THE TRANSIENT BEHAVIOUR OF

ACCELERATOR DRIVEN

SUBCRITICAL SYSTEMS

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The Transient Behaviour of Accelerator Driven Subcritical Systems

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INTRODUCTION: As the safety of a multiplying system depends to a large extend on fast transients caused by acciden- tal reactivity insertions it is assumed that contrary to a critical reactor accelerator driven subcritical assemblies respond with more benign transients to changes in reactivity.

To study the power changes in accelerator driven systems a kinetic model was developed and programmed which deals with fast transients as a function of reactivity insertion. Doppler feedback and the intensity of an external neutron source. The model allows a comparison with an equivalent critical reactor. It was tested by a comparison with a NEACRP (Nuclear Energy Agency Committee of Reactor Physics) benchmark. As a general tendency it turned out that accelerator driven systems behave quite benignly even if they are only slightly subcritical.

In the past accelerator driven systems were proposed by several authors as an alternative to fast breeders [Lewis (1953 and 1968). Steinberg (1977). Grand (1978). Takahashi (1980)] using the term *"electrical Iv-ceding"*.

[n the search for transmutation concepts accelerator driven systems are considered competitor of critical reactors serving as actinide burners [Bonnaure (1987). Takahashi (1992)]. This is due to the fact that the presence of actinides in a reactor might make its control more difficult since the fissile isotopes of Neptunium. Americium. and Curium have a considerably smaller fraction of delayed neutron emitters (as compared to the more common fuels U-235 and U-238). a small Doppler effect and a non-negative void coefficient. As is well known. all these parameters are essential for the control of a nuclear reactor in the critical state.

Especially in the US [Bowman (1991).] and Japan [Mukaiyama (1988). Kato (1992)] actinide transmuters of this kind have attracted a great deal of attention. The OECD Nuclear Energy Agency and the CEC have therefor been carrying out stud ies of new transmutation strategies in an international co-operative effort. It has been shown that an integration of transmutation techniques could reduce substantially the long-term radiation hazard from commercial waste. Transmutation could also contribute to a safe and even beneficial decommissioning of nuclear weapons. An additional benefit of this more economic use of fuel could be a reduction of radiation hazards from uranium mining.

In recent proposals Bowman (1991) and Rubbia (1993) promote new fission systems based on the Thorium cycle which are driven by particle accelerators .

THE KINETIC MODEL: In the following considerations we use the conventional point kinetics equation to which the term S(r) is added. It describes an external source which is the spallation neutrons generated by a proton accelerator.

$$\frac{dN}{dt} = \frac{\rho(t,N) - \beta}{A} N + \sum_{i=1}^{6} \lambda_i \, c_i + S(t) \tag{1}$$

$$\frac{d}{dt} = \frac{C_i \, \beta_i}{A} - \lambda_i c_i; \quad i = ,1. \ 2, \ \ldots, 6 \tag{2}$$

where: N = number of neutrons in the system (it is considered to be proportional to the power). C_i = delayed precursor concentration of the *i-th* delayed neutron group. λ_i = decay constant of the *i-th* delayed precursor group [see-1]. β_i = delayed neutron fraction of the *i-th* delayed neutron precursor group. β = total delayed neutron fraction (= $\beta_1 + \beta_2 + \ldots + \beta_6$). $\rho(t,N) = \rho_R (t)$ + ρ_D (N) total reactivity variation caused by the time dependent ramp-rate $\rho_R (t)$ and the power (neutron population) dependent Doppler reactivity ρ_D (N). A = prompt neutron lifetime [s]. S(t) = rate at which external neutrons are inserted. It is chosen such that a certain power level is maintained in the system.

The coupled equations (I) and (2) are solved by a numerical method employing a variable implicit technique [Cheng (1990)]. The method yields an efficient and accurate solution. The general features of the program include time dependence of the total reactivity. prompt neutron generation time and time step size. and a maximum of six delayed neutron precursor groups. In addition the total stored energy is also calculated by integrating the reactor power from $t = 0$ to the time of interest.

The solution of Equations (1) and (2) is based on the program of Cheng (1990) to which the following features were added:

1) The possibility of inserting a *linear* or *quadratic* time dependent reactivity ramp. The quadratic time dependent reactivity ramp serves for the simulation of gravity induced accidents like earthquakes. etc.:

2) A negative reactivity feed-back mechanism to take the Doppler-effect into account:

3) The possibility to switch off the proton current by an exponential. r dependent. decay law of the form $exp(-t/\tau)$;

4) A graphical display of the power and reactivity changes.

THE EXTERNAL SOURCE: The number of *fission* neutrons (per Spallation Neutron) in subsequent generations in a sub-critical assembly is

$$k_1 + k_1k_2 + k_1k_2k_3 + \ldots = k/(1-k) \quad \text{assuming that} \quad k_1 \approx k_2 \approx k_3 = \ldots = k$$

It follows that the power production P_{fi} of a subcritical assembly fed by spallation neutrons can be quantified as:

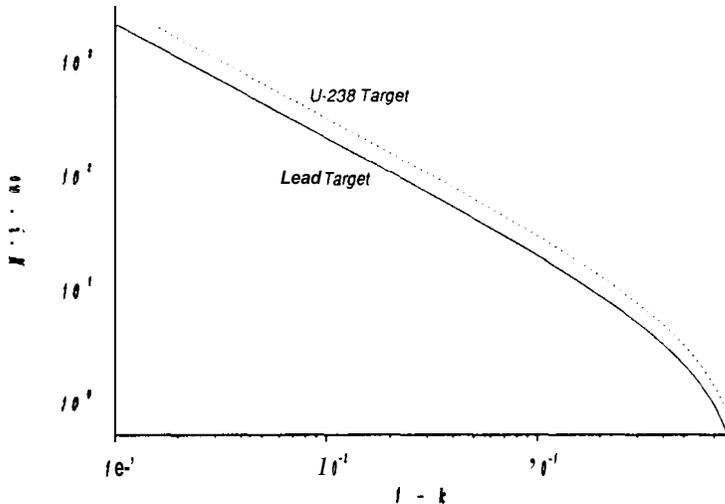$$P_{fi} = n_{sp} \frac{a \cdot k}{v(1-k)} \frac{I}{C} E_f \tag{3}$$

Figure 1: Power production of an accelarator driven booster as a function of the sub-criticality $(1-k_{eff})$ assuming a proton beam of 1mA at 1.5 GeV entering a lead or a U^{238} target.

where: k = multiplication factor of the subcritical system. a = importance of the target position and target neutron energy distribution (usually $a>1$ for a central target position). v = mean number of neutrons in a fission process. E_f = power release per fission $(= 3.2.10^{-11} Ws)$. n_{sp} = neutron yield from one proton. I = proton current. and C= proton charge $(= 1.6. 10^{-19}$ A s).

It can be seen that near criticality a 1mA current already generates a relatively high fission power. For $k = 0.97$ more than 100 MW can be achieved.

With this relation one can calculate $S(t)$ of equation (1) assuming that $S(t) \cong - \rho_0 n_{sp}/A$ is a good approximation since the spectrum of the spallation neutrons is quite similar to the fission spectrum. except for a tail of fast neutrons above 20 MeV. It follows therefore that

$$S(t) = P_{fi} \frac{v(1-k)}{A} \frac{C}{a \cdot k} \frac{1}{IE_f} \tag{4}$$

THE EFFECT OF UNPROTECTED REACTIVITY ACCIDENTS: Usually three types of unprotected reactivity accidents are considered: - Slow reactivity ramp insertion. - Fast reactivity ramp insertion. - LOF driven TOP (Fast reactivity ramp insertion due to sodium voiding caused by a loss of coolant accident.)

Slow reactivity ramp insertions without a scram are for example the inadvertent withdraw of a control rod(s) (*few cents/s* or 0,0001 k_{eff}/s).

A typical fast reactivity ramp insertion occurred in the EBR-I accident which was caused by an inward bowing of the fuel pins. All later fast reactors were constructed with grids or helical wire spacers to prevent bowing. Other accidents of this category are earthquakes or diagrid failures without a scram (up to a *few $ /s* or *0.01 k_{eff}/s*).

The NEACRP Benchmark Problem: As a first example the KfK benchmark problem defined as a rod ejection accident and proposed by the Nuclear Energy Agency Committee on Reactor Physics (NEACRP) is chosen. It consists of a fast reactor made up of a core with a bank of annular control rods. radial and axial blankets irnd sodium coolant. The essential features of the problem are: Axis-symmetry. two neutron groups and six delayed neutron precursor families and thermal feedback through Doppler effects in capture and fission cross sections.

The transient is obtained through steady control rod bank withdrawal. The reactivity insertion starts at *1 ms* and increases at a rate of 170 $/s for the duration of *16 ms*. (The speed of the control withdrawal is adjusted to produce a ramp of *0.548cm/ms*.) After this time the reactivity is kept constant.

The reactivity reduction by the Doppler coefficient was calculated from the sample data obtained from Beauwen (1992) as a heat generation coefficient of -0.921$ / GJ.

The analysis of this problem allows a comparison with transient calculations obtained by others to validate the code used in our analysis. It also gives a first indication of the mitigating effect of using a subcritical. accelerator driven system.

Figures 2a and 2b show the power and reactivity change in a critical reactor and in systems being sub-critical between -1 $ and -3 $ (dotted lines). These systems are driven by a spallation source dimensioned such that they generate in steady-state
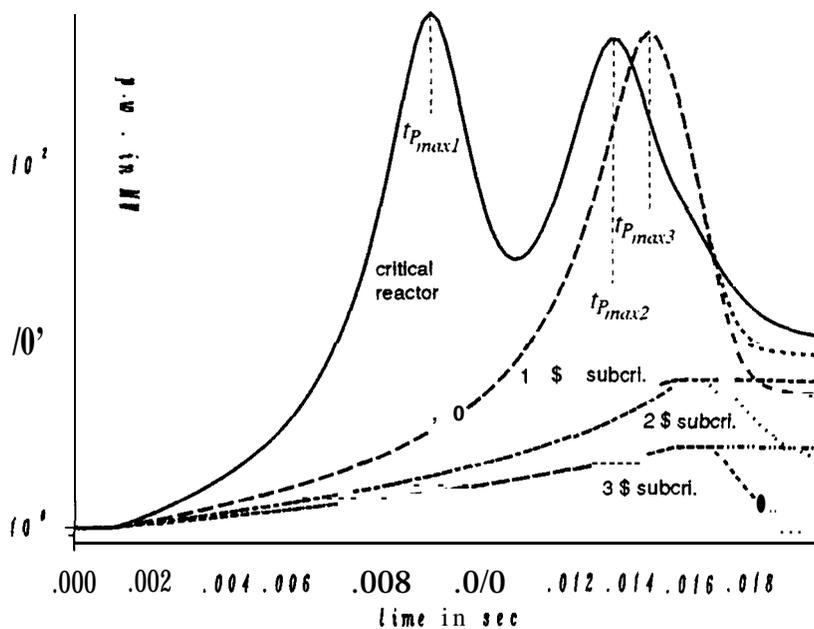
Figure 2a: Fast reactor power excursion benchmark (as defined in a comparative NEACRP exercise) assuming a rod ejection accident. The reactivity insertion rate is 170 $/ s during a period of 15 ms. The power ease ase from a critical reactor is compared with 1$ to 3$ subcritical accelerator-driven systems of the same initial power.
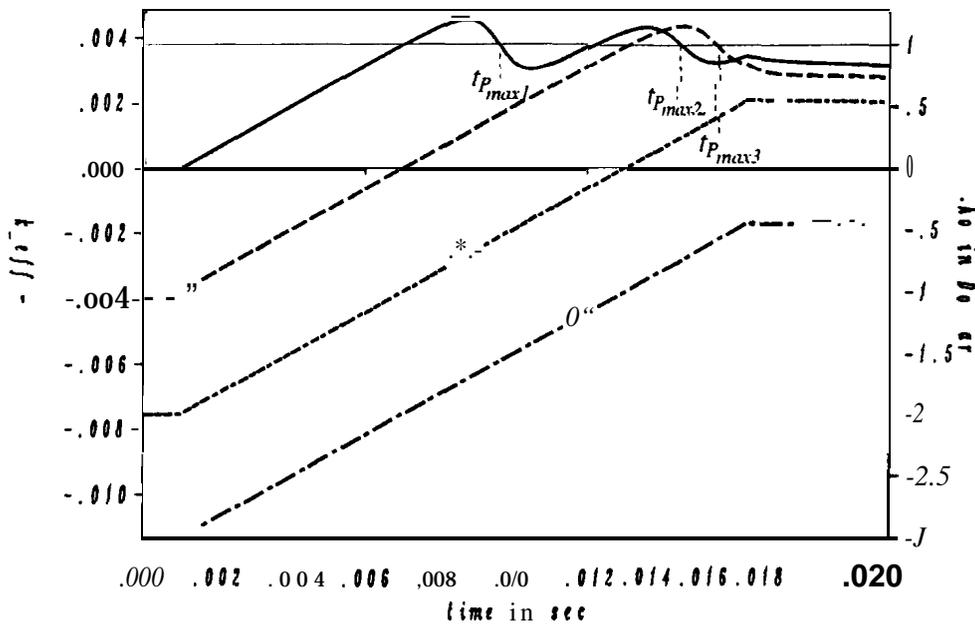

Figure 2b: The Reactivity Behaviour During the Accident Scenario for the NEACRP Benchmark Exercise.

operation the same power as the critical reactor. which is assumed to be $1\,GW_{therm}$.

The power excursion curve which corresponds to a critical reactor oscillates and has two distinct peaks in a short time interval. Super-prompt criticality produces these peaks. as can be seen in Figure2b.Thepower rises rapidly during the period of super-prompt criticality and reaches its peak value at the time when the Doppler effect reduces the reactivity to values below the super-prompt limit. (This characteristic is similar to a pulsed reactor).

In the case where the reactor is operated in a subcritical mode the neutron source is determined such that the system generates 1 GW thermal power and this source strength is maintained during the whole time the reactivity is increased. When the time reaches $17\,ms$. or when the thermal power of the reactor reaches 50 times of the initial power (50 GW). the neutron source is reduced by the shut-off function $exp(-t/\tau)$ $(r = 1\,ins)$. For an initial sub-criticality of -3 and -2 $ respectively. the power increases only to 2.2 GW and 6 GW respectively after 16 ms and after 17 ms the power decreases almost proportionally with the neutron source strength of $exp(-t/\tau)$. If on the other hand the neutron source is maintained constant (the accelerator is not shut-off). also the power remains almost constant in this time range. For a sub-criticality of only -1 $ a single peak-power of 530 GW was calculated. Even though this value is similar to the peak value of the critical reactor, the integrated power. i.e. the total energy release during the excursion is much less than for a critical system.

An interesting result of this analysis is the fact that the power decreases even between the prompt and delayed critical state. This is due to the long time constant of the delayed neutrons. When the reactor is in an under prompt-critical condition. the neutron flux is controlled by prompt neutrons which decrease for a sub-superpromt critical condition. For the case of a critical reactor two power peaks of 700 GW and 500 GW resp. were calculated which is in good agreement with the results obtained by participants of the NEACRP benchmark.
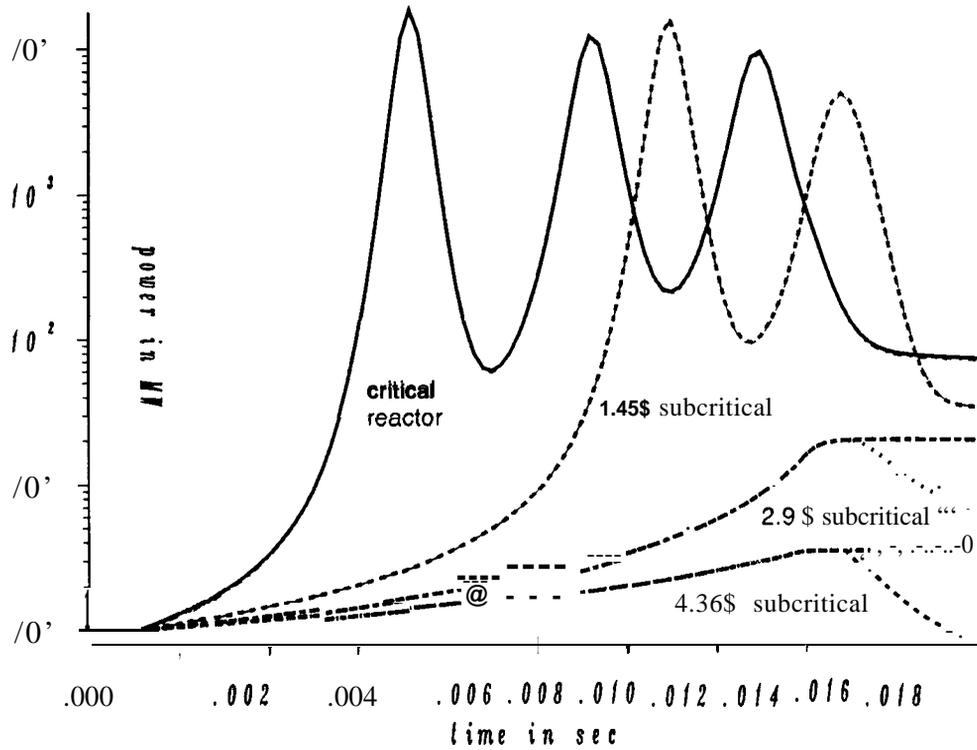
Fig ure 3a: Comparison of power excursions in a critical actinide burner (as proposed by Mukayama, JAERI) with subcritical accelerator driven systems for an accidental reactivity insertion of 247 $/s of 15 ms duration (see text).
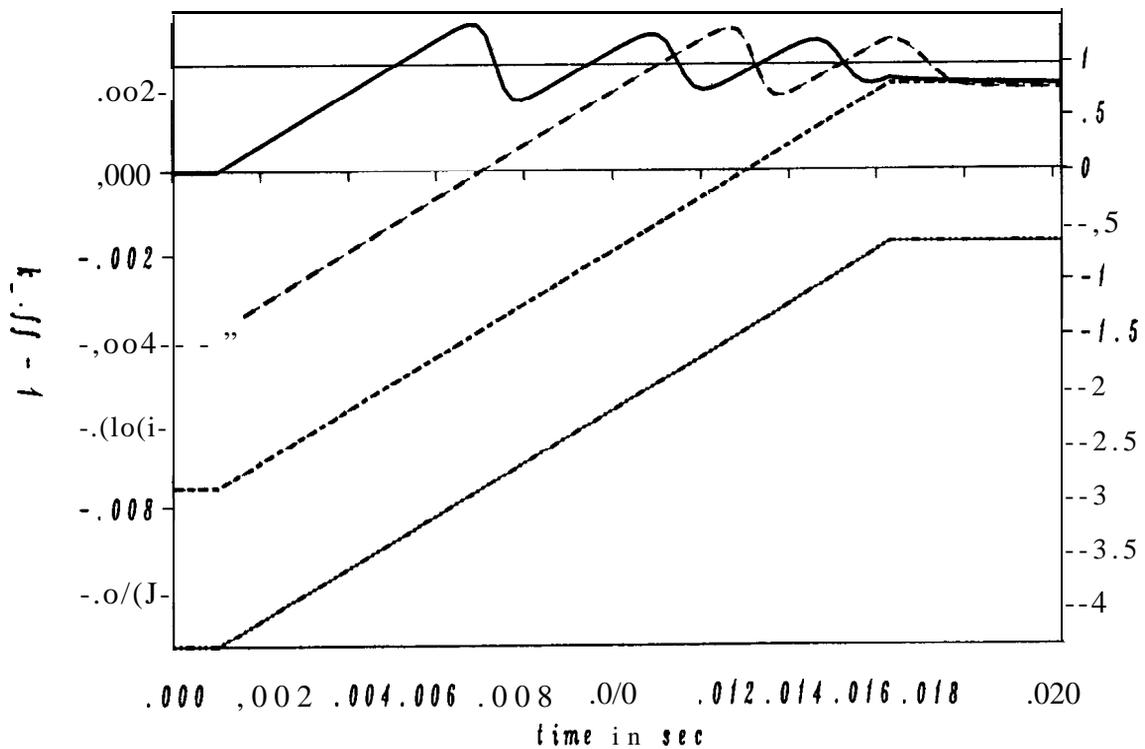

Figure 3b: The reactivity behaviour during the accident scenario for a typical actinide burner.

Figures **2 deal with the case of a typical** 'actinide **burner'** as for example proposed by Mukayama [ ]. Compared to the previous case this system has a shorter neutron generation time ($17\,ns$). a smaller delayed neutron fraction ($\beta = 0.0026$) and a less **effective Doppler coefficient (** $\Delta k_{eff} = -0.0053\ \$/MJ$).

CONCLUSIONS: A one point kinetics program was developed which allows the simultaneous calculation of a critical and sub-critical. externally driven system using the same input parameters. The code was validated by re-calculating a NEACRP specified benchmark dealing with the example of a rod ejection accident in a fast reactor.

The few examples treated show that even slightly subcritical systems which require only a low accelerator current. respond much more benignly to a sudden reactivity insertion than critical systems. In realistic accident scenarios with reactivity insertions of a few dollars **already** a subcriticality of $\Delta k_{eff} \cong 1\%$ reduces the power transients by orders of magnitude if compared with those of a corresponding critical reactor. To most authors it appears that systems with a k_{eff} of around 0.9- 0.95 (= -30\$--15\$ for a FR) would even look more attractive from the safety point of view. But for a well designed multiplying system there are simply no credible accident scenarios which would require such an amount of subcriticality. On the other hand these systems would require an expensive high current accelerator. In addition they are characterized by an inhomogeneous power distribution with a peak around the target area.

Accelerator driven slightly subcritical systems show a relatively flat power distribution, and require a proton current of a few mA only, This can be achieved with todays technology, possibly even with Cyclotrons considerably less expensive than LINACs. In addition small proton currents facilitate considerably the target construction: less target cooling problems; less difficulties with the target window and less fission product poisoning in the target.

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