Safety and Control of Accelerator-Driven Subcritical Systems

H. Rief [1] and H. Takahashi [2]
[1] *Commission of the European Communities, Ispra Establishment, I-21020 Ispra, Italy*
[2] *Brookhaven National Laboratory, Upton, L.I. NY, USA 11973*

Abstract. To study control and safety of accelerator driven nuclear systems, a one point kinetic model was developed and programed. It deals with fast transients as a function of reactivity insertion, Doppler feedback, and the intensity of an external neutron source. The model allows for a simultaneous calculation of an equivalent critical reactor. It was validated by a comparison with a benchmark specified by the Nuclear Energy Agency Committee of Reactor Physics. Additional features are the possibility of inserting a linear or quadratic time dependent reactivity ramp which may account for gravity induced accidents like earthquakes, the possibility to shut down the external neutron source by an exponential decay law of the form $exp(-t/\tau)$, and a graphical display of the power and reactivity changes. The calculations revealed that such boosters behave quite benignly even if they are only slightly subcritical.

INTRODUCTION

In quite a number of studies presented in the recent past it has been shown that an integration of transmutation techniques could reduce substantially the long-term radiation hazard from radioactive 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 the search for transmutation concepts the first candidates were actinide fuelled (critical) reactors. But soon it turned out that they pose a particular problem of control. This is due to the fact that 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 Pu-239) and a non-negative Doppler coefficient. As is well known, the fraction of delayed neutrons is essential for the control of a nuclear reactor in the critical state. To overcome these problems various concepts of accelerator driven subcritical systems aiming at the transmutation of actinides and long lived fission products have been proposed in the recent past.

The safety of multiplying systems depends to a large extend on fast transients caused by accidental reactivity insertions. To study the power changes in accelerator driven systems a kinetic model dealing with fast transients as a function of reactivity insertion, Doppler feedback and the intensity of an external neutron source, was developed and programed.

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 [1,2,3,4,5] using the term "*electrical breeding*". However, cost estimates for such a hybrid system, consisting of a subcritical reactor and an accelerator coupled to it, led to unreasonably high figures. In the search for new transmutation concepts, accelerator driven systems are now considered competitors of critical reactors serving as actinide burners [6,7].

Especially in the US [8] and Japan [9,10] actinide transmuters of this kind have attracted a great deal of attention. The OECD Nuclear Energy Agency and the CEU have therefore been

SUMMARY AND CONCLUSIONS

The ADAPT concept for plutonium burning appears very promising. It provides high integrity containment for plutonium and fission products, utilizes HTGR technology, has high temperature capability, uses inert coolants and materials, does not require reprocessing of spent fuel, and enables a simple, effective waste disposal approach. More detailed study of the concept is recommended, with particular attention to neutronic burnup analyses and fuel shuffling strategies. Experiments on the fabrication of fuel beads and their capability for high burnup are also recommended.

REFERENCES

[1] Van Tuyle, G. J., et.at., "Preliminary Topical Report for Revision-1 of a Preconceptual Design for the Spallation-Induced Lithium Conversion (SILC) Target for the Accelerator Production of Tritium (APT)", BNL ATD/APT94-0008 (Rev. 0), June 24, 1994.

[2] Ludwig, H., et.al., "Summary of Particle Bed Reactor Designs for the Space Nuclear Thermal Propulsion Program", BNL52408 (1993).

[3] DeMars, R., B&W, *Personal Communication*, (1994).

carrying out studies of new transmutation strategies in an international co-operative effort.

Recent proposals [11,12] promote new accelerator driven fission systems based on the Thorium cycle which is almost free of actinides.

THE KINETIC MODEL

In the following considerations we use the conventional point kinetics equation to which the term $S(t)$ is added. It describes an external source which consists of the spallation neutrons generated by a proton accelerator.

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

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} - \lambda_i C_i; \quad i = 1, 2, \ldots, 6 \tag{2}$$

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 [sec^{-1}],

β_i = delayed neutron fraction of the *i-th* delayed precursor group,

β = total delayed neutron fraction ($=\beta_1+\beta_2+\ldots+\beta_6$),

$\rho(t,N) = \rho_R(t) + \rho_D(N)$ total reactivity variation caused by the time dependent ramp-rate $\rho_R(t)$ and the power (neutron population) dependent Doppler reactivity $\rho_D(N)$,

Λ = prompt neutron lifetime [s],

$S(t)$ = rate at which external neutrons are inserted. This is chosen so that a certain power level is maintained in the system.

The coupled equations (1) and (2) are solved by a numerical method employing a variable implicit technique [13]. 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 described in [13] to which the following features were added:

- 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.
- A negative reactivity feed-back mechanism to take the Doppler-effect into account.
- The possibility to shut down the external neutron source by an exponential, τ dependent, decay law of the form $exp(-t/\tau)$.
- A graphical display of the power and reactivity changes.

THE EXTERNAL SOURCE

The multiplication Factor of *fission neutrons* (per Spallation Neutron) for subsequent generations in a sub-critical assembly is

$$k_1 + k_1 k_2 + k_1 k_2 k_3 + \dots \approx k/(1-k) \text{ assuming that } k_1 \approx k_2 \approx k_3 \approx \dots = k$$

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

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

where:

k = multiplication factor of the sub-critical system,

a = importance of the target position and target neutron energy distribution (usually $a > 1$ for a cen tral target position),

ν = mean number of neutrons in a fission process,

E_f = power release per fission (= $3.2 \cdot 10^{-11}$ Ws),

n_{sp} = neutron yield from one proton,

I = proton current,

C= proton charge (= $1.6 \cdot 10^{-19}$ A s).

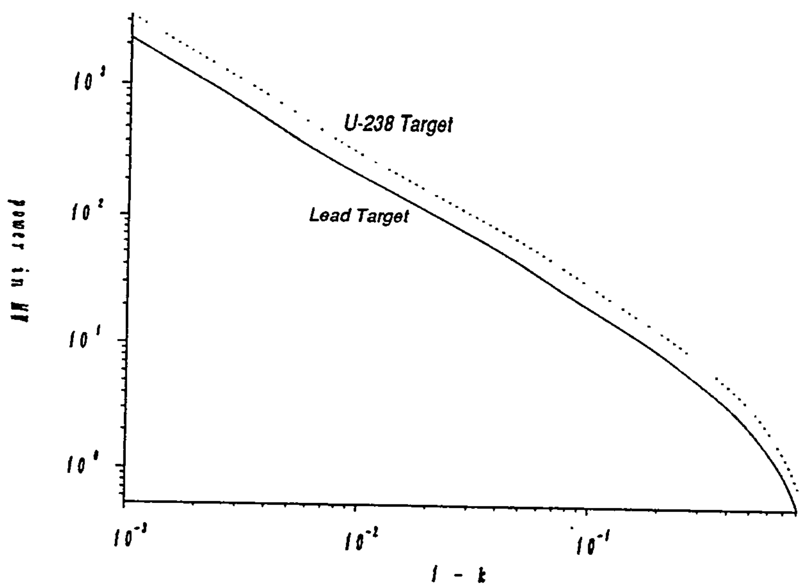

Fig. 1: Power production of an accelarator driven booster as a function of the sub-criticality ($1-k_{eff}$) assuming a proton beam of 1 mA at 1.5 GeV entering a lead or a U^{238} target.

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

One can assume that $S(t) \cong -\rho_0 n_{sp}/\Lambda$ 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

$$S(t) = P_{fi} \frac{\rho_0}{\Lambda} \frac{\nu(1-k)}{a \cdot k} \frac{C}{I E_f} \tag{4}$$

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 withdrawal 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).

Examples

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 and 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 so that they generate in steady-state 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 Figure 2b. The power 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 so 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 the initial power (50 GW), the neutron source is reduced by the shut-off function $exp(-t/\tau)$ ($\tau = 1\ ms$).

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

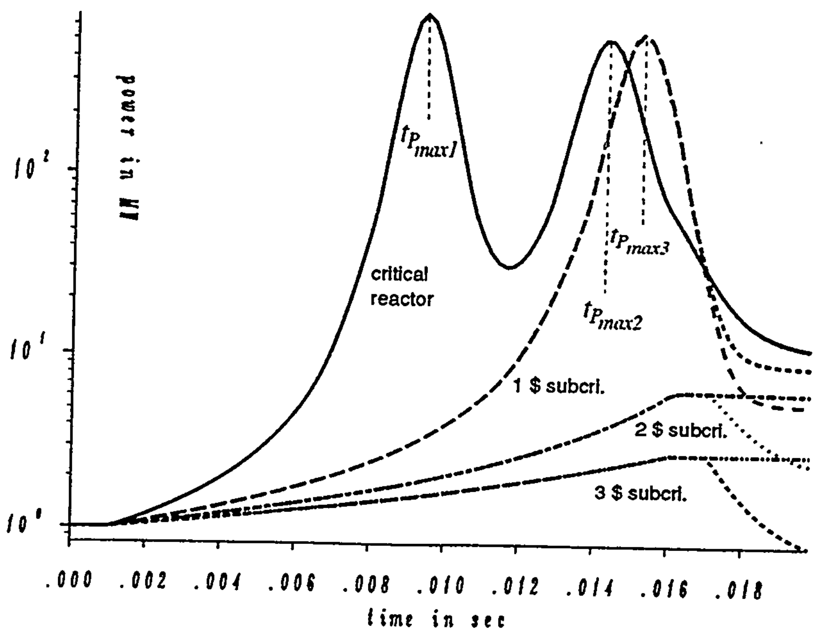

Fig. 2a: Fast reactor power excursion benchmark (as defined in a comparative NEACRP exercise) assuming a rod ejection accident. The reactivity insertion rate is 170 $/s during a period of 15 ms. The power release from a critical reactor is compared with 1$ to 3$ subcritical accelerator-driven systems of the same initial power.

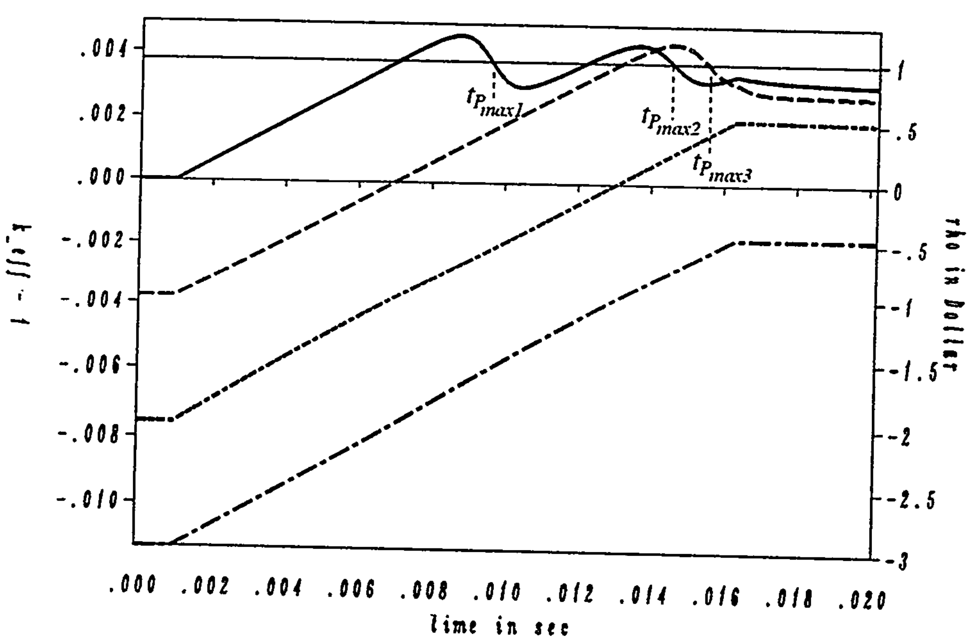

Fig. 2b. The Reactivity Behaviour During the Accident Scenario for the NEACRP Benchmark Exercise.

with the neutron source strength. 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 subcriticality 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

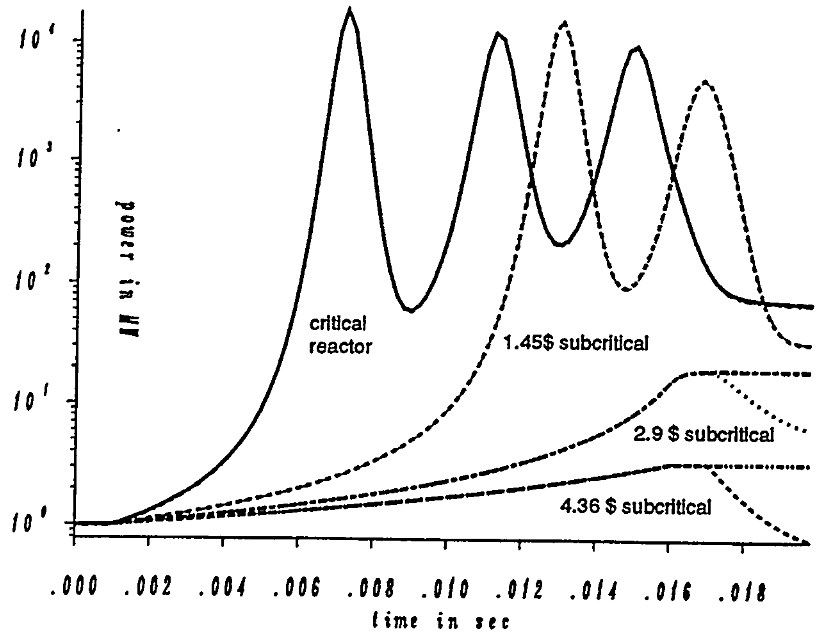

Fig. 3a: Comparison of power excursions in a critical actinide burner (as proposed by Mukaiyama, JAERI) with subcritical accelerator driven systems for an accidental reactivity insertion of 247 $/s of 15 ms duration.

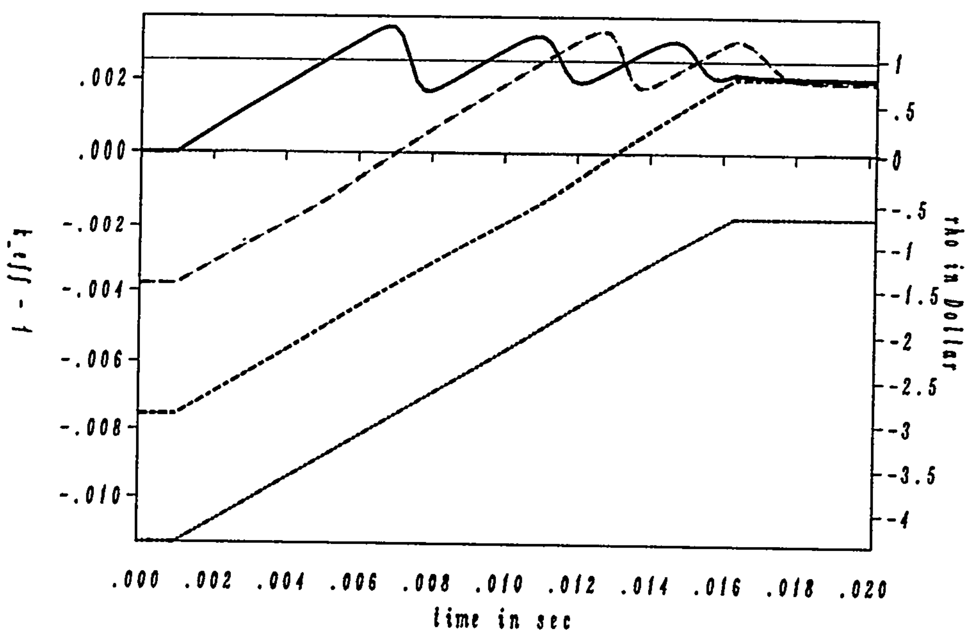

Fig. 3b: The reactivity behaviour during the accident scenario for a typical actinide burner.

prompt neutrons which decrease for a sub-supercritical 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.

A Typical Fast Actinde Burner. The next example illustrated in Figures 3a and 3b deals with a typical actinide burner as for example proposed by [9]. Compared to the previous case this system has a shorter neutron generation time (*17 ns*), a smaller delayed neutron fraction ($\beta = .0026$) and a less effective Doppler coefficient ($\Delta k_{eff} = -0.0053$ *$/MJ*).

When the power change is slow, the reactor can be controlled by a mechanical movement of control rods or by a hydraulic dispersion of liquid neutron absorbers which are disolved by melting fuel elements like an electric fuse mechanism. In a subcritical reactor operated by spallation neutrons, the power change is much slower than in a critical reactor. This provides a great advantage from the point of view of reactor safety.

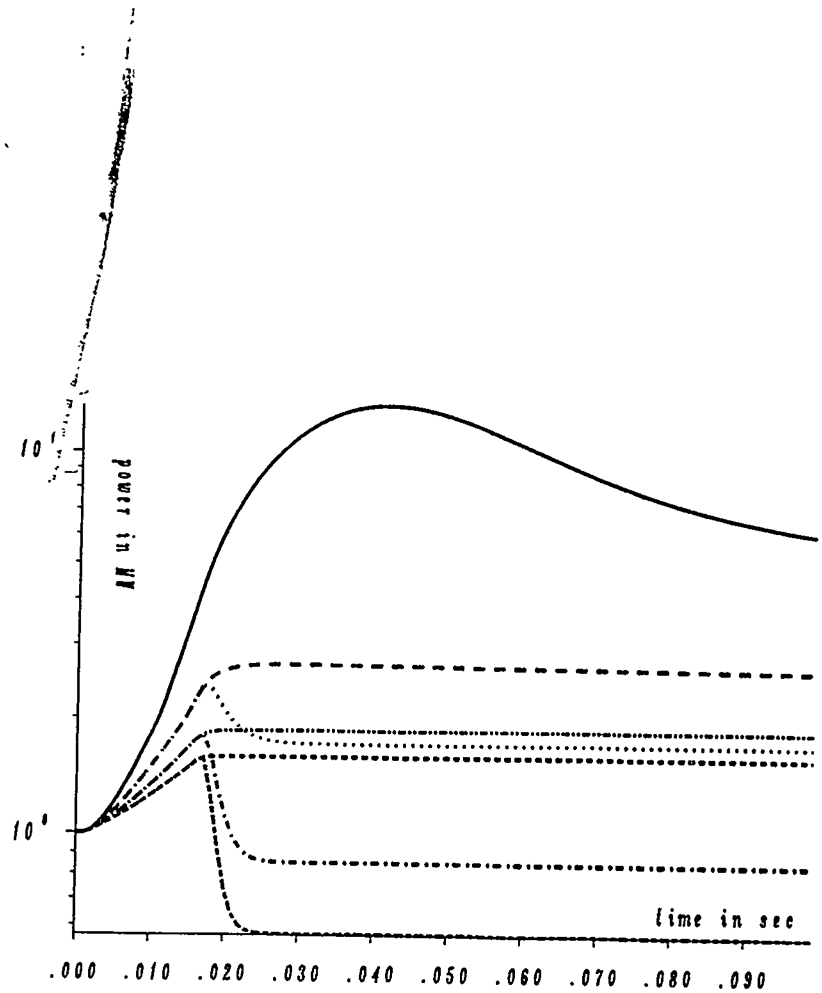

Fig. 3: Comparison of power excursions in a Light Water Reactor with subcritical accelerator driven systems for an accidental reactivity insertion of 66 $/s of 15 ms duration

Accelerator-Driven Thermal Systems. The last example deals with an accelerator-driven light water system. Again the same accident scenarios as in the previous examples are analyzed. The comparison with the critical reactor configuration shows first of all that for the same reactivity insertion as previously assumed, the power excursion is much smaller in the thermal system. Still it seems that the insertion of accelerator induced neutrons may be beneficial in avoiding power transients, but the gain in safety is less evident in this case since system-inherent mechanisms already mitigate such events. Almost all accident scenarios which cause reactivity changes in light water reactors make them less critical. In particular: depressurization, bubble formation, and loss-of-coolant. One of the few anticipated transients without scram is the ejection of control rods caused by a leak somewhere in the guide tubes and the "cold water" accident.

The main concern is the loss of coolant accident with subsequent fuel melt down and fission product release. This accident scenario typically occurs in the sub-critical state of the reactor.

CONCLUSIONS

A new one point kinetics program was developed. It 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. However, 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 sharp 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 today's technology, possibly even with Cyclotrons, presumably 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.

REFERENCES

[1] W. Lewis. Atomic Energy of Canada Ltd., Report AECL-969, (1953).

[2] W. Lewis. Atomic Energy of Canada Ltd., Report AECL-3190, (1968).

[3] M. Steinberg (ed.) Kouts H., in Proc. Inform. Meeting, Accelerator-Breeding, BNL, Report Conf. 770107, 1977.

[4] P. Grand, H. Kouts, J. Powell, M. Steinberg, H. Takahahshi: "Conceptual Design and Economical Analysis of Light Water Reactor Fuel Enrichment/Regenerator", BNL 50838, (UC-80, TID-4500), (1978).

[5] H. Takahashi, et al.: Atomkernenergie, Kerntechnik: 36, 195 (1980).

[6] P. Bonnaure, H. Rief, P. Mandrillon and H. Takahahshi, "Actinide Transmutation by Spallation in the Light of Recent Cyclotron Development", presented at the *4th International Conference on Emerging Nuclear Energy Systems*, Madrid, (1986) and NEACRP-A-910 (1987).

[7] H. Takahashi and H. Rief: "A Critical Review of Accelerator-based Transmutation Systems", invited paper in *Proceedings of the OECD-Nuclear Energy Specialists' Meeting on Accelerator-based Transmutation*, Würenlingen (CH), March 24-26, 1992.

[8] E.D. Bowman, E.D. Arthur et al., *Nuclear Energy generation and Waste Transmutation using an Accelerator-Driven Intense Thermal Neutron Source*, LA-UR-91-2601, 1991.

[9] T. Mukaiyama, H. Takano, T. Takizuka, T. Ogawa and M. Osakabe: "Conceptual Study of Actinide Burner Reactor": in *Proc. 1988 Int. Reactor Physics Conf.*, (Jackson Hole) 1988.

[10] Y. Kato et al., "Accelerator Molten Salt Target System for Transmutation of Long Lived Nuclides", in *Proceedings of the OECD-NEA Specialist's Meeting on Accelerator-Based Transmutation*, PSI Würenlingen/ Villigen, March 24-26, 1992.

[11] J. Toevs, et al., "Progress of ATW Project", in *Proceedings of 8èmes Journées SATURNE*, Saclay, May (1994).

[12] F. Carminati, R. Klapisch, J.P. Revol, Ch. Roche, J.A. Rubio and C. Rubbia, "An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Beam Accelerator", CERN/AT/93-47 (ET), (1993).

[13] H.S.Cheng: "A Point Kinetics Program" BNL Memo, April 26,1976; Revised "Point Kinetic Solution by VIP", BNL Memorandum 8/31/90.

[14] R. Beauwens, N. Guessous, E. Mund and A.Van de Velde: "Intermediate Report on the development of HEXNODYN-2", Service de Metrologie Nucléaire, Unversite Libre de Bruxelles, 1050, February 21, (1992).