A COMPARISON OF SOME NEUTRONICS CHARACTERISTICS OF CRITICAL REACTORS AND ACCELERATOR DRIVEN SUBCRITICAL SYSTEMS

C.H.M. BROEDERS
Forschungszentrum Karlsruhe, Postfach 3640
D-76021 Karlsruhe, Germany
E-mail: cornelis.broeders@inr.fzk.de

ABSTRACT

After a general introduction of characteristics of possible critical reactor systems (CRS) and accelerator driven systems (ADS) it is proposed only to compare similar systems, based on the same design principles. For fast neutron spectrum designs of CRS and ADS, comparisons concerning applied calculational procedures, flux and power distributions, power level control, burnup behaviour, incineration potential, aspects of dynamics and accident analysis and possible future R&D-work are discussed. Although ADS may have important advantages, especially related to safety aspects, it is not yet clear that during accidents with heat decay removal failures, fuel melting und fuel slumping with the potential of recriticality configurations may be avoided. If such recriticality cannot be excluded, reconsideration of thermal ADS may be a suitable solution.

1 Introduction.

In a critical reactor system (**CRS**) a neutron chain reaction is kept alive due to the balance of neutron productions and neutron losses. Due to the fact that a small fraction of the produced neutrons is not emitted as prompt neutrons immediately after the fission events but appears after characteristic delay times due to the decay of associated precursors, critical systems may be controlled fairly easily, e.g. for the adjustment of the required power level. Many different designs for CRS have been proposed and realized with very different characteristics. Examples of actual designs for power reactors are: light water reactors with boiling or pressurized coolant (BWR, PWR), heavy water moderated reactors (CANDU), gas-cooled reactors (AGR, HTGR), liquid metal cooled fast reactors (mainly sodium cooled). Molten salt reactors have been investigated since the early fifties.

Accelerator driven subcritical reactor systems (**ADS**) also have already been proposed in the fifties. A revival of these ideas was initiated by considerations at LANL by Bowman and coworkers for the incineration of longlived wastes from nuclear applications and by the proposals of Rubbia and coworkers for a so-called energy amplifier and for plants dedicated to the incineration of nuclear wastes e.g. arising from conventional LWRs. Further, in a number of countries like USA, Japan, France, Spain, Italy and others, dedicated projects are in progress for the realization of such systems. These ADS concepts also show different design features, varying from molten salt to conventional lumped fuel systems. The power level in an ADS is proportional to the applied accelerator currents and depends strongly on the level of subcriticality and on the position of the external sources.

In the present paper a comparison of important characteristics of CRS and ADS will be given for comparable designs of the reactor components of the systems.

2 Main properties of possible designs of CRS and ADS.

The characteristics of CRS are well known and are analyzed in many publications. In reference [1] an overview for modern reactors may be found. Reference [2] gives more detailed information for fast reactors. Concerning molten salt systems, an interesting review may be found in reference [3]. A comprehensive overview of ADS activities is collected in the IAEA status report [4].

For the comparison of CRS and ADS the most interesting topics are safety and reliability. Economic aspects may be of interest too, but they will not be discussed here. Although all nuclear reactors may claim to be safe, not all reactor concepts have the same **safety characteristics**. The most important safety related issue is the possibility of supercritical configurations of the reactor system with the potential of energetic reactivity accidents leading to core destruction and radioactivity releases. The probability of building critical masses during core damaging accidents also is an important question in this context. Thermal reactors with low enriched fuel are favourable, compared to fast reactors with higher enrichments. Another important property of a reactor system is its dynamic behaviour after disturbances in the nominal conditions. Important parameters for the dynamic reactor behaviour are reactivity coefficients for deviations from the nominal state like coolant density reactivity coefficient, fuel temperature coefficient etc. and neutron lifetime and delayed neutron fraction in the system. Thermal systems usually have positive **coolant density reactivity coefficients**, whereas fast systems have a tendency to have negative ones. A negative coolant density reactivity coefficient means that a decrease of the coolant density leads to a positive reactivity effect. Positive reactivity effects lead to increased power density, increased coolant temperature and decreased coolant density with positive reactivity feedback. In such systems other mechanisms, like fuel temperature coefficients, are required to avoid the reactivity increase. Positive coolant density reactivity coefficients are highly desirable in CRS. In ADS the level of subcriticality may avoid problems with negative coolant density reactivities. The main components of the **fuel temperature reactivity coefficient** are the temperature dependent reaction rates in the resonance region of the heavy isotopes (Doppler effect). The main contributor to the negative Doppler effect is usually the capture in U^{238} or Th^{232}. Other isotopes with significant contributions may be absorber fuel and structural materials. The compensating effects of fission and capture contributions of fissile isotopes usually lead to small net results. The **mean neutron lifetime** decreases with spectrum hardening and may vary from 2.5 10^{-5} seconds in PWR to 4.5 10^{-7} seconds in FBR [1]. Larger mean neutron lifetimes are favourable for the reactor dynamics behaviour. The **delayed neutron fraction** in reactor cores depends on the composition of the fuel isotopes. In most cases, delayed neutron fractions from fast fissions (e.g. in Th^{232} and U^{238}) are considerably larger compared to the effects for thermal fissions. Also a tendency to smaller values for inceasing charge numbers of the heavy isotopes may be observed [5]. The mean fraction of the delayed neutrons is associated with the value of 1 dollar of reactivity for dynamics behaviour.

The **reliability** of a reactor system is closely connected to the complexity of the technical realization and to the available experience with such a system. Water cooled reactors have proven reliability, despite the high pressures, especially in PWRs. Heavy metal cooled reactors also have demonstrated proven technology, but with less practical experience. Molten salt technology, as a potential candidate for ADS, has been investigated extensively in the past, but no realized projects exist at present. For ADS the coupling of a reliable powerful accelerator with a suitable subcritical reactor system is a new feature for which until now no practical experience exists. Recent observations with running accelerators indicate problems with disruptions of the proton beams with possible consequences for the residence time of some essential components of the subcritical core [6].

Because the designs of both CRS and ADS may vary significantly, a **comparison of such systems only seems meaningful for comparable proposals, based on the same design principles**. The present discussions and proposals for future ADS concepts concentrate on systems with fast neutrons. Such systems have favourable fission- to capture-rate ratios for most heavy isotopes, being an advantage with respect to actinide production and actinide transmutation. In the following sections a comparison of important characteristics of CRS and ADS with fast neutrons in a reactor core with lumped fuel (fuel-bundles) will be discussed.

3 Comparison of similar CRS and ADS.

The proposal of Rubbia and coworkers for a conceptual design of a fast neutron operated high power energy amplifier [7] lead to a number of related studies. In reference [7] the subcritical reactor core is placed in a huge lead-filled vessel with natural convection for the heat removal. The core consists of hexagonal fuel assemblies of fuel rods with two different lattices in inner and outer zones. The 1 GeV 12.5 mA proton current comes from a dedicated cyclotron accelerator and hits a spallation target near the center of this core. In 1996 the IAEA started a benchmark investigation for studying the long time behaviour of an ADS with Th/U^{233} fuel as specified in the Rubbia-proposal and with a somewhat simplified geometry model [8]. At FZK own investigations for an ADS similar to the Rubbia-proposal, are in progress, both for an energy amplifier (EA) and for Pu and minor actinide (MA) incineration. First analyses with tools available at FZK showed possible problems for the technical realization of this concept. Some of these problems are strongly related to the heat production and removal in the core. The investigations for the FZK-proposal will form the basis for the following comparisons. Alternatively to the lead coolant in ADS and CRS, sodium coolant also will be considered. Mainly neutron physics aspects will be discussed.

3.1 Applied calculational procedures.

For a specific reactor system the applied procedures for neutronic calculations of CRS and ADS are similar. Most codes for the solution of the neutron transport equations for CRS allow the treatment of external neutron sources. In those cases it is convenient to apply an additional code for the determination of the neutron source, produced by a proton beam hitting a spallation target. At present, most of the calculational procedures for ADS investigations apply below ≈20 MeV codes which are also in use for CRS calculations. These codes may be Monte Carlo type like MCNP or deterministic like S_n transport or diffusion solutions. The development of a unified MCNP-based Monte Carlo code for ADS investigations, including depletion, is in progress [9].

Usually the neutronic ADS calculations at FZK are performed within the code system KAPROS in combination with standard stand-alone codes like MCNP and DANTSYS. KAPROS has been developed for the calculation of fast reactor systems and has been supplemented with modules for the calculation of thermal and epithermal reactors. The subsystem KARBUS has been qualified for advanced depletion calculations for thermal, epithermal and fast reactor systems, see also reference [10]. Most of the applied multigroup libraries have an upper energy boundary of 10 MeV. The development of a new library with 75 energy groups up to 50 MeV is presently in progress. For the spallation calculations the LAHET code system LCS and the Jülich-version of HETC have been used. In reference [11] more information is given about these calculational procedures.

3.2 Flux and power distributions.

A practical nuclear reactor core design needs a power density distribution with acceptable peaking factors. The power shape in a nuclear core is determined by the space-dependent fission rates: neutron flux times fission cross section. Whereas the radial and axial flux shapes in thermal CRS are quite flat, the gradient at the core boundary in fast CRS is steeper. In order to obtain a flatter radial power shape, in fast CRS usually two or three radial fissile enrichment levels are applied. In ADS the power shape seems to be much more problematical. Already in reference [7] it was pointed out, that in a subcritical device far enough from criticality (K_{eff} ≈0.95) the neutron flux distribution has an exponential slope towards a neutron source in the center, compared to a cosine- or Bessel-function shape towards the center of a cylindical critical reactor. The consequences of this phenomena could be observed in the results of the IAEA ADS benchmark mentioned before [8]. In figure 1 the radial power distributions in 3 ADS with different initial values for subcriticality are shown with the corresponding radial formfactors f_{rad}, varying from 2.5 to 3.8. Such formfactors are not acceptable in practice. At FZK a number of measures have been investigated in order to improve these formfactors [11]. Both multiple enrichment zones and multiple neutron sources in the fast subcritical core allow designs with acceptable power distributions at system startup. As an example in figure 2 the midplane power distribution in an ADS with uniform fuel lattice and three distributed neutron sources is shown. The overall formfactor for this system is close to $f_{tot} \approx 2.0$ and is acceptable for a realistic reactor design.

3.3 Power level control.

The power level control in CRS and ADS may apply different principles. In both systems the power is determined by the absolute level of the neutron fluxes. The solution of the basic neutron transport calculations for a **CRS** does not provide a value for the absolute level of the fluxes. The principles of critical reactor control, based on delayed neutron fractions, neutron lifetimes and reactivity feedback mechanisms, allow the choice of any arbitrary absolute flux level within the technical constraints of the reactor design. Power level changes in a CRS are initiated by small reactivity disturbations, e.g. by control rod movements or by feedback from changes of thermodynamic properties of the reactor system.

Application of the same calculational tools for an **ADS** introduces an external source in the neutron transport calculation, resulting in absolute fluxes for the ADS case. The power production in the system is determined by the level of subcriticality (internal source) and by the strength and the position of the external neutron source(s). This means, that power level control in an ADS may be realized by changes of the external source strength or of the subcriticality level. Most of the proposals for ADS concepts do not provide active control devices for the subcritical cores and assume proton sources with a rather wide range of operation for the proton currents in order to extract the required amount of power from the core. Such concepts only can be accepted if it can be excluded that an upper level of the subcriticality can never be exceeded, e.g. by reactivity gain due to transmutation processes or decay or due to changes in the reactor configuration.

3.4 Burnup behaviour.

The main processes during fuel burnup are similar in CRS and ADS: changing of the isotopic composition of the fuel and buildup of fission products. Additionally in an ADS also spallation products may play a role, especially in systems with small subcriticality values and corresponding high proton currents. Generally fast neutron spectrum systems have smaller burnup reactivity effects compared to thermal neutron spectrum systems. The main reasons are the lower effective cross sections of the fission products and usually the better conversion of fertile to fissile material in the harder neutron spectrum. The IAEA ADS benchmark in reference [8] was organized to investigate the burnup behaviour of an ADS with Th/U^{233} fuel, see also section 3. Several institutions participated to this benchmark using partly different calculational procedures (codes and data). The FZK results of figure 3 were within the spread of the other contributions. The two curves for initial K_{eff}=0.96 were obtained with different geometrical models for the burnup zones: 7 zones as specified in the benchmark geometry compared to 22 zones with a finer subdivision in the fuel zones. All curves show a strong reactivity decrease during the first ≈100 full power days. This behaviour is typical for thorium fuel: neutron capture in Th^{232} leads to the absorber isotope Pa^{233} being the precursor with half-life ≈28 days of the fissile isotope U^{233}. After reaching nearly an equilibrium concentration of Pa^{233} (dependent on the power rating of the fuel), the buildup of U^{233} may lead to an increase of the reactivity. This reactivity increase is reduced by the absorptions in the fission products. One of the main objectives of the design of Rubbia et.al. was to obtain a flat curve for K_{eff} as a function of burnup. In this way only moderate changes in the proton current are required to maintain a constant system power, without a need for other control mechanisms.

Using Pu instead of U^{233} as fissile material in an ADS, e.g. as a burner of multirecycled Pu with high contents of Pu^{240} and Pu^{242}, results in a more complicated burnup behaviour. In figure 4 the results of KARBUS cell burnup calculations are compared for the Th/U^{233} fuel of the IAEA ADS benchmark with 10% U^{233} content and for a Th/Pu fuel with 10% Pu_{fis} and a Pu composition of 5% Pu^{238}, 40% Pu^{239}, 32% Pu^{240}, 6% Pu^{241}, 15.5% Pu^{242} and 1.5% Am^{241}. We may observe a good agreement between the shapes of the Th/U^{233} curve of figure 4 and the IAEA ADS benchmark results of figure 3. However, the Th/Pu fuel in figure 4 shows a strongly deviating burnup behaviour with a strong increase of reactivity with burnup. These preliminary results indicate problems with subcriticality during burnup in such a Th/Pu system and this may lead to a need for active control devices in this ADS, e.g. control rod systems.

3.5 Incineration potential.

One of the main objectives in the area of partitioning and transmutation (P&T) research is the incineration of Pu and MA. In the international CAPRA project these issues are studied for Superphenix (SPX) type fast reactor designs. In order to achieve acceptable incineration rates of Pu, as high as possible Pu-fractions in the MOX fuel should be chosen. At present the upper limit for the Pu-fraction seems to be determined by the MOX-solubility during reprocessing at a level of about 45%. These high Pu-fractions lead to a SPX core with highly diluted fuel and large burnup reactivity losses with complications for the reactivity control of this CRS. First exploratory investigations for the incineration of LWR-Pu in an ADS with Th/Pu fuel and sodium coolant show comparable Pu-incineration rates in this not optimized ADS and in the CAPRA reactor; about 70 kg(Pu)/TWe.h≈600 kg(Pu)/Gwe.a, see reference [12]. The required proton currents in the ADS vary between 18 and 40 mA at 1 GeV. These results indicate, that comparable CRS and ADS designs tend to comparable Pu-incineration potentials. Both systems will have specific advantages and drawbacks. Problems with safety issues in the CRS may be solved for an ADS, but probably at the expense of complex technical ADS designs, especially for the accelerator if high proton currents are required.

One obvious advantage of ADS is the neutron surplus provided by the spallation processes. These (expensive) extra neutrons enable the incineration of materials like fission products or the use of isotopic mixtures with K_∞ values not sufficiently exceeding unity for realistic conventional CRS.

3.6 Some aspects of dynamics and accident analysis.

Sodium versus lead coolant in fast reactor systems.

As explained in section 2, the dynamics behaviour of a reactor system strongly depends on its design, e.g. the choice of coolant and fuel. If we compare a CRS and an ADS with the same coolant and the same type of fuel, the most important difference is the required fissile fraction in the fuel. Depending on the level of subcriticality in the ADS, the enrichment of the ADS may be substantially smaller compared to the CRS. Lower enriched fuel tends to more favourable coolant density and fuel temperature reactivity coefficients and improved dynamics behaviour. Moreover, the number of possible critical masses in the reactor system during a core damaging accident will be smaller, if existent. The choice between sodium and lead for a fast reactor system also may influence the required fissile fuel fraction considerably. As an example, in table 1 preliminary results are shown from an investigation for the potential use of SNR300 fuel assemblies (FA) in a subcritical system. The K_∞ and K_{eff} values have been obtained from eigenvalue calculations using the KAPROS modules DIFF0U and D3E.

coolant	K_∞ DIFF0U	K_{eff} D3E
sodium	1.6048	0.9659
lead	1.6192	1.1416

Table 1: Comparison of reactivities with sodium and lead coolant for SNR300 type fuel.

The applied reactor model consists of 169 FA-positions (central position surrounded by 7 rings of FA) with the following loading: in the central 7 positions coolant with the proton source, the positions 8 to 91 (ring 2 to 5) SNR300-core1 FA and the positions 92 to 169 (ring 6 and 7) coolant. The criticality of this model has been investigated both for sodium and lead coolant. The K_∞ values show only small differences for the two coolants. However, in the case of sodium cooling we have an acceptable K_{eff} for the subcritical core, whereas the lead cooling case is far supercritical. This means, that for this SNR300 fuel in this specific design for a relatively small core with a coolant buffer zone at the outer boundary the enrichment may be substantially smaller with lead cooling, compared to sodium cooling and that lead cooling will have better safety characteristics.

Emergency shutdown in CRS and ADS.

Although the energy and heat production in an ADS can be stopped rather easily by interrupting the proton beam, this might not be a decisive advantage compared to CRS. First of all, shutdown and control mechanisms in CRS have demonstrated their extraordinary reliability, based on diversity and redundancy in design and activation. Further, the decay heat removal after shutdown poses an equally severe problem for both CRS and ADS. It has still to be proven that in comparable designs for CRS and ADS, in case of system failures leading to problems with decay heat removal with probably fuel melting and slumping, the consequences for an ADS would be less harmful than for an CRS.

Complications with neutron dynamics calculations of ADS.

The neutron dynamic analysis of **near to critical systems** with point or space dependent kinetecs, including perturbation theory, is well understood and many qualified codes are available for different reactor types. These CRS codes are not always applicable to ADS. Some possible complications are:

- For the calculation of feedback reactivities reliable power distributions are required. This means for an ADS that external neutron sources must be taken into account for the determination of the neutron flux distributions. Not all codes have this option.

• For near to critical systems, eigenvalue calculations are convenient and reactivity coefficients are well defined by differences between the eigenvalues. Perturbation theory enables the fast calculation of reactivity coefficients for disturbances from the nominal reactor configuration. In an ADS the multiplicity of the system may be calculated from neutron productions and neutron losses in the system. A straightforward application of perturbation codes is not possible, because these codes are based on real and adjoint fluxes from eigenvalue calculations. So the determination of reactivity coefficients in an ADS may be more complicated compared to CRS.

• For neutron dynamic calculations in near to critical systems usually the following flux synthesis is applied:

$$\Phi(\vec{x},t) = \Psi(\vec{x},t) \cdot P(t)$$

with

$\vec{x}$ variables for space, energy, direction

t time

A common assumption is that the shape function $\Psi(\vec{x},t)$ varies only slowly with time, whereas the amplitude function $P(t)$ may vary much more rapidly with time. The power density curves of figure 1 in section 3.2 indicate, that the **power shape in an ADS is quite sensitive to the subcriticality level**. The application of the flux synthesis formulations and simplified treatments such as the quasi-static approaches have still to be qualified for ADS investigations.

3.7 Comments addressing fields for further R&D-work for ADS.

The needs for R&D-work for ADS are related to several different areas. Some important topics are:

- Accelerator design for high reliable steady state proton currents.
- Spallation target design, including the window.
- Lead coolant technology.
- Thorium fuel cycle technology.
- In the case of MA transmuters, remote handling techniques for fabrication and reprocessing of fuel containing high MA concentrations.
- Calculational tools, e.g. for the improvement of
  - the spallation physics,
  - the coupling of spallation and neutron transport processes including burnup,
  - the neutron physics and thermohydraulic design and
  - the dynamics and safety analysis.

Concerning neutronics the following items may be identified:

• Development of a unified Monte Carlo code, including improved spallation physics coupled with neutron transport and burnup. This activity has been started [9]. Such a code is required for detailed design studies and may be applied for the determination of reference solutions for the qualification of codes with simpler approximations to be used in exploratory investigations.

• Implementation of multi-group libraries with energies above 20 MeV (up to 50..300 MeV), mainly for the deterministic solutions of the neutron transport equations. The upper energy boundary may be determined by sensitivity studies.

• Development of fast nodal neutron transport codes with an adequate external source option, e.g. modification of the HEXNOD code.

• Integration of the spallation product and the fission product treatment. This issue becomes of growing interest and significance with decreasing core subcriticality and related higher proton currents.

• Formulation of a modified perturbation theory for the calculation of reactivity coefficients for source driven subcritical systems.

• Analysis of the validity of quasi-static approaches for dynamics investigations and possibly development of more advanced methods in case this approximation is not justified and its application is not adequate.

4 Concluding remarks for future investigations for ADS.

In the past years a number of proposals for ADS applications have been presented, varying from an energy amplifier with lumped Th/U^{233} fuel and fast spectrum with lead coolant to fission product and actinide transmuters with fast and thermal spectra. The main argument for these ADS concepts is usually improved safety, compared to CRS. Some ADS objectives hardly may be realized with CRS, e.g. incineration of larger amounts of fission products or of heavy fuel isotopes with unfavourable properties for the dynamics behaviour (delayed neutron fractions, coolant density and fuel temperature reactivity coefficients, etc.). A comparison of similar CRS and ADS designs shows an improvement of the safety characteristics of an ADS, caused by the lower required fissile enrichments. However, it is not clear that in fast spectrum ADS recriticality during core damaging accidents can be avoided in all circumstances. In the case core damaging accidents with recriticality cannot be excluded, reconsidering thermal ADS may be a more suitable solution. Finally one has to keep in mind that both **critical and subcritical burner reactors** only may be run if reprocessing plants with adequate capacity for the fuel cycles of interest are realized.

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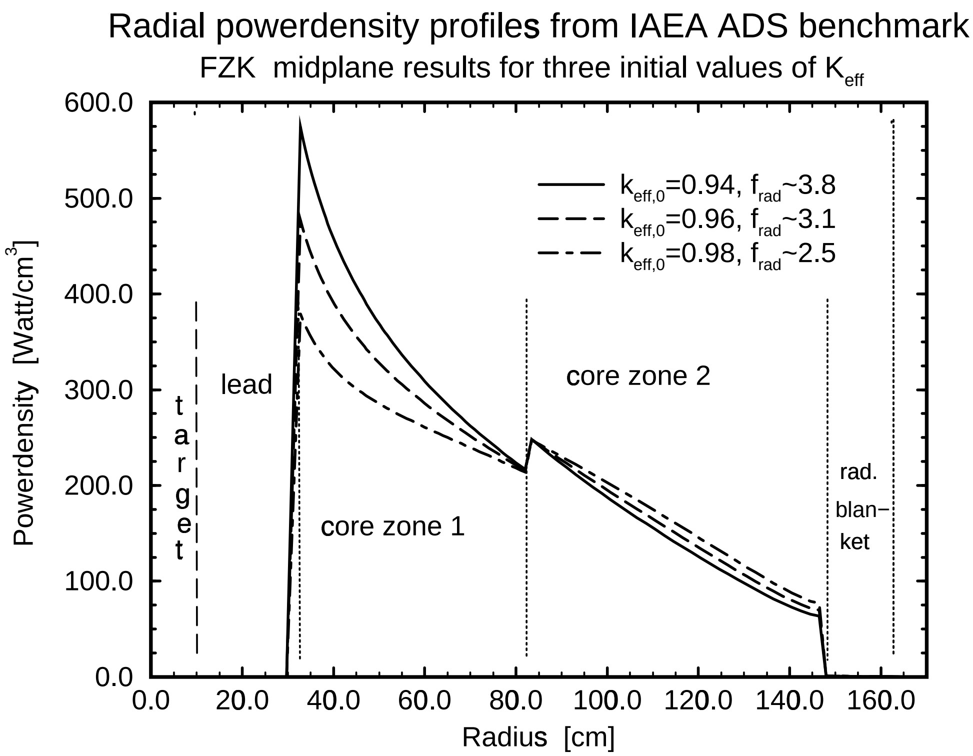

Figure 1: Radial power density profiles in an ADS with different criticality

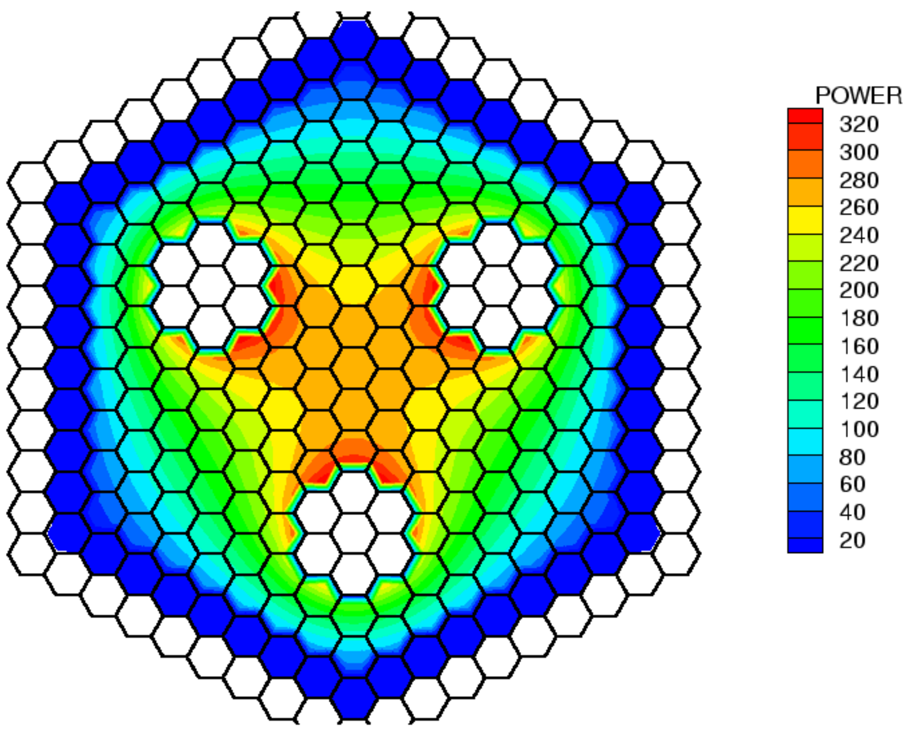

Figure 2: Midplane power density distribution in an ADS with three neutron sources

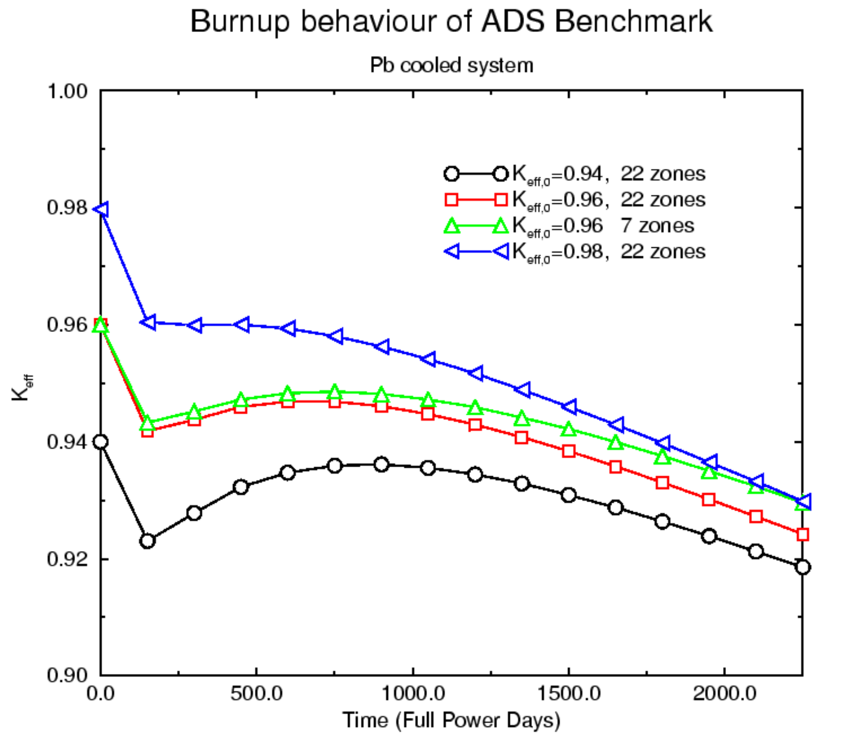

Figure 3: K_{eff} as a function of burnup for the IAEA ADS benchmark cases

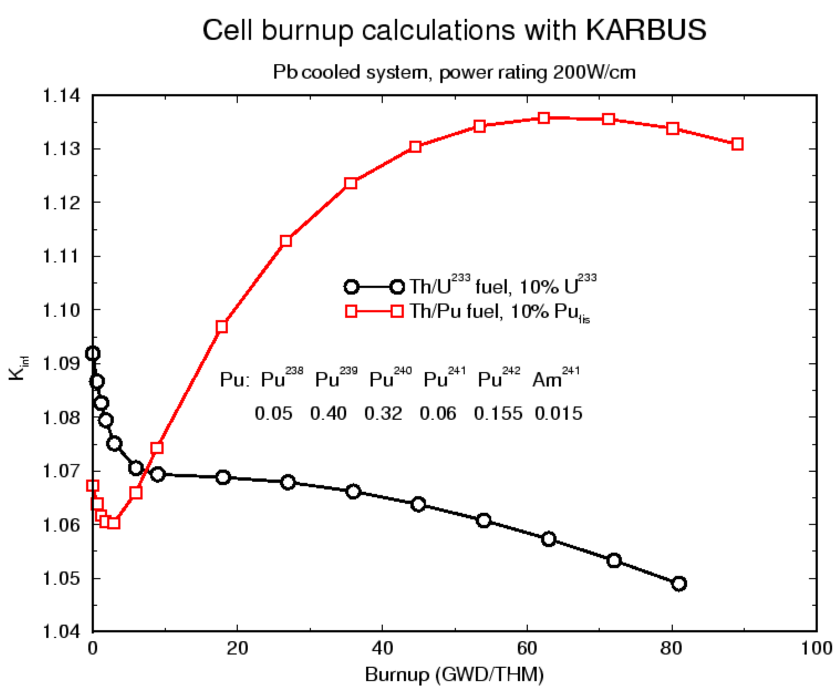

Figure 4: K_{∞} as a function of burnup for Th/U^{233} and Th/Pu fuel