view of safety (essentially due to a significantly large distance of \(K_{\text{eff}}\) from prompt criticality), and of incineration performance (due to the additional neutrons available for this purpose).

Basing on these preliminary indications, further research should be devoted to specific topics to enhance the safety performance of an ACS system, involving the design, materials, fuel distribution, source configuration, etc. Particular attention should be devoted also to the design of a self-regulating mechanism aimed at assuring a constant level of power during operation, as well as introducing an extra negative feedback effect.

## REFERENCES