The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1858-9

School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

19 - 30 November 2007

ADS Physics: Physics and Dynamics. Part III

Igor SLESSAREV

Mosco Physics & Enginnering Institute, Kurchatov Scientific Center and
CEA Cadarache, Reactor Physics Dept.
13108 St. Paul Lez Durance
France

SET II:
ADS SAFETY PHYSICS

CONTENT

II.4. SUB-CRITICAL SYSTEMS VERSUS CRITICAL REACTORS INTRINSIC SAFETY FEATURE MODELLING (EXAMPLE: MOLTEN SALT ADVANCED POWER PRODUCTION SYSTEM)

II.4.1. CHOICE OF THE SUBCRITICALITY LEVEL

II.4.2. ILLUSTRATION: SUBCRITICALITY AS A TOOL FOR INTRINSIC SAFETY ENHANCEMENT

Molten Salt Reactor model. Molten salt ADS kinetics. Fast Spectrum System: Thermo-Hydraulics And Feedbacks. Subcriticality Level aiming to Enhance Intrinsic Safety Features.

Unprotected Anticipated Transients. Reference Cores For Transient Simulation: Fast-Spectrum Molten Salt ADS. Unprotected transients in the fast-spectrum systems. Unprotected Transients Over Power/Transients Over Proton Current. Unprotected Loss Of Fuel Flow (ULOF). Unprotected Loss Of Heat Sink (ULOHS) Transients.

Discussion.

SET II.1

INTRODUCTION: CHALLENGES FACING NUCLEAR POWER

The current stagnation of the Nuclear Power (NP) is evident, but one may anticipate that this tendency has a temporal character.

There is still no real alternative for replacement of traditional fuels, principally hydrocarbons, which will be exhausted in the nearest future.

Even in these “favorable” conditions, the future nuclear technology has to meet some exigent requirements to be publicly acceptable and to take its own place in the pattern of the world’s energy production.

These requirements for the future nuclear technology are explicitly formulated in the framework of the **International Generation IV Forum**:

- ***Safety/reliability***

The future reactor design has to supply intrinsic safety and fault tolerance. It is imperative to exclude severe accidents with large radiation releases under conditions of any equipment failure, external impact or human error by using natural properties in nuclear reactor and their components.

- ***Long term sustainability***

A quasi-unlimited availability of fuel resources may be achieved due to the use of plutonium from spent nuclear fuel, through efficient use of natural uranium and thorium.

- ***Minimal nuclear waste***

The radiotoxicity of the waste issued from nuclear industry has to be minimized, ideally to the level comparable with the natural radiotoxicity of the extracted uranium/thorium (preserving of the natural radiation balance).

- ***Economic competitiveness.***

It should be economically effective when compared with other competitors, in terms of low costs and fuel availability (e.g., fuel breeding, high efficiency of thermodynamic cycle, etc);

- ***Proliferation resistance***

Future fuel cycles should aim to minimizing the inventories and accessibility of weapon-useable materials.

So-called *intrinsic safety* is one of the fundamental approaches to achieve some of these goals.

Intrinsic safety

Strategies of minimization of risks related to nuclear energy production have been developed and refined over many years for conventional (critical) reactors.

The release of radioactivity caused by reactor core disruptions is considered as the most significant among all other risks.

As for heavy accidents in NP, the damage related to these events could be unacceptably high.

Therefore, their risk has to be either precisely defined and accepted or, even better, it has to be "zeroed". In this case, all depends on the safety means being used for reactor safety.

When only **"active engineering" and organizing safety means** are used then the problem of their reliability becomes a decisive one. In practice, for the quantitative assessment of risks the Probabilistic Safety Analysis (PSA) is the only suitable instrument to be used. However, being applied to reactor accident analysis, the PSA has an important shortcoming in assessment of real risks: there is neither sufficient operating experience nor convincing theoretical data to support it.

Nowadays an alternative *deterministic* (also, *intrinsic or natural*) *safety* approach is proposed. According to this approach declared firstly by A. Weinberg (1984) just after the Three-Mile-Island accident, the intrinsic safety principle is one of fundamental means to build the deterministically safe NP:

all *severe* accidents "should be intrinsically excluded *by the use of physical and chemical properties and behavior of the fuel, coolant and other reactor components*".

Deterministic safety approach has to be applied for excluding *severe* accidents, whereas Defence in Depth Principle has to be used to minimize the residual risks.

Intrinsically secure properties in the safety area imply so-called "MP+MU principle"– *minimum risk probability with minimum associated uncertainties* - in the case of abnormal internal and external events **for the account of "purposeful designed" fundamental reactor and fuel cycle characteristics**.

Respecting intrinsically secure features, the potential of the proper "deterministic" defence against unprotected anticipated internal events is evidently the most preferable: $MP + MU \approx 0 + 0$**.**

However, its practical realization is an arduous task.

Hybrids would allow making a decisive step to solve this problem.

HYBRIDES and DETERMINISTIC SAFETY PRINCIPLES

To enhance the deterministic safety the system has to be designed in an appropriate way using the intrinsic safety features: fuel, coolant, structure materials with the sufficiently large margins to loose their basic properties; "passive" safety means based on nature laws and corresponding designs.

Among other, they include the following recommendations:

- **favorable inherent reactivity feedbacks or favorable behavior (Hybrids !!!) to keep heat production and removal in the "friendly" balance;**

- **large margins to damage temperatures (i.e. large "viability" domain);**

- **minimal reactivity margin (reactivity reserves necessary to compensate in-core reactivity effects):**

  ideally: smaller than the fraction of delayed neutrons (ACS!); this excludes a fast runaway of reactor power under condition of any erroneous actions or failures in the reactivity control system;

COMMENTS:

The use of *hybrids*, where a *subcritical core* is associated with an *external* intensive *neutron source* (e.g. Accelerator-Driven Systems, fusion-fission hybrids,…), may offer a new opportunity to reach deterministic safety even for the systems for which the inherent safety-related drawbacks do not permit to attain this goal in critical configurations.

ADS SIMPLIFIED KINETICS

One group (delayed neutrons) kinetics equations for all hybrids :

$$\frac{dn(t)}{dt} = \frac{-\rho\ -\beta}{l} n(t) + \lambda C(t) + q(t)$$
$$\frac{dC(t)}{dt} = \frac{\beta n(t)}{l} - \lambda C(t)$$

n(t) is neutron density;

q (t) is the external source of spallation neutrons and

$\rho = (\frac{1}{K_{eff}} - 1)$ - the reactivity including the subcriticality level in an ADS.

Evidently, in order to prevent a dangerous fast power burst (TOP-type events), one needs to have the initial subcriticality level ρ_0 exceeding $\Delta\rho_{TOP}$ - β.

EXAMPLE:

FAST REACTOR AREA: PHENIX versus ADS with fast spectrum subcritical blanket

The time before core melting (T) as well as power maximum have been presented in Table: reactivity insertion 0.55 $=β/sec

Table 1. The time before core melting (T), maximum power P_{max} (in nominal power unit) for PHENIX and for "similar-core medium" ADS

	PHENIX	ADS
T seconds	2	12
Total reactivity insertion (dollars)	1.1	6.6
P_{max}	2.2	1.5

There is the specific type of heavy accidents in ADS when all margin of accelerator current has been inserted into ADS-core: so called Unprotected Transient Over Current (UTOC).

In critical reactors there is small (less 1 W) neutron source which does not play a role compared with the fission energy.

In ADS, this source is much more important, ADS power follows this source change instantly and this can cause the problems of stresses in the core structure.

ACS SYMPLIFIED KINETICS

In ACS, the external source depends on neutron density $q(t) \sim n(t-t_{SP})$ with the time delay t_{SP} required for transformation of fission energy to proton current.

Set of equations is "homogeneous-like" and similar to critical reactor kinetics.

For stationary conditions ($dn/dt = 0$, $\rho = \rho_0$, $K_{eff} = K_{eff,0}$):

$$q_0 = \frac{\rho_0 n_0}{l}$$

The most dangerous case:

all the margin in proton current is introduced in an ACS when subcriticality ρ_0 is minimum (at Beginning Of core Life - BOL) and K_{eff} is maximum.

$$\frac{dn(t)}{dt} = \frac{-\rho_0 - \beta}{l} n(t) +$$

$$\lambda C(t) + \frac{\rho_0}{l}\left[1 + \frac{\Delta\rho_{TOP}}{\rho_0}\right] n(t - t_{SP})$$

$$\frac{dC(t)}{dt} = \frac{\beta n(t)}{l} - \lambda C(t)$$

The solution of this system can be found by the Laplace transformation:

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

Then

$$N(s) = \frac{l\left\{n(0) + \frac{\lambda C(0)}{s+\lambda}\right\}}{sl + \rho_0 + \frac{s\beta}{s+\lambda} - \left(\rho_0 + \Delta\rho_{TOP}\right) e^{-t_{SP} s}}$$

After the **inverse Laplace-transformation**, solution is:

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

where ω_i are roots of the characteristic equation :

$$\omega l + \frac{\beta\omega}{\omega+\lambda} + \rho_0 = \left(\rho_0 + \Delta\rho_{TOP}\right) e^{-t_{SP}\omega}$$

Two types of transitions can be considered:

1. **slow** when $|\omega| << \lambda$ and
2. **rapid.**

Slow transients

If $t_{SP} \approx 10$ s (which seems to be a reasonable value) then

$(t_{SP} \times \omega) << 1$

because the decay constant for delayed neutrons λ is equal to $\approx 0.08\ s^{-1}$.

With a reasonable accuracy:

$$e^{-t_{SP}\omega} \approx 1 - t_{SP}\omega$$

FINALLY:

ACS	CRITICAL REACTOR
$\omega = \dfrac{\Delta\rho_{TOP}}{l + \dfrac{\beta}{\lambda} + \rho_0 t_{SP}\left(1 + \dfrac{\delta i_0}{i_0}\right)}$	$\omega = \dfrac{\Delta\rho_{TOP}}{l + \dfrac{\beta}{\lambda}}$

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

- **ρ_0 plays the role of a fraction of spallation neutrons in total neutron numbers (like the fraction of delayed neutrons β),**
- $t_{SP}\left(1 + \dfrac{\Delta\rho_{TOP}}{\rho_0}\right)$ or $t_{SP}\left(1 + \dfrac{\delta i_0}{i_0}\right)$ **play the role of a delay time (similar to 1/λ for delayed neutrons) and**
- $t_{SP}\rho_0\left(1 + \dfrac{\delta i_0}{i_0}\right) = t_{SP}(\Delta\rho_{TOP} + \rho_0) = l_{SP}$ **plays the role of the "life time of spallation neutrons"** in analogy with prompt neutron life time (l) and with the "traditional" delayed neutrons life time (β/λ).

The appearance of a relatively long "life time of spallation neutrons" $t_{SP}(\Delta\rho_{TOP}+\rho_0)$ makes dangerous transitions of the TOP-type in ACS slower than in critical reactors.

the rate of transients (ω) is defined by the expression :

$$\omega = \frac{\Delta\rho_{TOP}}{l_{SP} + l + \dfrac{\beta}{\lambda}} < \frac{\dfrac{\delta i_0}{i_0}}{t_{SP}\left(1 + \dfrac{\delta i_0}{i_0}\right)} \langle \frac{1}{t_{SP}}$$

Hence, Slow transient ACS kinetics favourable features:

"slow" transient rate never exceeds the following limit

$$\omega = 1/t_{SP}$$

and, unlike the situation with the "standard" delay effect, can be chosen to be optimal respecting safety.

Rapid transients. $\Delta\rho_{TOP} > \rho_0+\beta$

($\omega >> 1/t_{SP}$) and then

$$\omega = -\frac{\rho_0 + \beta}{l}$$

II.2. ON INTRINSIC SAFETY POTENTIAL OF ADS.

Safety Potential Assessment by asymptotic Reactivity Balance Consideration: extention of D. Wade's methodology so to include subcritical systems.

The approach consists of consideration of the balance of "asymptotic" reactivity after the transition

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

where

P and F are power and coolant flow,

δT_{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.

Usually, A, B , C are negative and

Doppler effect is dominating in A while

Doppler, void and fuel expansion effects - in B and

grid plate thermal dilation (core radial expansion) in C.

In Eq. (1), it is assumed that convergence (criticality) has been reached asymptotically.

$\delta\rho_{ext}$ **is an external reactivity insertion.**

Typical values for fast reactors of IFR-type are:

A = - 1.5 \$, B = - 0.5\$, C = - 0.005 \$/°C

Equilibrium conditions:

$$\bar{\rho} - (P-1)A - (P/F-1)B - \delta T_{in} C - \delta\rho_{ext} - \bar{\rho}\left(1 + \frac{\delta i}{i}\right) = 0 \qquad (2)$$

$\bar{\rho}$ is the subcriticality level (1-K_{eff}).

One of important quantities is the output temperature T_{out}.

If ΔT_C - the coolant temperature **rise** at nominal power/flow ratio, T_{in} -the coolant **inlet** temperature, then

the growth of T_{out} is defined by:

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

Returning back to analize

UNPROTECTED (without scram) TRANSIENTS.

ADS INTRINSIC SAFETYANALYSIS

Transients over-Power (UTOP) / Transients over-Current (UTOC).

One of the most dangerous for critical reactors is the ingress of all positive reactivity to cores without scram. Similar accident for subcritical systems (i.e. ADS) is the current increase (Δi_{TOC}) of the all reserve of current preparing for compensating of the reactivity loss, including burnup swings, temperature effect, operational margin, etc.

The coolant flow F remains unchanged in this model.

From (2), it follows that (T_{in} is unchanged) the asymptotic power P will increase comparing with its nominal value (P = 1):

$$P = 1 - \frac{\Delta\rho_{TOC}}{(A+B) - \overline{\rho}} \tag{3}$$

In the case of critical reactors, one has to put $\Delta\rho_{TOC} \rightarrow \Delta\rho_{TOP}, \overline{\rho} = 0$

The increase of the maximum coolant temperature:

$$\delta T_{out} = -\frac{\Delta\rho_{TOC}}{(A+B) - \overline{\rho}} \Delta T_C \tag{4}$$

Smaller reactivity margin and larger (in absolute values) A, B (higher Doppler and another negative temperature effects) as well as
larger subcriticality are desirable to minimise the asymptotic maximum temperature.

When δT_{in} gradually increases (the "long term" consideration, $P \rightarrow 1$) then

$$\delta T_{out} = -\frac{\Delta\rho_{TOC}}{C} \tag{5}$$

for both critical and subcritical cases, a large C value is desirable in this case.

FINALLY:

"short term"

System type	Critical	ADS
Asymptotic power (nominal value $P = 1$)	$P = 1 - \frac{\Delta\rho_{TOP}}{(A+B)}$	$P = 1 - \frac{\Delta\rho_{TOC}}{(A+B) - \overline{\rho}}$
Increase of the maximum coolant temperature δT_{out}	$\delta T_{out} = -\frac{\Delta\rho_{TOP}}{(A+B)}\Delta T_C$	$\delta T_{out} = -\frac{\Delta\rho_{TOC}}{(A+B) - \overline{\rho}}\Delta T_C$

Remark:

smaller reactivity margin and larger (in absolute values) A, B (higher Doppler and another negative temperature effects) as well as larger subcriticality are desirable to minimise the asymptotic maximum temperatures.

"long term"

System type	Critical	ADS
Asymptotic power (nominal value $P = 1$)	$P = 1$	$P = 1$
Increase of the maximum coolant temperature	$\delta T_{out} = -\frac{\Delta\rho_{TOP}}{C}$	$\delta T_{out} = -\frac{\Delta\rho_{TOC}}{C}$

Remark:

for both critical and subcritical cases, a large C value is desirable

Unprotected Loss of Flow (ULOF) – pumps stop

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

Two cases are possible:

The current is shut off (ADS), then P→0

$$\delta T_{out} = \left(\frac{A}{B} + \frac{\overline{\rho}}{B} \right) \Delta T_C \qquad (6)$$

This expression is also valid for critical reactors by zeroing the $\overline{\rho}$.

subcriticality helps reducing ($\frac{\overline{\rho}}{B}$ is negative) the maximum temperature with respect to critical reactors.

The current fails to be shut off (ADS):

In this case the power is sustained down to a lower limit. The integrated energy, if not adequately absorbed via the natural circulation, may lead to unacceptable temperature levels.
For a small natural coolant flow (~1% of the nominal flow):

$$P \propto \sqrt{-\frac{F_{NC}}{B}\overline{\rho}} \qquad (7)$$

Subcriticality could stimulate a dangerous level of power (compare, in critical reactors, P→0!) and, hence, the critical reactor behaviour during ULOF is potentially safer !!!.

Remark:

subcriticality helps (proton current "shut off case") reducing the maximum temperature with respect to critical reactors

FINALLY:

The current is shut off (ADS), long term:

System type	Critical	ADS
Increase of the maximum coolant temperature	$\delta T_{out} = \left(\frac{A}{B}\right)\Delta T_C$	$\delta T_{out} = \left(\frac{A}{B} + \frac{\bar{\rho}}{B}\right)\Delta T_C$

Remark:

subcriticality helps reducing the maximum temperature with respect to critical reactors

.

The current fails to be shut off (ADS):

System type	Critical	ADS
Asymptotic power (nominal value P = 1)	$P \rightarrow 0$	$P \propto \sqrt{-\frac{F_{NC}}{B}\bar{\rho}}$ at a modest natural flow (~1% of the nominal)
Increase of the maximum coolant temperature	$\delta T_{out} = \left(\frac{A}{B}\right)\Delta T_C$	*δT_{out} is continuously increasing if natural convection is limited*

Remark:

critical reactor behaviour during ULOF is potentially safer (respecting intrinsic safety features) in he case of current fails to be shut off.

Unprotected Loss of Heat Sink (ULOHS)

Proton current shuts off ,

the coolant flow remains unchanged, while $P \rightarrow 0$.

$$\delta T_{in} = \frac{A+B}{C} + \frac{\overline{\rho}}{C} \tag{8}$$

Since as power decreases, the outlet (maximum!) temperature T_{out} collapses into T_{in} ($T_{out} \approx T_{in}$)

$$\delta T_{out} = \left[\frac{(A+B)+\overline{\rho}}{C\Delta T_C} - 1 \right] \Delta T_C \tag{9}$$

For a subcritical system, there is a reduction of the maximum coolant temperature with the decreasing of (A+B)/C and the increasing of the negative term $\overline{\rho}/C$.

Subcritical system behaviour is safer, but it requires accelerator SHUT OFF

(non-deterministic approach!).

Proton current fails to be shut-off.

Power P is sustained down to a lower limit proportional to subcriticality level. The integrated energy may lead to unacceptable temperature levels.

FINALLY:

<u>Proton current shuts off ,</u>

System type	Critical	ADS
Increase of the maximum coolant temperature	$\delta T_{out} = \left[\frac{(A+B)}{C\Delta T_C} - 1\right]\Delta T_C$	$\delta T_{out} = \left[\frac{(A+B)+\bar{\rho}}{C\Delta T_C} - 1\right]\Delta T_C$

Remark:

In ADS, there is reduction of the maximum coolant temperature with decreasing of (A+B)/C and with increasing of a subcriticality level.

Subcritical system is intrinsically safer.
In the case of DEGRADATION of the DOPPLER (coef. A reduction) , SUBCRITICALITY is preferable!!!

<u>The current fails to be shut-off.</u>

System type	Critical	ADS
Increase of the maximum coolant temperature	$\delta T_{out} = \left[\frac{(A+B)}{C\Delta T_C} - 1\right]\Delta T_C$	Because of P is sustained down to a limit proportional to subcriticality level, δT_{out} *is continuously increasing if natural convection is limited*

Remark:

the critical reactor behaviour during ULOHS is intrinsically safer.

CONCLUSION:

- ***subcriticality can help to enhance safety features for majority of Unprotected AT if proton current is shut off.***

- ***subcriticality is useful to limit over-reactivity accidents (UTOP-type), however, critical reactor intrinsic safety features are preferable respecting "thermohydraulic" accidents (ULOF, ULOHS).***

INTRINSIC SAFETYANALYSIS: ACS versus ADS

ACS produce a "delay" between fission's and proton beam creating by fission energy.

This delay depends on the subcritical system particular design and can be optimised respecting desirable safety features.

As mentioned,

- subcriticality level $\overline{\rho}$ plays the role of "yield"(fraction) of delayed supplementary neutrons;
- $t_{SP}\left(\overline{\rho}+\Delta\rho_{TOC}\right)$ may be called the "effective delayed spallation neutron lifetime" similar to β/λ.

Instant insertion of whole proton current margin (UTOC)

instant power "jumps":

ADS/ACS	Critical reactors with similar core medium
$\Delta P = \frac{\Delta\rho_{TOC}}{\overline{\rho}+\beta}$	No UTOC

Instant insertion of whole margin of reactivity (UTOP)

instant power "jumps":

ADS/ACS	Critical reactors with similar core medium
$\Delta P = \frac{\Delta\rho_{TOP}}{\overline{\rho}+\beta}$	$\Delta P = \frac{\Delta\rho_{TOP}}{\beta-\Delta\rho_{TOP}}$
COMMENTS : smaller ADS/ACS power growth if assuming similar reactivity margin values	

Subcriticality could be consider as a favourable feed-back (like Doppler effect) **and is able to compensate even drastic degradation of safety characteristics of a system as in the case of TRU-incineration.**

Similar inter-comparisons between ADS and ACS show that the short-term transient behaviours are very similar for all UTOC.

Respecting "thermohydraulics" accidents , ACS behaviour is similar to critical reactors.

ULOF (no shut off of proton current):

ACS : $$T_{out} = \frac{B\left(F_{NC} - 1\right)}{B + AF_{NC}} \Delta T_C$$

while ADS behaviour can be **more dangerous**. This indicates a clear advantage of ACS with respect to a corresponding ADS.

COMMENTS:

The importance of spallation neutrons can be significantly enforced if they could be "transformed" (completely or partially) to a supplementary group of "delayed" neutrons.

II-3. NON-LINEAR COUPLED ADS

ACCELERATOR-blanket COUPLING DIVERSITY: Two coupling modes

Coupling can be realized via changing of energy of incident charged particles instead of the beam current intensity.

At least **two modes** of coupling between external neutron source and blanket could be envisaged:

1. ACS (I-mode)

One can modify the intensity of an external neutron source S by varying the proton beam current I_p at a fixed nominal value of the proton energy:

$$I_p = I_{p,0} \frac{P^{out}}{P_0^{out}}.$$

Here P^{out} is the output power of blanket (we assume for the simplicity, that $\eta_a = const$, $\eta_e = const$ and, therefore, the parameter P^{out} denotes either electric output power or thermal output power), and a subscript "0" denotes nominal values of the corresponding variables.
This mode of the "accelerator-blanket" coupling is designated as "*I*-mode".

2. NON-LINEAR COUPLING: ACS (E-mode)

any *change of the output power leads to a proportional change of the proton energy* ϵ_p at a fixed "nominal" value of the proton current:

$$\epsilon_p = \epsilon_{p,0} \frac{P^{out}}{P_0^{out}}.$$

The difference between the *E*- and *I*-modes is based on a *non-linear behavior of the neutron yield* Y_n *with respect to the proton energy* ϵ_p *variation* (hereafter "Y_n*-effect*").

When the energy of incident protons becomes higher than ~1 GeV,
the **neutron yield** normalized per incident proton energy

$$y_n\left(\epsilon_p\right) \approx \frac{Y_n\left(\epsilon_p\right)}{\epsilon_p}$$

becomes nearly constant and even slightly decreases with proton energy.

The value of proton energy $\epsilon_p^{optimum}$, which can be considered as "optimal" with respect to the neutron economy (i.e. the neutron yield (y_n) per one incident proton and per consumed energy reaches its maximal value.

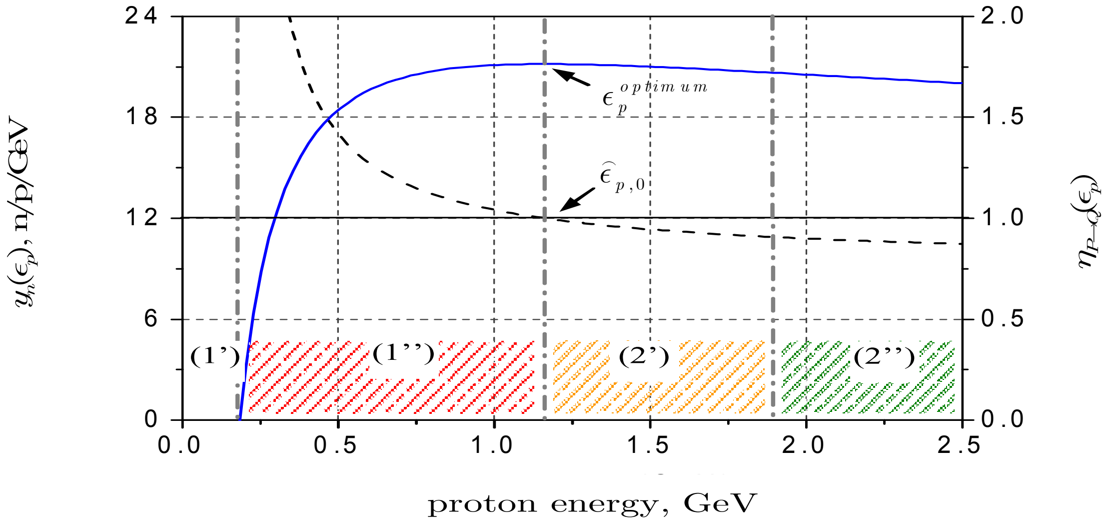


Fig. Dependence of the spallation neutron yield $y_n(\epsilon_p)$ (solid line) and that of the source effectiveness $\eta_{P\to Q}(\epsilon_p)$

PRINCIPLE OF THE OPERATION

The Y_n-effect can be compared to the Doppler feedback effect respecting the external source. Similarly as the Doppler feedback effect, the Y_n-effect is intrinsic. It would be quite advantageous for the system safety to have this supplementary feedback influencing on the entire neutron balance if the "standard" core feedbacks are degraded and can not play their stabilizing role indispensable for the intrinsic safety features.

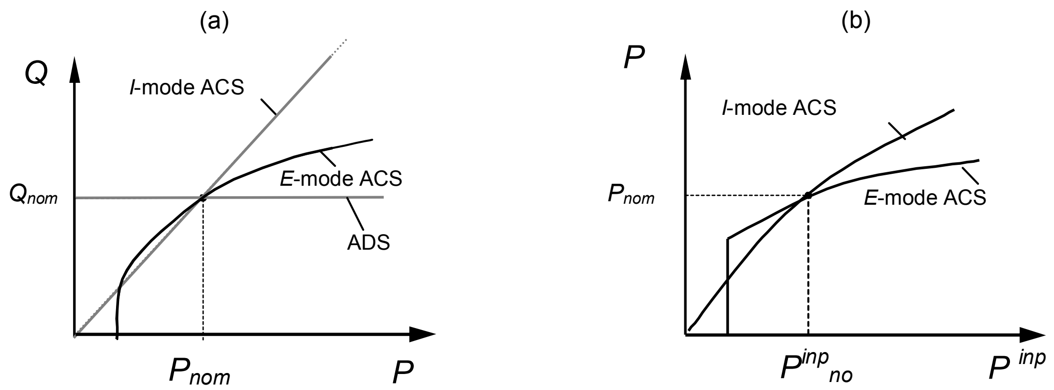


Fig. Diagrams of the intrinsic dependences of: (a) the external neutron production Q on the core power P, and (b) the equilibrium core power P on the accelerator power P^{inp} for different concepts of a coupled hybrid system.

CONCLUSIONS

- **ACS (E-mode) is based on the particularity of the neutron production forming a quasi-linear dependence between energy production in the core (coupled to the proton accelerator via its energy) and the external neutron yield Y_n in the spallation target (Y_n-effect).**

- **This dependence provides an auto-regulating behavior of the ensemble “accelerator – subcritical blanket”.**

  Kinetics of this system is similar to critical reactors with artificial group of delayed neutrons as in the case of the “ordinary” ACS.

  The external neutron production contains the “supplementary” feedback which is able to stabilize the power around its nominal value;

- **a significant improvement of the feedback effect due to non-linear coupling between the accelerator and subcritical blanket (denoted as *E*-mode coupling) could be achieved.**

The proposed Y_n-effect can be compared to the Doppler feedback. Similarly as the Doppler-effect, the Y_n-effect is intrinsic.

II.4. SUB-CRITICAL SYSTEMS VERSUS CRITICAL REACTORS: INTRINSIC SAFETY FEATURE MODELLING

II.4.1. ON the CHOICE OF the INITIAL SUBCRITICALITY LEVEL

Successful choice of the initial subcriticality level is very important respecting intrinsic safety.

Several practical situations can be taken into account when the subcritical level is being chosen:

Significant neutron production support – significant subcriticality level (≈ 10 - 20 β)

- **concept of breeders fed by natural Th-fuel**

EA of C. Rubbia ;

Innovative concepts of intrinsically secured reactors (see SET IV) ……………

The final choice depends upon neutron shortage of a system considered

2. Aiming intrinsic SAFETY POTENTIAL radical enhancement

- **in the cases of degradation of intrinsic safety of TRU-burners,**
- **reduction of dangerous feed-back effects (void effects)**

The level of subcriticality put a significant influence on transients.

In majority of unprotected transients, subcriticality reduces both power oscillations and the increase of core temperatures.

If all reactivity related transients were sufficiently slow, a significant improvement of the safety potential would be expected in terms of the extended the "grace" time.

In this case, subcriticality would have such a potential if the following basic choice of the subcriticality level is applied:

RECOMMENDATION

sum of absolute values of all independent in-core reactivity effects ($\Delta\rho_{tot}$) including their uncertainties plus the maximum reactivity insertions $\Delta\rho_{\mathrm{TOP}}^{\max}$ does not exceed the nominal level of subcriticality

$$r_0 = \left(1 - k_{eff,0}\right) / \, k_{eff,0},$$

i.e.

$$r_0 > \Delta\rho_{tot} + \Delta\rho_{\mathrm{TOP}}^{\max}.$$

II.4.2. ILLUSTRATION: SUBCRITICALITY
AS A TOOL FOR INTRINSIC SAFETY ENHANCEMENT

MOLTEN SALT ENERGY PRODUCER MODEL

- **Point-kinetic approximation of core neutronics;**

- **simplified "two-point" thermo-hydraulics in the cooling/energy generating circuit;**

- **"*external cooling*" scheme for reactor/ADS**

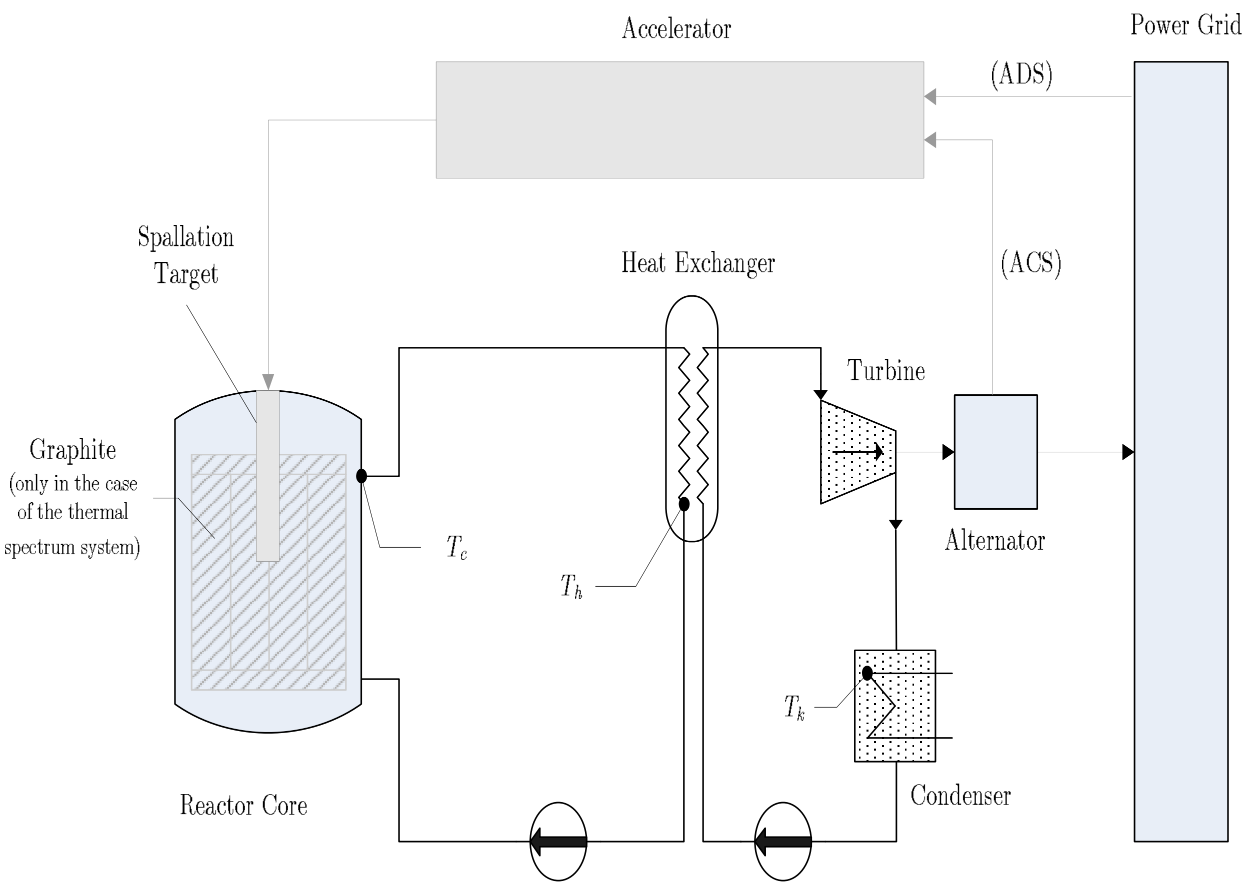


Fig. Simplified "two-point" thermo-hydraulics in the cooling/energy generating circuit.

MOLTEN SALT ADS/ACS KINETICS

The explicit expression for the external source depends on the realization of the hybrid system (coupled or independent source).

For **ADS** (normalized to the nominal reactor power P_0):

$$S^{(ADS)}(t) = \frac{r(t)}{\Lambda} P_0, \text{ where } r(t) = r_0 + \Delta\rho_{\text{TOC}}(t).$$

$r_0 = -\rho_0 = \left(1 - k_{eff,0}\right) / k_{eff,0}$ is the *nominal (initial) subcriticality level*, $\Delta\rho_{\text{TOC}}$ describes the perturbation of the external neutron source due to variations of the proton beam current.

For **ACS**,

$$S^{(ACS)}(t) \propto P^{out}(t).$$

(It is supposed that electric energy is produced immediately after the first cooling loop)

Newton cooling model:

$$P^{out}(t) = P_0 \frac{\left(T_h(t) - T_k\right)}{\left(T_{h,0} - T_k\right)},$$

where T_h is the temperature of salt in the heat-exchanger and T_k is the temperature of the heat sink (e.g. the temperature of steam in a condenser).

Hence:

$$S^{(ACS)} = \frac{r(t)}{\Lambda} P_0 \frac{\left(T_h(t) - T_k\right)}{\left(T_{h,0} - T_k\right)}.$$

FINALLY:

$$\rho(t) = -r_0 + \Delta\rho_{\mathrm{TOP}}(t) + \Delta\rho_{feedback}(t).$$

FAST SPECTRUM SYSTEM: FEEDBACKS

$$\Delta\rho_{feedback}^{Doppler}(T) = \int_{T_0}^{T} \frac{K_D(T_0)}{T} dT = K_D(T_0)\ln\left(\frac{T}{T_0}\right).$$

K_D is the Doppler constant,
T is the fuel temperature and
T_0 is the fuel temperature at nominal conditions.

UNPROTECTED ANTICIPATED TRANSIENTS in MOLTEN SALT ENERGY PRODUCERS

The control of subcritical systems has the following peculiarity – these systems can use either mechanical rods, or the proton current variation mechanisms. In both cases, different failures could provoke some transients.

Presence of control rods requires the subcriticality level correction, while the use of proton current correction does not cause the reactivity change and the subcriticality level r_0 is allowed to be smaller.

Salt boiling temperature of 1300°C was chosen as the disruption criterion for the molten salt systems, i.e. $T^{\dagger} = 1300°\mathrm{C}$ is assumed to be the maximal limit of acceptable core temperature.
The lower limit of acceptable parameters is the temperature of fuel solidification of $450°\mathrm{C}$.

Reference Core Parameters For Transient Simulation: Fast-Spectrum Molten Salt ADS

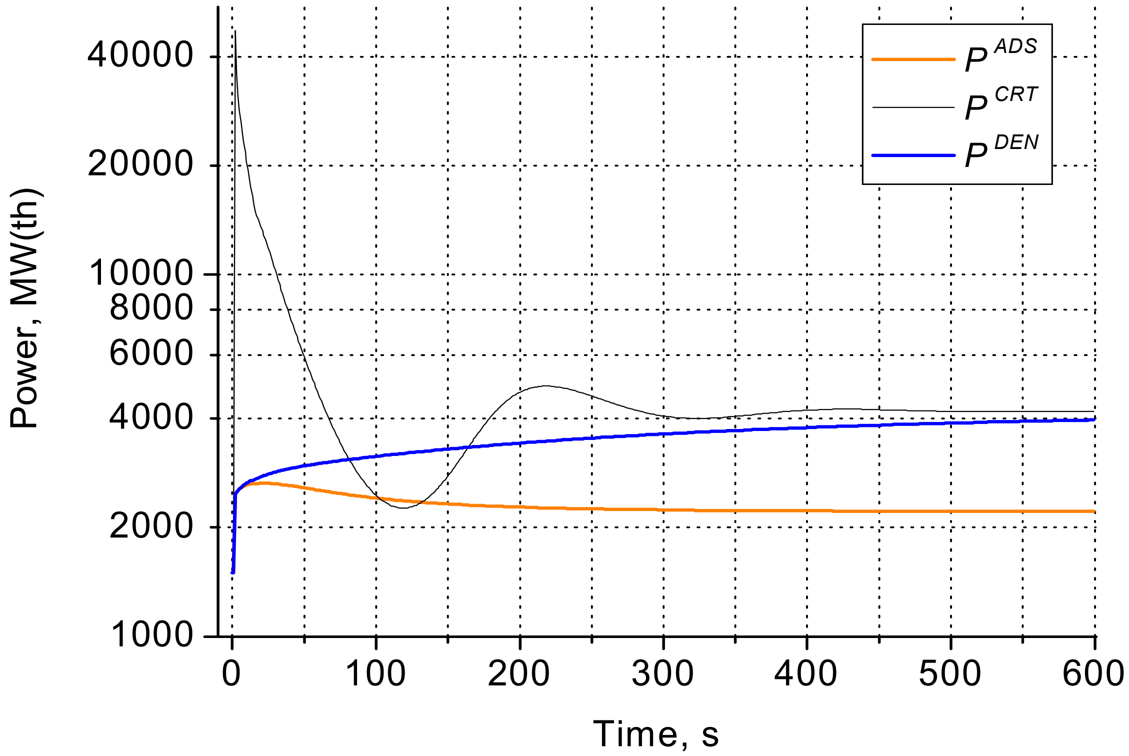
Following the recommendations, the subcriticality levels both for ADS and ACS has to be approximately chosen for FAST MOLTEN SALT ENERGY PRODUCER:

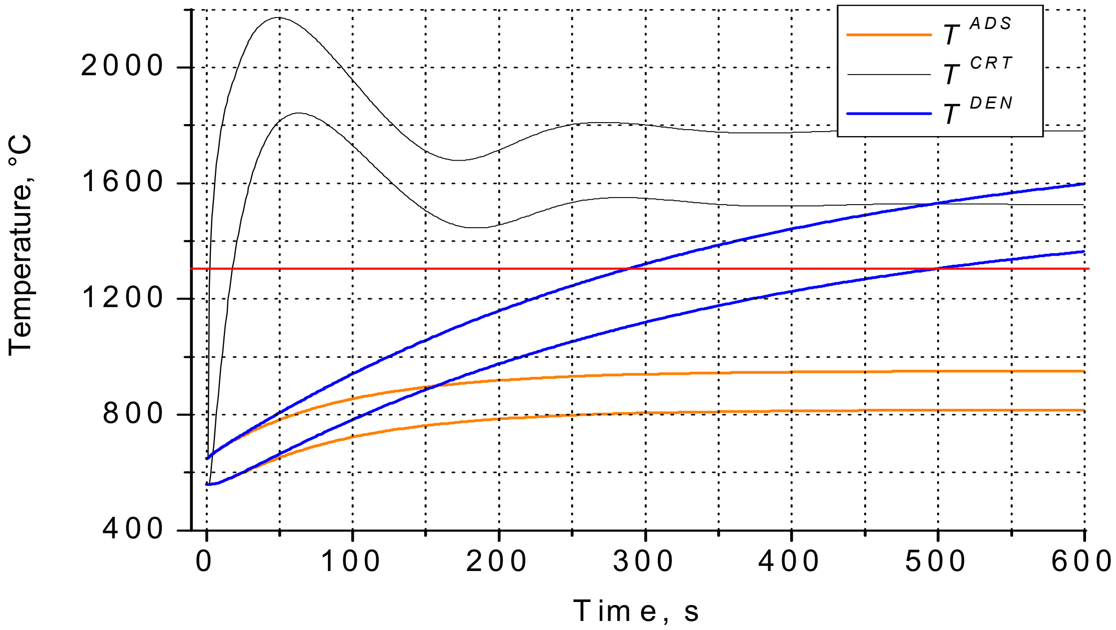
- $r_0 = 2\beta$ if **all reactivity reserves** are preserved on control rods;
- $r_0 = 1.4\beta$ (or $k_{eff} = 0.995$) if all reactivity reserves are replaced by the proton current variation $\Delta\rho_{\mathrm{TOP/TOC}} \approx (0.75 \div 1)\beta$.

For simplification,

$r_0 = 2\beta$ has been chosen for analysis of unprotected transients.

UNPROTECTED TRANSIENTS IN FAST-SPECTRUM ENERGY PRODUCERS





UTOP ($\Delta\rho_{\text{TOP}} = \beta$ in the period of 1 s) transient in fast-spectrum systems.

UTOP-behavior of the **Critical reactor (CRT)**

There is a narrow and significant power jump with the maximum amplitude higher by factor of 30 in the magnitude compared with the nominal power followed by power oscillations for 300 s after the reactivity insertion.

An asymptotic power at the end of the transient is achieved if the total feedback temperature effect is negative. The behaviour of the core temperature is similar but with wider oscillations. The maximum core temperature (~2200°C) exceeds the upper temperature limit ($T^{\dagger} = 1300°\text{C}$) considerably.

The asymptotic core temperature depends directly upon the Doppler-effect value and this temperature is expected to be too high (~1800°C) for the core.

UTOP will lead to core disruption and it is not acceptable in terms of intrinsic safety criteria.

UTOP-behavior of the **ADS**

is much smoother: both the asymptotic power and the core temperature are weakly dependent on feedback effects and are defined by the reactivity jump value.

For this particular case, the maximum power jump amplitude does not exceed the factor of 2 of the nominal power without power oscillations.

The asymptotic power is about 1.5 of the nominal power, while the maximum core temperature does not exceed 1000°C.

All these parameters do not ruin core integrity and can be considered as acceptable.

ACS behavior

takes an intermediate position between critical reactors and ADS:

similar to ADS, there is a small power jump. Neither power nor temperature oscillations are observed.

ACS ("DEN") eliminates short but dangerous fluctuations of power and of the core temperature in the beginning of transients.

However, later during the transient, asymptotic parameters become dangerous as in the case of critical reactors.

UNPROTECTED TRANSIENTS OVER POWER (UTOP) and OVER PROTON CURRENT (UTOC)

The direct inter-comparison between UTOP and UTOC for subcritical core systems outlines advantages of hybrids controlled by proton current variation.

Transients of UTOC-type are less dangerous compared with UTOP at the same subcriticality level.

For example, it leads to a supplementary core temperature reduction in ACS:

about 200°C in 10 minutes after the UTOC has started.

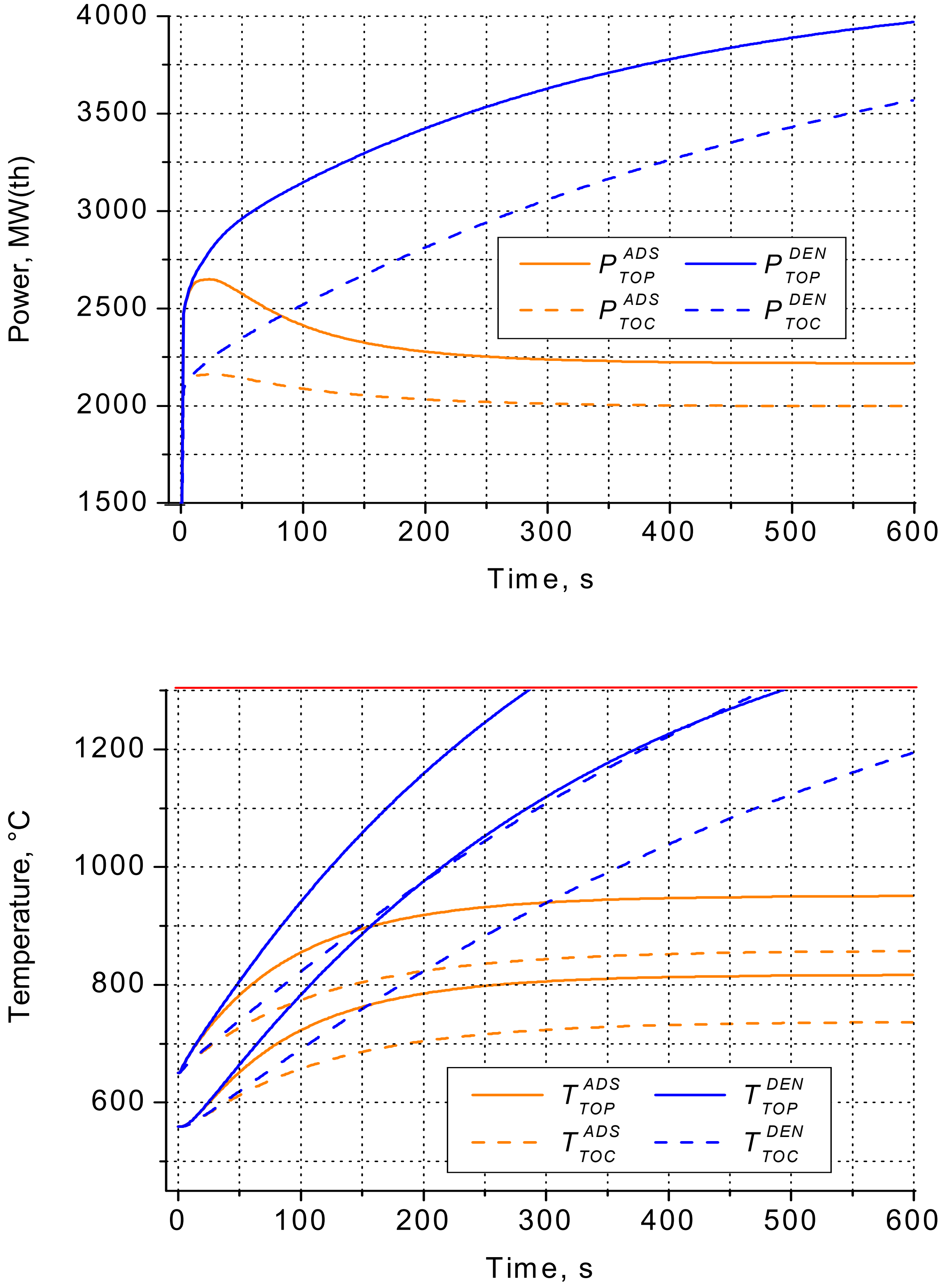


Fig. Inter-comparison of unprotected TOP/TOC transient ($\Delta\rho_{\mathrm{TOP/TOC}} = \beta$ in the period of 1 s; Th-fuelled; fast-spectrum systems

COMMENTS:

Similarly as in the case of UTOP, UTOC transients in ACS are expected to be slower compared with critical reactors (case of UTOP).

However, the *asymptotic* values of power for both critical system and ACS will remain similar.

ADS demonstrate the safer behavior regarding TOC transients.

As for ACS, the interval of the acceptable response is sufficiently large, up to 500 s after the reactivity insertion.

Despite significant reduction of the transient temperatures and the increase of the grace time for ACS,

the complete intrinsic safety features are foreseen only for ADS

UNPROTECTED LOSS OF FLOW (ULOF)

Unprotected Loss Of fuel Flow (ULOF) accidents were simulated by significant flow reduction from the nominal value down to 10% of nominal value in the period of 10 s supposing that remaining flow can be continuously supported later on due to the fuel natural circulation .

The following effects take place because of fuel flow slowing down:

the increase of delayed neutron fraction in the core and, hence, the insertion of reactivity;

core overheating followed by consequent feedback effects.

critical reactors

there are

- **important oscillations of power (factor of 1.4 in the power amplitude during the first 30 seconds) and of fuel temperature (a rise up to 1050°C).**
- **danger that the heat-exchanger will become overcooled for both low (20°C) and elevated (350°C) "heat sink temperatures" T_k.**

However, this threat can be avoided by further elevation of heat sink temperature up to 400°C.

ADS (no proton beam stop)

is unable to reduce its power sufficiently (feedback effects do not play such important role as it does in critical reactors) and there is an "asymptotical" growth of the core temperature which can **exceed finally (in approximately 10 minutes) the temperature limit.**

Behavior of power and temperatures is more favorable in the case of ACS.

Due to the reduction of accelerator power, core power is significantly reduced by 40 % of the nominal level.

Finally, the increase of core temperature up to 900°C still keeps the system away from the limiting conditions.

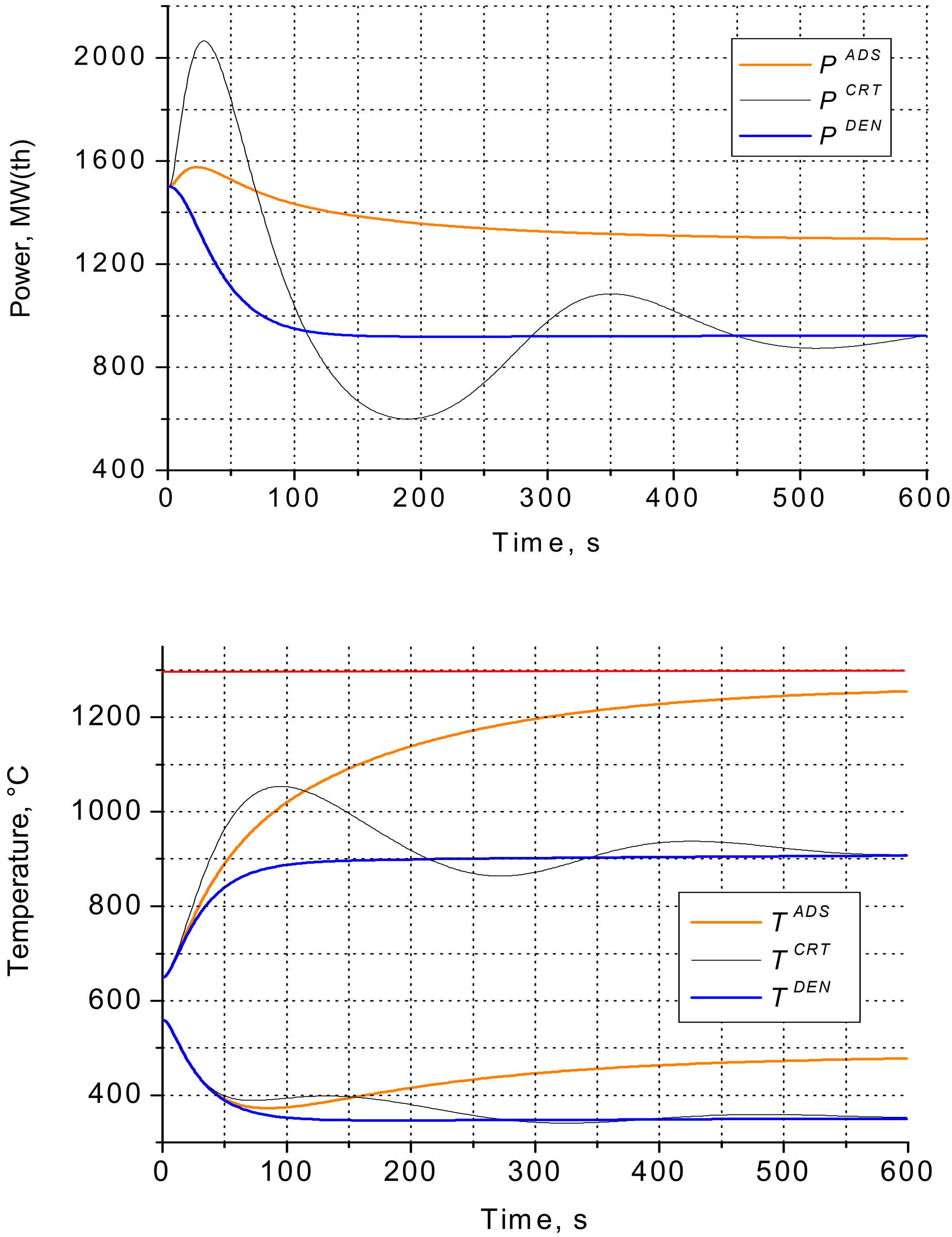


Fig. ULOF (pump power fall: 90 % in the period of 10 s) transient in the fast spectrum system.

UNPROTECTED LOSS OF HEAT SINK (ULOHS)

These transients have been simulated by the "linear" (in the period of 3 s) **stop of the heat transfer** through the heat-exchanger causing the rapid core overheat.

Feedbacks of **critical reactor** reduce core power rapidly, while the core temperature, after a negligible growth, returns back close to the nominal level in about 500 s.

ADS is not able to reduce sufficiently its power

(feedback effects are not effective for ADS). This leads to high temperatures: one observes the continuous increase of the core temperature and, after 5 minutes, it exceeds the limit of the viability.

ACS behaviour is again more favourable

compared with both ADS and Critical Reactors due to the prompt and intrinsic reduction of accelerator power thanks to the coupling and, hence, of total power which approaches to about 10 % of its nominal value.

Core and heat-exchanger temperatures remain around the nominal core temperature level.

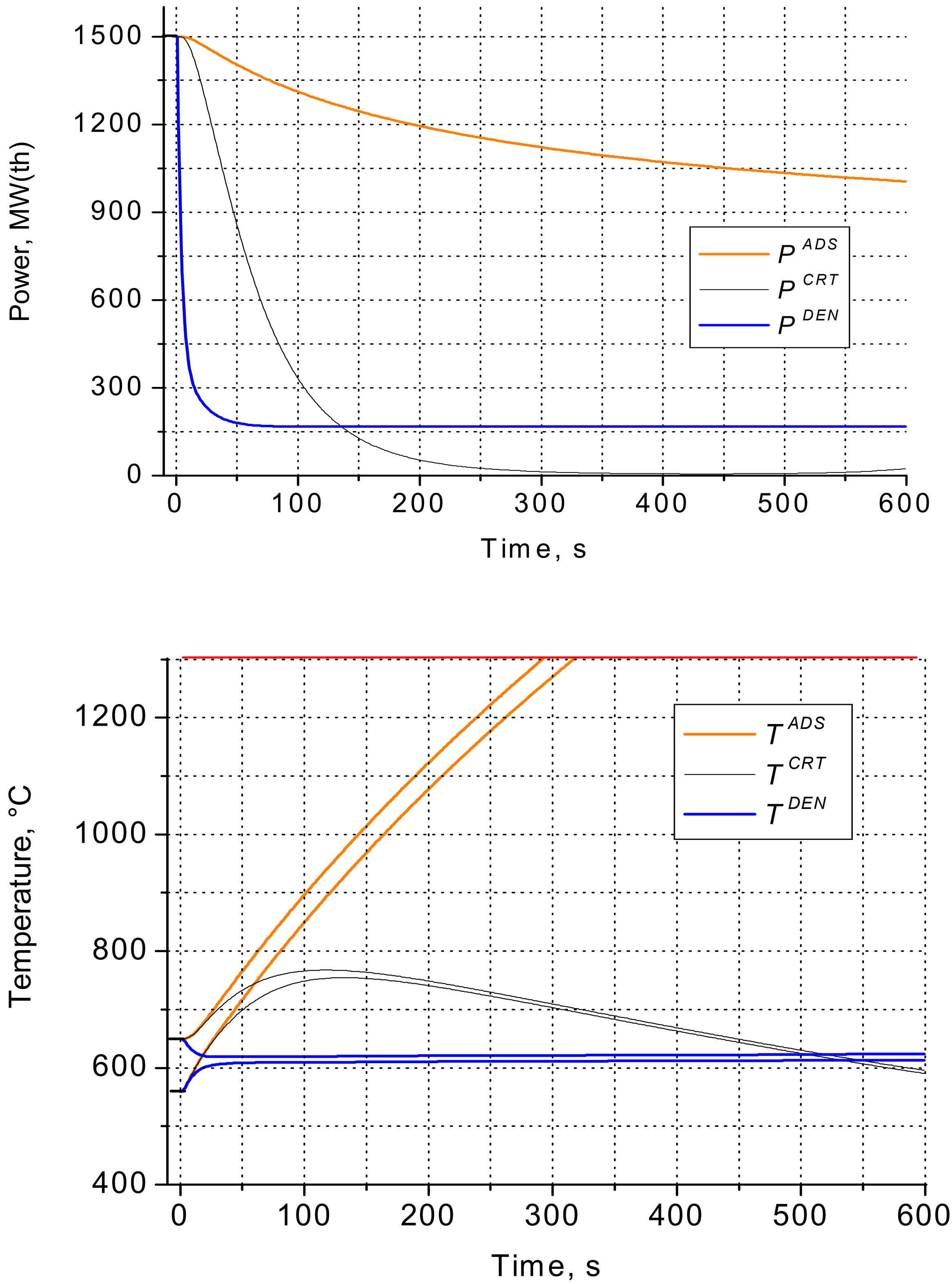


Fig. ULOHS transient (heat sink falls by 90 % in the period of 3 s)

DISCUSSION

Despite the very favorable safety physics potential of the molten salt critical cores (small reactivity margins, the limited change of reactivity, etc.), critical systems possesses the limited chance in achieving the intrinsic safety features.

Significant oscillations of power and fuel temperatures are the main drawbacks of unprotected transients.

GENERAL INTRINSIC SAFETY FEATURES are the following:

- **In the cases of positive feedback effects and, particularly, of significant Doppler-effect degradation, sufficient intrinsic safety features of critical systems are generally not achievable.**

- **The subcritical regime (both ADS and ACS) improves the safety potential significantly, leading to the considerable increase of the grace time up to dozens of minutes in the case of "degraded" feedback effects and up to several hours in the case of the "standard" negative feedback effects. This phenomenon is observed even for small subcriticality levels of 1-3 dollars.**

- **One of the most important safety effects of subcritical systems is the suppression of power and fuel temperature oscillations during unprotected transients. Such significant enhancement of safety could play an important role in the case of long-lived waste transmutation (degraded safety property case).**

- **The weakest point of ADS in respect to the deterministic safety is thermo-hydraulic unprotected transients which exhibit a continuous increase of temperatures despite favorable feedback effects. It means that ADS are unable in some cases to possess the "unlimited" grace time.**

- **Unlike ADS, ACS demonstrate acceptable behavior with respect to most unprotected transients (ULOF, ULOHS, etc.), while the TOP/TOC transients remain a point of concern.**

- **ACS inherit the "preferable" intrinsic safety features compared with both critical reactors and ADS.**

As demonstrated, even a very small subcriticality level improves significantly the intrinsic safety potential of a nuclear system.

Therefore, respecting energy production effectiveness, economics of subcritical power producers should not be penalized significantly when compared with critical reactors due to the small consumption of energy for proton acceleration:

neither powerful accelerators, nor large energy consumption are required for spallation in this case.

According to pessimistic assessments, about 0.002 - 0.003 mA of the nominal proton current per MW(th) of total power is expected to be sufficient.