SYNOPSIS

In recent years, Accelerator Driven Systems (ADSs) have attracted worldwide attention due to their superior safety characteristics as compared to critical reactors and their potential to incinerate Minor Actinides (MAs) and transmute Long Lived Fission Products (LLFPs). In a critical reactor, the number of neutrons produced by fission is exactly balanced by the number lost by leakage and absorption in various materials in the reactor. This balance is responsible for maintaining reactor power at any desired level. In sub-critical reactors, the number of neutrons produced by fission is less than that lost by leakage and absorption and hence, such reactors need an external neutron supply in order to maintain a constant power level. This external supply of neutrons comes from the interaction of a high energy proton beam with a heavy atom nucleus such as lead through a process known as spallation.

Such systems, first proposed for production of fissile material, were not pursued mainly due to the technological difficulties associated with building the required high power (about 1 GeV energy and few hundred mA current) proton accelerators, and developing suitable targets and windows which could withstand the severe thermal and radiation environment associated with such high power beams. The other reason was that uranium prices did not increase significantly so as to make accelerator breeding economically attractive. In the mid nineties, the Nobel laureate Carlo Rubia proposed ADSs for energy production using thorium fuel in a self sustaining cycle and requiring relatively modest power accelerators (about 1 GeV energy and 10 mA current). This initiated a renewed interest in sub-critical systems, and has presently caught the attention of the world for the equally important role of nuclear waste transmutation.
Indian interest in ADS is primarily related to the planned utilization of our large thorium reserves for future nuclear energy generation. Thorium has an added advantage that it produces much less quantities of long-lived radioactive wastes as compared to uranium.

The main R&D efforts are related to development of accelerator technologies leading to construction of a high energy high current accelerator. A major effort is also directed towards target and window technologies. Basic research activities in the area of the sub-critical reactor physics include new measurements and evaluations of nuclear data both at traditional reactor energies as well as at high energies, development of computer codes for describing the interaction of high energy protons with targets, and new Monte Carlo codes for predicting the properties of the sub-critical cores including the effects of fuel burn-up. Theoretical studies on new and more suitable definitions of parameters such as sub-critical reactivity, reactivity worth and the parameter $k_s$ in addition to $k_{eff}$ are being carried out. Considerable theoretical and experimental effort is being devoted to developing methods for measuring and monitoring the sub-criticality of an ADS. The fission power in an ADS is directly proportional to the neutron source strength and inversely proportional to the degree of sub-criticality. To get a high power, the sub-criticality should be low. However if the reactor is operated too close to criticality, it may go critical due to addition of reactivity during operating transients such as xenon decay or decay of $\text{Pa}^{233}$ to $\text{U}^{233}$. Thus, sub-critical reactivity is an important parameter from the point of view of ADS operation. It decides not only the accelerator current that will be required to produce the desired power but also the margin of safety available. Measurement and continuous monitoring of this parameter in operating ADS reactors will be an essential safety requirement.

Several low power experiments (Kitamura et al., 2004; Kloosterman and Rugama, 2005) have been performed for evaluating various methods (deterministic as well as stochastic) for
measuring the sub-critical reactivity in ADS. The well known pulsed neutron method and a recently proposed method viz., the source jerk method are the deterministic methods that have been studied in these experiments. There have also been suggestions regarding use of noise techniques for monitoring the sub-criticality of ADS (Behringer and Wydler, 1999; Carta and D’Angelo, 1999; Munoz-Cobo et al., 2001). Similar experiments are planned to be carried out in the Purnima sub-critical facility at BARC.

Noise methods have long been used for measurement of reactor kinetics parameters and as diagnostic tools for monitoring the health of a nuclear power plant. It is conceivable that noise techniques would find similar applications in ADS. For this reason, theoretical and experimental studies on ADS noise methods have appeared since the late nineties. The earliest theoretical studies on various noise techniques for ADS (Pazsit and Yamane, 1998; Kuang and Pazsit, 2000; Behringer and Wydler, 1999) assumed that the neutron producing source events in an ADS form a Stationary Poisson Point Process (SPPP). Each such event (spallation) was assumed to produce neutrons with a large multiplicity distribution.

However, the principal difference between critical reactor noise and ADS noise is due to the statistical properties of the source. Unlike the source due to radioactive decay present in ordinary reactors, the accelerator produced neutron source in an ADS cannot be assumed to be a Poisson process. Moreover, the source may be pulsed. It was first pointed out by Degweker (2000, 2003) that a new theoretical approach is required to describe noise in ADS.

In the present thesis, we discuss theoretical work aimed at developing noise methods for measurement of the sub-criticality in the light of the new theoretical approach mentioned above. The scope and content of the theory has been considerably expanded by us (Degweker and Rana, 2007; Rana and Degweker, 2009; Degweker and Rana, 2011; Rana
A diffusion theory based analogue Monte Carlo method (Rana, Singh and Degweker, 2013) has been developed for simulating the noise experiments planned at BARC. These are the new results presented in this thesis. The thesis is divided into seven chapters as elaborated below.

1. Introduction and Overview

Chapter I is a brief introduction to the ADS concept. The concept of ADS and its evolution over the years is discussed. A survey of the theoretical and experimental studies on such systems is presented.

2. Reactor Noise in Traditional Reactors and ADS

Chapter II gives a general introduction to the subject of reactor noise and presents an overview of theoretical methods employed for studying the subject. The Kolmogorov forward and backward equations are discussed and the probability generating function method for obtaining their solutions is described. The Bartlett formula for source dependent problems is presented. A discussion on the space dependent effects in reactor noise is included as also the theoretical approaches to this problem. The Langevin method, which is an alternative theoretical approach for studying reactor noise problems, is discussed.

Measurement of the variance to mean ratio in counting intervals, the Rossi alpha function, the Auto Correlation Function (ACF) or the Cross Correlation Function (CCF), of the number of counts in one or two detectors, or in the frequency domain, the Power Spectral Density (PSD) or the Cross Power Spectral Density (CPSD) are some of the commonly used experimental methods for noise analysis. The theory is used to obtain expressions for these quantities which include various parameters such as the sub-critical reactivity, delayed neutron fraction and neutron lifetime. The parameters are extracted by fitting measured...
quantities to these expressions. A discussion of various experimental procedures used for analyzing reactor noise and the connection of the theory with these procedures for extracting reactor physics parameters is also included.

This is followed by a review of the various theoretical studies on Reactor Noise in ADS. The earliest theoretical studies on various noise techniques for ADS (Pazsit and Yamane, 1998; Kuang and Pazsit, 2000; Behringer and Wydler, 1999) did not account for either periodic pulsed source or for its non-Poisson character. By a Poisson source we mean that the arrival times of protons or ions (and therefore the injection times of neutron bunches) constitute a stochastic Poisson point process. For such sources, the Bartlett formula is valid whether the source is stationary as in ordinary radioactive sources or even if it is pulsed, with finite or infinitesimal width.

On the other hand if the arrival times do not constitute a Poisson point process, the previously described and commonly used theoretical approaches such as the Kolmogorov forward equation or the Bartlett formula are inapplicable and we call such sources as non-Poisson sources. These features were considered by Degweker (2000, 2003) treating the individual pulses as Dirac delta functions, uncorrelated with one another. In these papers, it was shown that reactor noise in ADS is different from that in critical or radioactive source driven sub-critical systems due to non-Poisson character of the periodically pulsed source. Various noise descriptors, such as Rossi alpha, Feynman alpha (or variance to mean), PSD and CPSD were derived.

The method developed for treating non-Poisson sources consisted of obtaining the probability generating function (pgf) of detected counts for a single neutron injected in a source free medium. Using the multiplicative property of pgfs for different source events, the pgf for the case of an arbitrary source was obtained. This property is due to the
independent propagation of chains initiated by different source neutrons and is a consequence of the linear character of the neutron transport and multiplication.

A similar treatment was subsequently used by Ballester & Munoz Cobo (2005a). Using a space dependent model the authors derived CPSD for sub-critical assemblies driven by external non-Poisson source. The results were validated (Ballester & Munoz Cobo, 2005b) against the data gathered in MUSE-4 experiments to investigate the application of the Feynman-alpha method using an external pulsed source as a sub-criticality level monitoring technique. They also made an attempt to study the influence of the non-Poisson nature of the pulsed source. Pazsit et al. (2005) and Kitamura et al. (2005) included periodic pulsing but with a Poisson source. They considered the pulse to be of finite width of rectangular and Gaussian shapes and also included the effect of delayed neutrons.

3. Finite Pulses and Correlations between Different Pulses

In Chapter III, we extend the scope of the earlier papers (Degweker, 2000, 2003) to include the possibility of correlations between different pulses and finite pulses of different shapes. A possible reason for the non-Poisson nature of the source is identified as being due to fluctuations in the beam current. Measurements of the number of protons per shot during the TARC experiments (Abanades et al., 2002) clearly show that the fluctuations in the current are much too large so as to be described by a Poisson distribution.

At any instant of time, the probability per unit time for a spallation (neutron producing reaction) event to occur is taken to be proportional to the instantaneous proton (ion) current \( I(t) \) at that time. \( I(t) \) itself is treated as a stochastic process which is moreover having a periodic modulation corresponding to the pulsed nature of the proton (ion) beam. The source is thus treated as a doubly stochastic Poisson point process. Each pulse can have any shape but calculations are done for the two commonly occurring shapes – rectangular and
Gaussian. Thus, this approach allows us to extend the earlier formulation based on delta function pulses to take care of finite pulses as well as correlations between different pulses.

The development in this chapter is restricted to the case of prompt neutrons only.

Expressions for v/m, Rossi alpha, ACF and PSD are obtained for the cases of Gaussian and rectangular pulses. The correlations in the source fluctuations introduce additional terms which could confuse interpretation of alpha measurements by the variance method. The Rossi alpha and PSD methods might perform better in this case. The finiteness of the pulse width introduces small corrections to the formulae for delta function pulses.

4. Theory of Reactor Noise in ADS with Delayed Neutrons

In Chapter IV, we develop the theory further to include delayed neutrons and derive Feynman alpha and Rossi alpha formulae by considering the source to consist of periodic pulses (delta functions) with non-Poisson statistics, but without correlations between different pulses. By carrying out calculations of the Feynman alpha and Rossi alpha for typical experimental parameters, it is shown that the delayed neutron effects become important in those situations where the prompt and delayed neutron timescales are not very distinct and the formulae derived by us would serve as corrections even on prompt neutron timescales. The derived formulae provide important corrections for delayed neutron effects to the formulae obtained earlier.

We find that in addition to the terms due to source and fission chain correlations, the formulae contain periodic variations in the uncorrelated terms. The terms representing neutron chain correlations in the formulae have forms similar to that given in the literature and have been expressed by us in terms of the properties of the zero power transfer function. The term due to source correlations is different from that appearing in recently published formulae because of the non-Poisson character of accelerator-based sources.
An analysis of the results of experiments in the KUCA facility (Pazsit et al., 2005) using our formulae also clearly shows the presence of a source contribution to the Feynman $Y$ function. Such a contribution is not expected for D-D or D-T sources since neutron production in these reactions is in singlets (i.e., there is no bunching) and can be explained due to the non-Poisson character of the ion beam. In the absence of delayed neutrons, the expressions reduce to the form derived in an earlier paper (Degweker, 2003), as they should.

Subsequently, we also include correlations between different source pulses. It is assumed that source can be described as a periodic sequence of delta function non-Poisson pulses, with exponential correlations. Feynman alpha and Rossi alpha formulae are derived for such a source taking into account the effect of delayed neutrons.

Calculation of the Rossi alpha formula for typical experimental parameters shows that if the external source fluctuations are correlated with correlation times greater than or of the order of the prompt neutron decay times, it will be difficult to use methods such as Rossi alpha.

It is therefore important to study the current fluctuation statistics of ion beams from accelerators, either theoretically or experimentally.

5. The Langevin Approach to Reactor Noise in ADS

Behringer and Wydler (1999) considered the Langevin approach for ADS noise, but they used a modified Schottky prescription to include the Noise Equivalent Source (NES) for source fluctuations. This formulation is valid only for Poisson sources. Thus the pulsed non-Poisson character of the source is not brought out in their paper. Another paper based on the Langevin approach for ADS noise is due to Pazsit and Arzhanov (1999). They however have presented a treatment using the Langevin approach in the context of power reactor ADS noise.
In Chapter V, we develop the Langevin approach to reactor noise in ADS. Apart from being simpler, the Langevin approach allows treatment of feedback effects arising in ADS with significant power as well as other noise sources if any. We examine if it is possible to treat zero power neutron fluctuations in an ADS with non-Poisson source using this formulation. We show that this is possible and for this purpose, the external source fluctuations cannot be treated only as an NES or only as an external parametric fluctuation but rather as a combination of an internal noise described by the Schottky formula and as an external fluctuating function. This way, non-Poisson sources of all kinds can be treated.

We first demonstrate, for two models of the source studied by us earlier, that it is possible to obtain the correct expressions for various noise descriptors using the Langevin approach with Schottky prescription for fission, detector, and capture events but with a separate treatment for ADS source fluctuations. In both these cases we show that our earlier results by the more rigorous method are reproduced. The demonstration is important as it fixes the recipes required for treating a new system (ADS, in this case) using the heuristic Langevin approach.

The method is then applied to treat the more general problem of zero power ADS noise viz., correlated non-Poisson pulsed sources with finite pulse width including delayed neutrons. The rather complicated nature of this problem makes the calculations by the pgf method wholly intractable and this necessitates the use of a simpler approach. We find that the Langevin method fits the bill. We obtain the PSD of the noise as the Langevin method is simplest to use in the frequency domain. This is the main new result presented in this chapter.
6. Simulation of Noise Experiments in Sub-critical Systems by Diffusion Theory Based Analogue Monte Carlo

Various low power experiments are being planned (Rasheed et al., 2010) to be carried out at Bhabha Atomic Research Centre (BARC) with the aim of demonstrating pulsed neutron and noise methods for measuring the sub-critical reactivity of ADS. One of the aims of the experiments would be to verify the theory of reactor noise in ADS developed by us and interpret the results in terms of the theory. The system planned is a natural uranium sub-critical assembly moderated by water or high density polyethylene. The maximum $k_{\text{eff}}$ of such a system is expected to be about 0.9. At such a low value of $k_{\text{eff}}$, noise experiments for determining alpha are likely to face difficulties in interpretation due to modal contamination effects at such low values of the $k_{\text{eff}}$. By the time the higher modes have died out and the fundamental mode decay of the correlation sets in, very few correlated counts remain and the background noise dominates. However, for both types of experiments it is possible to select certain detector positions where the modal contamination of many of the higher modes immediately above the fundamental mode can be eliminated.

As part of the planning of the experiments, a simulation of the kind of results that might be expected with different detector locations and counting and analyzing setups is necessary, particularly in view of the difficulty mentioned above. Simulations with standard code packages (MCNP, 1987; MONALI 1991) are not appropriate because of several non-analogue features built into such codes. These need to be modified into completely analogue simulation codes. Munoz Cobo et al. (2001) coupled the high energy code LAHET with another Monte Carlo code MCNP-DSP and simulated cross power spectral density between the proton current signal and a neutron detector signal for a typical fast energy amplifier configuration. While LAHET simulates the spallation process and transport of charged
particles, MCNP-DSP is used to simulate the counting statistics from neutrons counters. Pozzi et al. (2012) have developed a variant of MCNP, called MCNP-PoliMi. The code can simulate correlated statistics of neutrons and photons. It can also handle the effect of delayed neutrons. However, completely analogue computations are very time consuming. There have been attempts to remedy (Máté Szieberth and Gergely Klujber, 2010) some of these problems by special methods of correcting tallies which give not only the correct value of the first moment but also of the second moment. The simulation is still having many time reducing features and takes less time compared to purely analogue simulations.

But the purpose of simulations of proposed experiments is often not to obtain the ‘correct’ value of say the variance to mean ratio but rather to obtain the kind of results that are expected. For example one may be interested in knowing the magnitude of this quantity for given values of system parameters such as $k_{eff}$, detection efficiency etc., and how it compares with the background random noise for a given counting time or the magnitude of the space dependent effects, delayed neutron contributions and dead time effects that invariably appear in the experiment. All this is possible only if the simulation is completely analogue and, as mentioned above, such simulation requires long computing times.

In Chapter VI, we describe an analogue Monte Carlo code developed by us for carrying out such simulations. The simulator generates a detailed time history of counts in the detector so that any method of analysis can be carried out. Since analogue MC takes very long computing time, instead of carrying out a simulation to yield results equivalent to transport theory, we attempt to reproduce results equivalent to few-group diffusion theory, which requires much less time. While few-group diffusion theory may not be as accurate as exact MC simulations, it will be adequate for the purpose mentioned above. Moreover, it is always possible to substitute the diffusion equivalent simulation with a transport equivalent
simulation in regions where diffusion theory is not valid. We discuss the basic theory of the
simulation method and some results of our simulations. We describe some simple reactor
models for which analytical diffusion kernels can be used very effectively to get some of the
required results. We also describe a numerical approach based on the finite differenced
diffusion equation which is applicable to more general situations.

The few group diffusion theory based analogue MC code for simulating reactor noise
experiments is used to study the problem of suitable location (at the intersection of the zeros
of the symmetric modes) of the neutron detectors to avoid contamination due to contribution
from higher modes. A simplified model of one of the proposed Purnima sub-critical
assemblies is used for the purpose of the study. We simulate the ACF and Feynman alpha
experiments. The value of alpha obtained from the simulation agrees well with the value
obtained from the analytical solution for the geometry. The simulations show that proper
location of detectors gives an almost single exponential (fundamental mode) response
making alpha measurements by the noise methods possible even in deeply sub-critical
systems.

7. Summary and Conclusions

Chapter VII gives a brief summary of the results presented in the thesis and the main
conclusions drawn.

Reactor noise in ADS is different from ordinary reactors due to the different statistical
characteristics of the driving source. Since Reactor Noise techniques are potential candidates
for sub-criticality measurement / monitoring of ADSs, it is important that these are put on a
sound theoretical footing. A beginning was made in this direction by Degweker through two
pioneering papers (Degweker, 2000, 2003) in which the individual pulses are treated as
Dirac delta functions, uncorrelated with one another. The theory treated all neutrons as prompt.

In this thesis we (Degweker and Rana, 2007; Rana and Degweker, 2009; Degweker and Rana, 2011; Rana and Degweker, 2011) present developments carried out to include the effects of finite pulses, delayed neutrons and correlations between different pulses of the source. Formulae for Rossi alpha, Feynman alpha (or variance to mean), PSD and CPSD have been derived. While much of the work is based on the probability generating function approach, for the more complicated problems, we have successfully developed the simpler, though somewhat heuristic, Langevin approach to ADS noise theory. A novel method (Rana, Singh and Degweker, 2013) for simulating noise experiments (planned to be carried out at BARC) using diffusion based analogue Monte Carlo, and some interesting results on the spatial dependence of noise in ADS, thus obtained, are also discussed in the thesis.

References:

Abanades A. et al. (2002), “Results from the TARC experiment: spallation neutron phenomenology in lead and neutron-driven nuclear transmutation by adiabatic resonance crossing”, Nuclear Instrumental Methods A478, 577


Alpha Formulas with Multiple Emission Sources”, *Nucl. Sci. Engg. 136*

Máté Szieberth and Gergely Klujber (2010), “Monte Carlo simulation of neutron noise
measurements”, *ADS benchmark CRP, 4th RCM, Mumbay, India, 22-26 February*

“MCNP — A General Monte Carlo N-Particle Transport Code”, *Report LA-UR-03-1987*

“MONALI – Rev.1, A Monte Carlo code for analyzing fuel assemblies of nuclear reactors”,
Report BARC-1543 (1991)

Systems”, *Annals of Nuclear Energy 28*, 1519

Cimento 7 (Suppl.), 25-42*

by a spallation source”, *Annals Nuclear Energy 25*, 667

Fluctuations in Accelerator Driven Sub-critical Reactors”, *Annals of Nuclear Energy 26*
1371

Pazsit I. et al. (2005), “Calculation of the Pulsed Feynman-Alpha Formulae and Their
Experimental Verification”, *Annals of Nuclear Energy 32*, 986

Pozzi, S. A. et al. (2012), “MCNPX-PoliMi for nuclear nonproliferation applications,”
*Nucl. Instr. Meth. A, 694(2) 119*

Rana Y.S. and Degweker S.B. (2009), “Feynman Alpha and Rossi Alpha Formulae with
Delayed Neutrons for Sub-critical Reactors Driven by Pulsed Non-Poisson Sources”, *Nucl.
Sci. Engg. 162*, 117


