APPLICATIONS OF D-T/D-D NEUTRON GENERATOR FOR THE INVESTIGATION OF ADS NEUTRONICS, FISSILE MATERIAL DETECTION AND NEUTRON IMAGING

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Abstract

D-T/D-D neutron generators have been used for several applications such as neutron driver for a zero power accelerator driven subcritical system (ADS), fissile material detection, explosive detection, neutron imaging etc. We have been working on the development and applications of D-T/D-D neutron generator. In this paper, we discuss three important applications which have been carried out using such generators.

D-T/D-D neutron generator driven ADS

Accelerator driven subcritical systems are increasingly attracting worldwide attention due to their superior safety characteristics and their potential for burning actinide and fission product-wastes and energy production. 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. In ADS, the high energy accelerator would accelerate a beam of protons to GeV energy before impinging them into a lead target inside the subcritical reactor core. The bombardment induces the target to release large number of neutrons by spallation which then induces neutron multiplication and fission reaction in a surrounding subcritical reactor producing power. The system shuts off once the accelerator beam is switched off.

There are many challenges both related to technology and physics of ADS which needs to be solved before such a system becomes reality. There are new physics issues which are specific to subcritical reactor and not encountered with critical reactors. For example, the power in subcritical system depends inversely on subcriticality and directly proportional to external neutron source strength. The spatial and energy distribution of flux is quite different from critical reactor due to effect of centrally peaked external source neutrons whose energy spectrum is different from that of fission neutrons. This leads to new concept called source importance \( k_s \) instead of \( k_{\text{eff}} \) which affects neutron multiplication and power in the system. Measurement of source importance, injected neutron source strength and most important online criticality monitoring become an important issue in ADS as final output power depends critically on these parameters. The reactor kinetics of ADS is quite different from the critical reactors. New measurement techniques need to be developed especially for ADS applications as the flux in ADS is a combination of fundamental and higher modes.

Before a full fledged ADS using spallation neutrons becomes a reality, many countries have initiated extensive program to study these physics issues of ADS using low power subcritical assemblies driven by neutrons generated using D-T, D-D, photonuclear reactions as spallation sources meeting the requirement of commercial ADS are yet to be developed. Some of these programmes include YALINA in Russia, MUSE in France, RACE in USA, VENUS-1 in China and GUINEVERE...
in Belgium. These low power ADS could serve as a useful surrogate for investigating many of the physical characteristics and potential applications of high-power, full-scale ADS systems that are under design but remain to be built. With this in mind, a low power subcritical system **BRAHMMA (BeO Reflected And HDPE Moderated Multiplying Assembly)** has been designed and installed at Purnima Laboratory. The subcritical core is coupled to an indigenously developed deuteron accelerator producing D-D and D-T neutrons. This is a first step within the country to develop experimental ADS. The development of such a zero power facility will enable study of various physics parameters related to neutronics, reactor physics and dynamic characteristics of ADS, validating codes and nuclear data as well as development of new but important techniques of a subcriticality measurement. There are several novel features in the design of both subcritical assembly and deuteron accelerator based neutron generator developed by BARC. These two components of zero power ADS (a) Subcritical assembly and (b) neutron generator are described below.

**BRAHMMA Subcritical Core**

The subcritical core is designed using metallic natural uranium as fuel, high density polyethylene (HDPe) as moderator and beryllium oxide (BeO) as reflector. Polyethylene has better moderating ratio and moderating power compared to light water. The use of polyethylene sheets makes the system modular. As a reflector material, BeO has excellent neutron reflecting properties and has helped to make the system compact. The core consists of 160 fuel rods in a 13 X 13 square lattice and embedded in HDPE with a pitch of 4.8cm. The central 3 X 3 positions of the lattice are vacant and serve as the central cavity for inserting the neutron source. The target is located at the centre of the core. Behind the target, lead block is used. The purpose of using lead is to soften the energy spectrum of the monoenergetic D-T neutrons.

![3D model of BRAHMMA subcritical core](image1)

![Photograph of BRAHMMA subcritical core](image2)

![Simulated flux profiles in BRAHMMA](image3)
The core is surrounded by beryllium oxide (BeO) reflector of thickness 20cm. The whole assembly is finally surrounded by borated polyethylene and cadmium for neutron shielding. This is important for preventing back reflected neutrons from the walls of the room interfering with effect due to source neutrons.

The assembly has several unique features such as polyethylene as moderator and BeO as reflector and due to these it has become modular and compact. The estimated theoretical $k_{eff}$ value is 0.889 with 2.8 tonnes of fuel. Due to its modular nature, there is a provision for replacing about 25% fuel rods with 1.3% SEU at later stage to achieve a $k_{eff}$ value of 0.95.

**PURNIMA Neutron Generator**

The coupling of the external source to the subcritical system is provided by the Purnima deuteron accelerator (Fig.3). This indigenously developed neutron generator is presently the most powerful non-reactor neutron source within the country. It is a Cockcroft-Walton type accelerator in which D$^+$ ions are accelerated to impinge either on Ti-D and Ti-T target. It can produce both D-D (2.45 Mev) and D-T (14.1 MeV) neutrons depending upon the target used. To make this generator suitable for ADS physics study, several new features have been introduced in the system such as both DC mode and pulsed mode generation of neutrons, programmable interruption of generator, provision for online neutron yield measurement using “neutron tagging” technique wherein neutrons are monitored using associated alpha in the nuclear reaction d(T,$\alpha$)n. Several novel miniature neutron detectors have been developed for the first time to measure neutron flux online and thus enabling study of both static and dynamic characteristics of ADS. These detectors include a miniature fibre optic scintillator detector (1mm) wherein a neutron sensitive scintillator is coupled to a long optical fibre which is then coupled to a photomultiplier tube. This enables online measurement of flux in the narrow experimental channels of subcritical assembly. A trial coupling of accelerator with subcritical was done and some preliminary neutronics experiment with D-D neutrons were carried out. Further validation with D-T neutrons are being planned.

**Experimental Results**

BRAHMA subcritical core has been coupled to Purnima Neutron Generator (Fig.4). Results of preliminary experiments with D-D neutrons are being reported here.

**Flux measurement**

The axial flux profile (Fig.5) inside the subcritical core was measured with a miniature $^3$He detector (Active...
length: 70mm; diameter: 6.5mm). D-D neutron source was used for flux profile measurement. Figure 5 shows the flux profile along the axial direction inside the core at the experimental channels EC1, EC2 and EC3. The axial profile is peaked at the center of the core. Similarly the flux is maximum at EC1, which is nearest to the core.

Reactivity measurement
The reactivity was measured using pulsed neutron techniques - Source Jerk method, Area Ratio method and Slope Fit method. A brief description of the three methods is described.

Area Method & Slope-Fit method
Reactivity ($\rho$) is determined by investigating the neutron flux decay during repeated injection of neutron pulses at constant frequency. After large number of neutron puls, equilibrium level of delayed neutron precursors is obtained. These delayed neutron precursors will decay at a constant rate which will cause constant delayed neutron background, but prompt neutron shows very fast time dependent behavior. By operating the neutron generator in pulse mode and registering the detector signals after each pulse, a pulse response of the system can be obtained. For the Area Ratio method, the reactivity is given by the ratio of the prompt and delayed areas. In the slope-fit method, the slope of the prompt decay part gives $\alpha$ which is used to determine reactivity.

\[
\rho/\beta_{\text{eff}} = -A_p/A_d \quad \text{(for area ratio method)}
\]

and

\[
\alpha = (\rho - \beta_{\text{eff}})/\Lambda \quad \text{(for slope-fit method)}
\]

where $A_p$ is the prompt area and $A_d$ is the delayed area, $\beta_{\text{eff}}$ is the delayed neutron fraction, $\Lambda$- mean generation time and $\alpha$ is the prompt decay constant. The experimentally measured $k_{\text{eff}}$ values are 0.886±0.005 and 0.887±0.003 for Area Ratio and Slope Fit method respectively. It has been observed that the experimental $k_{\text{eff}}$ values are in good agreement with the theoretical estimate.

Source-Jerk Method
The idea behind the Source Jerk method is to operate the subcritical system at a steady flux level $n_0$ and then suddenly switch off the neutron source. The neutron population inside the core will jump to a lower neutron level $n_1$. This quasi static level will decay according to the decay rate of delayed neutron background. From the point kinetic equation the reactivity of the subcritical core is given by:

\[
\rho/\beta_{\text{eff}} = (n_1 - n_0)/n_1,
\]

Fig. 6(a) shows the decay of neutron flux. This plot is used for estimating the reactivity using area-ratio and slope-fit method. Fig. 6(b) shows the plot of neutron flux during beam ON and OFF times. This plot is used...
for estimating the reactivity using Source-Jerk method. The experimental result using this method is presently being analyzed.

**Fissile material detection using active neutron interrogation (D-T/D-D)**

Active neutron interrogation technique is another application using pulsed neutron generator which has been developed at Purnima Labs. This technique is being used world-wide for improving sensitivity of fissile material detection for security as well as in nuclear waste assay for nuclear material accounting. The advantage of this method is that it can detect very small quantities of fissile materials even in presence of high neutron and gamma background and it is much more sensitive compared to passive neutron or gamma techniques. This technique is based on differential die-away analysis \[^2\] and works by exposing a medium to pulses of neutrons. An external fast neutron detector measures the time-dependent fast neutron flux resulting from the irradiation. When no fissile material is present in the inspected medium (e.g. waste drum, hull, a truck or cargo container being inspected for nuclear material, etc.) the detector should only measure a signal representing the diffusion of the thermalized neutrons in the detector body (detector neutron “die-away” time). If fissile material is present, the detector will show, in addition to a signal decaying with the detector die-away time, an additional signal decaying with the die-away time of the inspected medium (Fig.7). If the latter is significantly longer than the former, it will dominate the decay curve at later times and unequivocally establish the presence of fissile material in the inspected object. The amplitude of the signal and its time constant is determined by several factors, among them the quantity and location of fissile material present in the inspected medium. We have carried out laboratory based studies using this technique and initial results are reported.

**Experimental Results**

An experimental facility comprising of pulsed D-T neutron generator and He-3 detectors has been set-up to verify the detection limits using this approach especially for the case of leached hull-monitoring. Dry pieces of zircaloy weighing approximately 150kg was used simulated the dry hull (Fig. 8). Experiments were carried by placing 1gm-to-50gm of U-235 (in the matrix of natural metallic uranium) at the centre of the hull matrix (Figs. 9 & 10). Active neutron (10^4n/s), gamma background (20mR/hr) and moisture conditions were simulated by keeping 5mCi Am-Be neutron source, 100mCi Cs-137 gamma source and water (60gm), which represent the background radiation and moisture levels typically encountered in hulls. The data was acquired and it was proved that even under these stringent conditions, up to 1gm of U-235 could be easily detected. Experiments are underway to test for lower limits of ^235^U.

![Fig.7: Basic principle of Differential Die away technique for fissile material detection](image)

![Fig.8: Simulated Hull Matrix](image)
Thermal Neutron Imaging using D-T Neutron Generator

Thermal Neutron imaging is a well known non-destructive technique commonly applied to the inspection of nuclear fuel, turbine blades, pyrotechnic devices, etc. Till now, this technique has been mostly used with reactor neutrons which provide a high neutron flux. However, there are many situations such as inspection of pyrotechnic devices used in defence and space applications which require detection of small quantity of explosive charge inside a metal matrix. Detection of these are crucial for qualification of components being used in space flights or missile component. Such a small amount of explosive material cannot be clearly discerned using X-ray and neutron imaging is the only solution. Due to the nature of sample and explosive charge within, such material have problems being taken near reactors. This demands neutron imaging to be carried out at the site. There are many other such applications. Such a situation demands that neutron generators be used for neutron imaging. The problem in this approach is that the neutron sources based on commonly available neutron generators can provide collimated fluxes which are one to two orders of magnitude less compared to those obtained using reactors. Also the sample has to be kept close to generator otherwise the flux will further decrease. This affects the sharpness of the image. Thus the problem of using neutron generator based imaging is to optimize the neutron flux and collimation ratio with limited source strength. This requires very careful design of moderator collimator assembly in order to get maximum possible neutron flux at the sample with reasonable collimation. Added with this, a sensitive imaging system has to be designed which form images even with low neutron flux. Even though image quality at these low flux and collimation ratio is not expected to be as good as those obtained using reactors, nevertheless it has its utility in providing qualitative radiography where presence or absence of some neutron attenuating material is to be detected.

We have tested this concept using Purnima neutron generator in D-T mode. As the D-T neutron produces 14 MeV neutrons, the first challenge has been to effectively thermalize these neutrons in a small volume by using suitable moderators. This required very careful design of layered hybrid moderator. Another criterion which defines the imaging quality is the collimation of the beam which is determined by the L/D of the collimator (where L is the length of the collimator and D is the diameter of the collimator inlet opening). Large L/D improves the quality of the image albeit at the cost of thermal flux. Hence, a tradeoff between the thermal flux and the L/D is required.

A prototype thermal neutron radiography assembly was designed at Purnima lab using a 14 MeV D-T neutron generator in order to test the feasibility of this concept. We tested various designs of neutron moderator...
assembly which produces an optimum thermal neutron flux at various L/D ratios. A highly sensitive electronic imaging system was especially developed for obtaining images at low flux level. We tested this system with some dummy pyrotechnic devices which contained wax instead of explosive charge. Fig.11 shows initial radiography images of dummy pyrotechnic devices using this assembly at D-T neutron source strength of $\sim 10^9$ n/s which gave a collimated thermal flux of about $2\times10^3$ n/cm$^2$/s at the sample with a collimation ratio defined by $L/D = 10$.

Development of such a technique has several immediate applications in nuclear, space and defence as neutron imaging can be carried out at the site using neutron generators of limited strength rather than only at high flux reactors. The image quality though not as good as reactor, can be improved by using more powerful neutron generator which is under development at our laboratory.

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