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The physics of accelerator driven sub-critical reactors

S B DEGWEKER, BIPLAB GHOSH, ANIL BAJPAI and S D PARANJAPE
Theoretical Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India
E-mail: degweker@apsara.barc.gov.in

Abstract. In recent years, there has been an increasing worldwide interest in accelerator driven systems (ADS) due to their perceived superior safety characteristics and their potential for burning actinides and long-lived fission products. Indian interest in ADS has an additional dimension, which is related to our planned large-scale thorium utilization for future nuclear energy generation.

The physics of ADS is quite different from that of critical reactors. As such, physics studies on ADS reactors are necessary for gaining an understanding of these systems. Development of theoretical tools and experimental facilities for studying the physics of ADS reactors constitute important aspect of the ADS development program at BARC. This includes computer codes for burnup studies based on transport theory and Monte Carlo methods, codes for studying the kinetics of ADS and sub-critical facilities driven by 14 MeV neutron generators for ADS experiments and development of sub-criticality measurement methods. The paper discusses the physics issues specific to ADS reactors and presents the status of the reactor physics program and some of the ADS concepts under study.

Keywords. Accelerator driven systems; nuclear waste transmutation; computer codes; reactor physics; reactor noise; kinetics; burnup; transport theory; Monte Carlo; thorium utilization; neutron multiplication; sub-criticality; sub-critical facilities.

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1. Introduction

Accelerator driven systems (ADS) are attracting worldwide attention increasingly due to their superior safety characteristics and their potential for burning actinide and fission product-waste and energy production. A number of countries around the world have drawn up roadmaps for development of ADS.

Indian interest in ADS has an additional dimension, which is related to the planned utilization of our large thorium reserves for future nuclear energy generation. Thorium has the added advantage that it produces much less quantities of long-lived radioactive actinide wastes when compared to uranium. However, thorium by itself is not fissile and must be first converted to fissile ^{233}U by neutron irradiation. In ADS, the accelerator delivers additional neutrons over and above those coming from fission. Moreover, it is possible to design Th-fuelled ADS [1,2] such that long-term reactivity changes due to burnup are minimal. Together with a variable proton current, this obviates the need for parasitic absorbers for long-term reactivity control. The ADS is therefore expected to possess superior breeding characteristics when compared to critical reactors. In ADS, since reactors are not required to maintain criticality, it is possible to increase burnup, i.e. to extract more energy from a given mass of fuel till such a time that k_{eff} of the system falls to a value below which it is not possible to maintain the power by increasing accelerator current.

The physics of ADS is quite different from that of critical reactors. Critical reactors can be operated at any power that can be safely removed whereas the power of ADS is determined, additionally, by the operating k_{eff} and the available accelerator beam current. The power in an ADS is very sensitive to the value of k_{eff} and it becomes essential therefore, to accurately predict this parameter over the entire length of the burnup cycle. Since the spatial and energy distribution of the external spallation source is different from that of the fission source, there is another factor, called the 'source importance' factor which decides the power of ADS. This difference has led to the concept of k_{s}, in addition to k_{eff} familiar to all reactor physicists. The stationary spatial flux distribution and the neutron spectrum in ADS and the dynamic response of ADS to transients and perturbations are quite different from that of the critical reactors.

The sub-critical reactivity is an important parameter from the point of view of operating ADS. It decides the accelerator current that will be necessary to produce the desired power as well as the margin of safety available. Measurement and continuous monitoring of this parameter in operating ADS reactors will be an essential safety requirement. Theoretical and experimental studies are being carried out around the world for developing suitable methods for this purpose.

For such reasons, physics studies on ADS reactors are necessary for gaining an understanding of these systems. For carrying out these studies, it is important to have the necessary theoretical tools and experimental facilities. Development of these tools and facilities constitutes an important aspect of the ADS development program at BARC. The theoretical tools under development include computer codes for burnup studies based on transport theory and Monte Carlo methods, codes for studying the kinetics of ADS and studies for evolving suitable reactivity measurement/monitoring methods, including a new theory of reactor noise in ADS. As regards experimental studies, there is a program to set up a sub-critical facility driven by a 14 MeV neutron generator described in a later section for ADS experiments. The aim of these efforts is to develop the capability for evolving our own ADS design which is appropriate from the Indian perspective of thorium utilization.

The paper discusses the principal differences in the physics of critical and ADS reactors and the consequent differences in design and analysis methods. It also presents the status of the program outlined above and some of the sub-critical ADS reactor concepts under study.

2. Reactor physics of sub-critical ADS

2.1 Sub-critical multiplication in ADS

Unlike critical reactors, which can be operated at any power that can be safely removed, the neutron multiplication in ADS, M and the fission power P are simply related to k_{eff}, k as follows:

$$M - 1 = \frac{k}{1-k}$$
$$P = F\frac{i\nu_{\mathrm{sp}}e_{\mathrm{f}}k}{\nu(1-k)} = \frac{Fi\nu_{\mathrm{sp}}e_{\mathrm{f}}(M-1)}{\nu} \tag{1}$$

where i is the accelerator current, e_{f} is the energy per fission, ν and ν_{sp} stand for the number of neutrons produced in fission and spallation respectively and F is a factor depending on the units used. The above equations are best regarded as simple thumb rules and are exactly valid if the external source distribution in space and energy is exactly the same as the fission source distribution. Since in general this is not true, there is an additional factor in the numerator of the above equations. This is referred to as the source importance factor. This factor depends upon both the spatial and energy distribution of the source and can assume values quite different from unity. For example, this factor is 2.0 for a homogeneous spherical reactor with a point source at the centre. This possibility, of having a source importance factor much larger than unity, can be exploited to obtain higher power for a given k_{eff}. For example, in the one-way coupled ADS concept, the neutron multiplication and power are reported to be about five times larger than that predicted by the above equations.

Another way of looking at this aspect of sub-critical multiplication is used by some authors [3]. In their view, instead of using the fundamental eigenvalue k_{eff}, eq. (1) is used to define the multiplication factor k which is called k_{source} and M is computed as the ratio of the total neutron production and the external neutron source using a detailed calculation based on either transport theory or Monte Carlo for the source problem. It is important to keep in mind the difference between these two definitions of k.

2.2 Thorium utilization in ADS: Advantages and limitations

Since ^{233}U has the highest value of η (among the fissile nuclides) in the thermal range, there are several attempts to obtain a self-sustaining or breeding Th–U cycle using thermal reactors. However, most designs need an external supply of fissile fuel such as Pu to sustain them. Likewise, the studies in fast reactors have shown that a self-sustaining Th–U cycle is possible but with little or no breeding. Since the ADS has an external supply of neutrons in addition to those produced from fissions, there is the hope that ADS might support self-sustaining thermal and possibly breeder systems based on the Th–U cycle. While our studies show that this is indeed possible and it must be remembered that neutrons from the accelerator are rather costly due to the extra cost of the accelerator and due to the fact that the accelerator consumes electricity. It is therefore important that the accelerator performs other functions in addition to simply supply extra neutrons. This could, for example, be to increase the burnup or to simplify the fuel cycle. Considerations such as these led us to the Th-burner concept discussed in a later section.

There are other interesting questions in this context. Is it possible to start an ADS system without any fissile material at all, i.e. in which the system runs on fissile material generated *in situ*? Would the multiplication of the source neutrons in a sub-critical multiplying assembly enhance the fissile material production rate? Can this effect accelerate the fissile material accumulation and the consequent approach to full power of an ADS initially fuelled with a purely fertile material such as Th? We have presented simple elegant arguments [4,5] in some earlier publications to answer these questions. The conclusion is that fissile material accumulation is a slow process; that sub-critical multiplication would enhance the fissile material production rate only if the sub-critical reactor is a breeder; and in a reactor initially fuelled with pure fertile material, the reduction in fissile material accumulation time due to this multiplication process is marginal.

2.3 *Sub-critical ADS kinetics and monitoring of the degree of sub-criticality*

The kinetic response of the sub-critical ADS reactor is quite different from that of conventional critical reactors. Various studies have shown that in the deeply sub-critical region, the response of the ADS to fairly large addition of reactivity is quite benign and the delayed neutrons and feedback coefficients have little bearing on the nature of the response. However, feedback effects are important in systems closer to critical. For this reason, two distinct regimes; the 'source-dominated' and the 'feedback-dominated' have been identified. To gain an understanding of these effects, the TRADE series of experiments in medium power experimental facilities have been proposed [6].

Most ADS kinetics studies [2,7] have been based on the point kinetics model. Space-dependent modeling would however be important since the flux distribution in source-driven systems would have contributions from several modes whose relative contribution would be dependent on the reactivity. Hence, changes in the shape function are expected even in the absence of localized perturbations. Even for the point kinetics studies, the best weighting function is an open question.

Questions regarding the measurement/monitoring of the degree of sub-criticality are important from the safety point of view. Various methods such as the 'pulsed neutron' and various noise methods have been studied in the MUSE and YALINA experiments [8–11]. Other methods studied include source modulation method [12], and a method using cross-correlation between the proton current and neutronic fluctuations [13]. It is important to keep in mind that those methods, which require some kind of calibration at delayed critical are unusable since the ADS will never be made critical under normal operating conditions.

3. Theoretical and experimental reactor physics related developments at BARC

We have seen earlier that ADS are quite different from critical reactors with regard to the neutron spectrum and the flux shape in the presence of a spallation source, and depend on the degree of sub-criticality. The absolute power and the power distribution of ADS are sensitive to the value of multiplication factor (k). This imposes restrictions on the error in the calculated value of k_{eff} that may be tolerated throughout the burnup cycle. Since ADS is meant for higher burnup (typically 100 GWd/t), lumping of fission product (FP) may not be a correct process and explicit calculation of the concentrations of a large number of fission products becomes necessary. Inventories of FPs are important from the radiological point of view and this again needs explicit treatment. All these call for a new approach to ADS analysis. The availability of large computing power has made it feasible to use continuous energy MC method for core reactor physics analysis including burnup.

We have developed the codes McBurn and BURNTRAN [14,15] for carrying out fuel burnup simulations based on the Monte Carlo method and the multi-group transport theory method respectively. The codes are functional for fixed fuel (one batch fueling) and are being put to use for evaluating some of the interesting ideas for applications of ADS. Further development of McBurn is being carried out to include fueling operations (insertion, removal, or shuffling of fuel assemblies).

3.1 *McBurn: A continuous energy Monte Carlo burnup code*

The region of interest (or the entire reactor core) is divided into a suitable number of burnup zones. McBurn works in tandem with a MC code, where the MC code calculates the reaction rates in each burnup zone at any instant of time while McBurn solves the burnup equations using the reaction rates thus computed. About 300 actinide and fission products can be considered for the following nuclear reactions: neutron capture, fission, n2n, alpha and beta decay. Burnup with energy (thermal, fast and high) dependent fission yields are taken from a recent table of England *et al* [16]. Numerical integration of the burnup equations over a time step is carried out using Gear's method [17], which is suitable for a system of stiff equations. Within a burnup zone and during a burnup step, the reaction rates per atom of any species are assumed to be constant.

Validation of the code has been carried out by (i) study of the IAEA ADS benchmark (fast system) [18] and (ii) cell level burnup of 19 rod U and Th cluster used in Indian 220 MW PHWRs [19] previously studied by other codes [20]. Figure 1 shows how our results compare with those obtained by other participants of the benchmark exercise using different codes and nuclear data. Our results fall within the same band. However, the overall spread in the results is fairly large and it is not possible at this stage to resolve the differences and ascertain the causes. The k_{inf} for the PHWR lattice cell with 19-rod Th fuel cluster compares well with CLUB, the maximum difference being about 0.004.

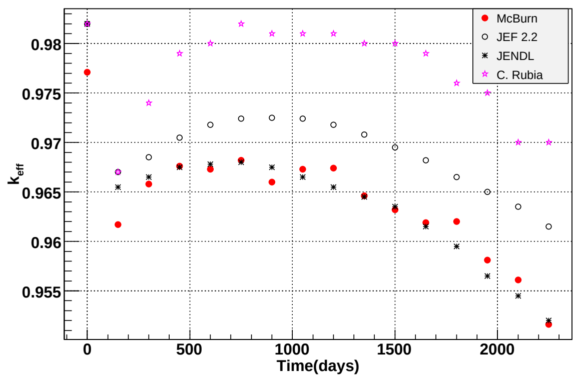

Figure 1. Comparison of McBurn with other participants of the ADS benchmark exercise.

3.2 *BURNTRAN: A transport theory burnup code*

The code package BURNTRAN [15] consists of a burnup module, BURN, developed by us, and the one- and two-dimensional multi-group discrete ordinate codes DTF [21] and ATRAN [22], and a 172-group WIMS neutron data library [23]. A number of modifications were carried out in the transport theory modules. As discussed in the case of McBurn, the region of interest is divided into several burnup zones and the transport theory codes provide the necessary reaction rates. The burnup module is based on Gear's method [17] for integrating a system of stiff differential equations. The code package BURNTRAN will be quite useful for fast scoping studies of various ADS configurations. Highly detailed and (time consuming) Monte Carlo burnup computations need to be undertaken only at the final design stage

Validation has been done by studying ADS benchmarks and 19-rod and 37-rod [24] PHWR clusters and comparing the results with other codes. Some of the results of this exercise are shown in table 1 and figures 2 and 3. We again observe that while PHWR lattices involving 19-rod Th and 37-rod U are predicted well, due to the large spread in the results of the ADS benchmark exercise, it is difficult to draw any definite conclusion.

3.3 *Theoretical studies on reactor noise in ADS*

Reactor noise methods have long been used for measuring reactor kinetics parameters in low power critical and sub-critical reactors. The interest in accelerator driven sub-critical systems (ADS) and the necessity of measuring/monitoring their degree of sub-criticality has created a renewed interest in these methods. Several low power experiments on ADS using noise techniques similar to those for conventional reactors have already been performed. There have also been suggestions regarding the use of noise techniques for monitoring the sub-criticality of ADS. In view of the above, several theoretical studies on various noise techniques for ADS [25–32] have appeared of late.

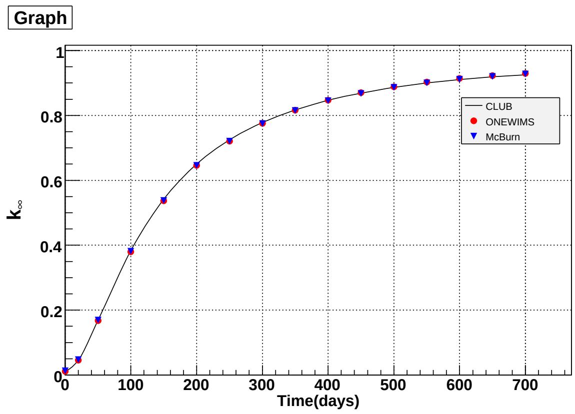

Figure 2. Comparison of McBurn and ONEWIMS (of the BURNTRAN package) with CLUB for PHWR lattice cell with 19-rod Th cluster.

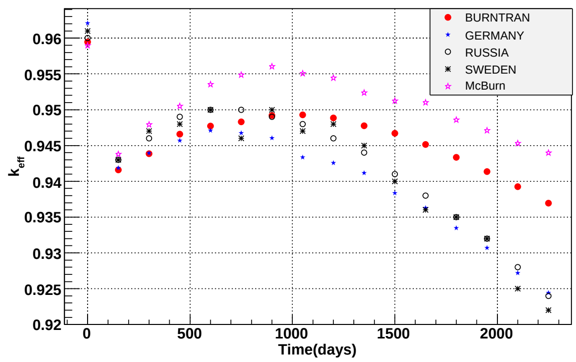

Figure 3. Comparison of BURNTRAN with other participants of the ADS benchmark exercise.

Table 1. Inter-comparison of important parameters obtained by BURNTRAN and by various other participants for the IAEA PHWR benchmark.

					Reactivity (mk)	
Burnup (MWd/t)	Code/participant	k_{inf}	^{235}U (%)	^{239}Pu	Void	Doppler
0	CLUB	1.1150	0.7114		15.97	5.58
	WIMS (Arg.)	1.1155	0.7110		16.82	5.78
	BURNTRAN	1.1154	0.7113		15.17	5.27
4000	CLUB	1.0413	0.3796	1.931	13.51	2.81
	WIMS (Arg.)	1.0456	0.3837	1.979	13.76	2.03
	BURNTRAN	1.0411	0.3813	1.932	12.96	1.29
8000	CLUB	0.9749	0.2020	2.490	13.66	1.88
	WIMS (Arg.)	0.9777	0.2073	2.539	13.72	0.37
	BURNTRAN	0.9762	0.2059	2.496	13.27	0.67

In the initial years, the most important difference perceived between critical reactors and ADS [25–28] was that the spallation reaction would produce a large number of neutrons at the same time in what could be called as a source event. Associated with this reaction, there would be a multiplicity distribution of the number of neutrons and its mean and the second factorial moment. From a theoretical point of view, there is little to differentiate such a situation from that of a spontaneous fission source, which also emits neutrons in multiplets. Such situations have been thoroughly analysed in the past, in the context of critical reactor noise, including the effect of delayed neutrons and space energy dependence.

At a theoretical level, we believe, that the principal difference between ADS and critical reactor noise is due to the accelerator characteristics [29,30]. In general, whatever may be the kind of accelerator actually used for any experimental or demonstration ADS, it cannot be tacitly assumed that the source events would constitute a stochastic Poisson point process. Some of the accelerators used for experimental purposes could actually be pulsed accelerators operating at frequencies ranging from several Hertz to Kilo Hertz. Even the so-called continuous wave (cw) accelerators produce protons in sharp bursts at a frequency related with the RF frequency driving the system.

In an earlier publication [30] and in a forthcoming paper, we have derived formulae for interpreting some of the classical noise methods such as Rossi alpha, the variance to mean, auto- (and cross-) correlation functions and (auto- and cross-) power spectral density, as well as some recently proposed methods [13], such as the cross-power spectral density between the proton current and the neutron detector signals for systems driven by periodically pulsed sources having a large multiplicity. It was shown that the rather high contribution due to the large multiplicity of the accelerator driven source to the variance (or any other measure of the noise) is significantly different for a periodically pulsed source as compared to that for Poisson source events.

The second point we wish to make is that the usual procedures [13] for deriving reactor noise formulae are invalid with correlated or periodic sources and can lead to contradictions [30]. In particular, we have shown that the periodic source cannot, generally speaking, be considered as a random source with a periodically modulated intensity.

More recent publications [31,32] on the subject consider the pulsed nature of the source and some of these also account for the [32] non-Poisson character of the ADS source.

3.4 *Program for experimental studies on ADS at BARC*

A facility for carrying out experiments on the physics of ADS and for testing the simulation methods under development, is being set up at PURNIMA laboratory, BARC. A 14-MeV neutron generator has been in existence in this laboratory for several years for performing fusion blanket neutronics studies. It consists of an accelerator, which produces a 200 mA current of deuterons accelerated to an energy of 300 KeV. These deuterons fall on a Ti target loaded with tritium. The 14-MeV neutrons are produced by the D–T fusion reaction resulting in a continuous source of about 3×10^9 n/s. Efforts are on to increase its strength and to have pulsed mode of operation for pulsed neutron source-based experiments.

A simple sub-critical assembly of natural U and light water was chosen for the purpose of basic reactor physics experiments. It consists of U metal rods of 3.45 cm diameter clad in 1 mm thick Al placed horizontally in Al tubes arranged in a hexagonal lattice of pitch 5.5 cm. A central axial Al tube houses the tritium target. The core length is 100 cm and a loading of 300 rods gives a k_{eff} that is about 0.87. The sub-critical assembly design is over and procurement/fabrication of various components is in progress. This facility is expected to become operational the next year. Measurement of flux distribution, flux spectra, total fission power, source multiplication, and degree of sub-criticality will be carried out during planned experiments. A report on the experimental program has been prepared [33] and the experiments will commence once the facility becomes operational. Measurement of the degree of sub-criticality is one such important experiment being planned, as monitoring this parameter for ADS will be an important safety requirement. This will be done by pulsing the accelerator beam and by reactor noise analysis. The new theory of reactor noise in ADS, described above can be tested in the facility.

4. Some ADS concepts evolved at BARC

In view of the many advantages for thorium utilization using ADS reactors, some questions assume importance. What is the reduction in the annual fuel requirement of a thorium fueled heavy water reactor if operated in the ADS mode? Is a self-sustaining cycle possible? How much extra energy can be extracted from a given mass of Th-based fuel before it is discharged? What would be the accelerator power required to drive such a reactor? Our studies for some time have been focused on these issues and the following remarks on various ADS concepts of interest to our program, are based on our present assessment.

The one-way coupled fast-thermal ADS reactor, conceived independently at BARC [34] and in Russia [35] is being studied. The inner core is a fast Pb/LBE cooled and mixed oxide (MOX) fuelled system which serves as a booster of the spallation neutrons. These neutrons then enter the second (main) reactor region which is thermal and of the PHWR type, but fuelled ^{233}U–Th MOX.

The thorium burner concept, proposed by us [5] is basically a heavy water reactor ADS utilizing Th in a once-through cycle, with no requirement of initial or subsequent feed of fissile material. The scheme allows 10% thorium to be burnt before the fuel is discharged, and results in a very simple once-through Th fuel cycle. However, the energy gain is small and we are examining various means to enhance the gain such as optimization of the k_{eff}, minimization of the parasitic capture and use of a target with a larger spallation yield, use of a booster around the target etc.

The one-way coupled fast-thermal ADS reactor described above can also be used for increasing the gain of the Th burner. The addition of a central booster can considerably bring down the accelerator power requirements. It has the added advantage that the inner booster region can be used for burning long-lived waste produced in our first and second stage reactors based on uranium and plutonium fuels.

5. Summary and conclusions

A brief review of the physics of sub-critical ADS reactors has been presented. We have also presented the status of the theoretical and experimental activities being carried out at BARC for studying the physics of such reactors and developing the necessary tools required for their design together with a discussion on the one-way coupled ADS and the Th burner concepts for Th utilization by the ADS route.

The continuous energy MC-based burnup code and the multi-group transport theory burnup code BURNTRAN have been described. Preliminary validation studies show encouraging results. Further development with regard to incorporating refueling schemes in McBurn is in progress. The discussion on sub-critical reactivity measurement methods and reactor noise in ADS brings out the distinctive features of ADS reactors.

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