The Accelerator Driven System (ADS) is an innovative concept of employing a sub critical reactor coupled to a high power proton beam accelerator, through a spallation neutron source. This system gains immense importance due to its ability to transmute radioactive waste, inherent safety, efficient fuel usage and its direct applicability in the large-scale thorium utilisation under the three-stage power programme. The important ongoing activities highlighted in this challenging research area are the spallation target studies, experimental programmes and thermal and structural analysis of the radio frequency quadrupoles in the high intensity proton linear accelerators.
8.1 ACCELERATOR DRIVEN REACTOR SYSTEMS

The Accelerator Driven System (ADS) is a new type of reactor which produces power even though it remains sub-critical throughout its life. All operating reactors in the world are “critical” reactors - which means that the number of neutrons produced by fission is exactly balanced by the number lost by leakage and absorption by various materials in the reactor. This balance is responsible for maintaining a constant reactor power at any desired level. Sub-critical reactors produce fewer neutrons by fission than are lost by absorption and leakage, and require an external supply of neutrons to maintain a constant reactor power. This external neutron supply comes from the interaction of a high energy proton beam with a heavy atom nucleus such as lead through what is known in nuclear physics as spallation. The power level in an ADS is greater for stronger external sources and for reactors which are closer to “critical”.

Such reactors were conceived by the Nobel laureate physicist, Carlo Rubbia (Report CERN/AT 95-53) and his team at CERN, among others, for power generation, but have caught the attention of the world for an equally important role - that of burning nuclear waste. It is well known that nuclear reactors generate radioactive waste which retains its radio-toxicity for millions of years and disposal of this waste has been a major source of public concern. The new reactor is designed to safely transmute the waste into stable elements or those whose radio-activity is relatively short lived, while producing useful power.

Indian interest in ADS has an additional dimension, which is related to the planned utilisation of its large thorium reserves for future nuclear energy generation. Thorium has the added advantage that it produces much less quantities of long lived radioactive wastes as compared to uranium. However, thorium by itself is not fissile and must be first converted to fissile U-233 by neutron irradiation, a process called breeding. In ADS, the accelerator delivers additional neutrons over and above those coming from fission. Moreover long term reactivity changes due to burnup are not controlled using parasitic absorber rods. The ADS is, therefore, expected to possess superior breeding characteristics as compared to critical reactors. Since ADS 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. This effect is rather large for thorium based fuel. Being a new type of reactor, the ADS requires development of several technologies related to high power accelerators, removal of the intense heat generated by the interaction of the high power proton beam with the target, and associated materials development.

Accurate computer simulations play a very important role in determining the performance of the ADS reactor. The studies are geared to develop accurate computer simulation codes for ADS, compile necessary nuclear data for this purpose, carry out experimental and numerical tests regarding the adequacy of the simulations and finally to use these simulations to evaluate ADS performance with regard to the design objectives. The “state-of-the-art” codes have been developed for carrying out fuel burnup simulations based on the exact Monte Carlo method and the (accurate and quicker) multigroup transport theory method for this purpose. The codes are functional for fixed fuel ADS and are being put to use for evaluating some of the interesting ideas conceived for applications of ADS. Further development of these codes is being carried out to include fueling operations (insertion, removal, or shuffling) and it is expected to be completed within a year.

A facility for carrying out experiments on the Physics of ADS is being set up at Purnima labs, BARC. A report on the experimental program has been prepared and experiments will commence once the facility becomes operational. The experiments will serve the equally important purpose of testing the simulation methods under development. Measurement of the degree of sub-criticality is one such important experiment, as monitoring this parameter for ADS will be an important safety requirement. This can be done by pulsing the accelerator or by studying tiny fluctuations in the reactor power, called “noise”. A new theory of Reactor Noise in ADS has been developed and is gaining international acceptance.

The Advanced Heavy Water Reactor (AHWR) is being designed and developed at BARC for the purpose of thorium utilization. In view of the remarks on thorium utilization in ADS made earlier, the following questions assume importance. What is the reduction in the annual fuel requirement of a thorium fuelled 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 fuel before it is discharged? What would be the accelerator power required to drive such a reactor?
The scheme allows 10% thorium (1 GWd/t is equivalent to fission of 1% fuel mass) to be burnt before the fuel is discharged. However, the energy gain is small and hence, a large fraction of the reactor power (about 30%) would have to fed back to the accelerator. If light water is used as the coolant, the multiplication factor is lower and the ADS would require greater accelerator power.

The one-way coupled fast-thermal ADS reactor conceived at BARC can be used for this purpose. This is illustrated in Figure. The neutron source produced by the interaction of the proton beam with the target is first boosted in a small fast region (surrounding the target) having Pu as fissile material and a liquid metal coolant such as lead. These neutrons then enter the main thermal reactor region where most of the power is produced. The outer region will be a heavy water moderated reactor for which the technology is well established. Such an arrangement 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 generation reactors based on uranium and plutonium fuels.

Many such studies are required to evolve a suitable ADS design and the associated fuel cycle strategies for thorium utilization. The R&D program of the ThPD group on ADS is geared to provide the necessary simulation tools and the theoretical direction for this activity.

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8.2 SPALLATION TARGET STUDIES

One of the key components of the ADS is the spallation target. Based on neutron yield, thermal-hydraulics, radiation damage issues, liquid Lead-Bismuth-Eutectic (LBE) has been chosen as spallation target. An R&D programme has been initiated to address various technology issues. Under this programme, a mercury and LBE experimental facilities are presently being set up. In view of many similarities of mercury with LBE, a mercury experimental facility is being setup.

- Mercury experimental loop

This loop is being setup primarily to study and develop diagnostics for target development. The loop consists of mixer, riser, downcomer, separator, window and windowless target simulation regions, dump tank. In addition to normal instrumentation, various special diagnostics like Ultrasonic Velocity Profile (UVP) monitor system for velocity field mapping, free surface level measurement based on laser triangulation technique, $^{60}$Co based gamma-ray measurement system for void fraction distribution have been setup. Both window and windowless target flow simulation corresponding to around one-fifth the actual target geometry but without heat input is being simulated in this facility. The circulation of the liquid metal is achieved by injecting nitrogen in to the loop through mixer located above window simulation region of the riser. The two-phase that is generated in the riser gives rise to the liquid metal circulation. The nitrogen is separated in the separator and mercury alone flows through windowless simulation region, downcomer pipe and enters the riser pipe and window simulation region. The maximum mercury flow rate of 6kg/s can be achieved in this facility.
Plasma torch as heat source for ADS target thermo hydraulic simulation

In accelerator driven sub critical reactors operating in window configuration, heat deposition in the window material and thermo hydraulic profiling of the liquid metal flow near the window are parameters of extreme significance. The actual experiment requires 10 GeV, 10 mA proton beams, the thermal effect could very easily be simulated by a 100 kW plasma beam tailored to deliver powers up to 1-2 kW/cm² uniformly on the entire target window surface. A transferred arc plasma torch operating in argon up to 100 kW has been tested by delivering powers up to 1.6 kW/cm² on a water cooled substrate of 80 mm diameter and shaped as the actual window. A rotating magnetic field has been used to increase the width of the heat flux profile to make the delivery more uniform.

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8.3 THERMAL AND STRUCTURAL ANALYSIS OF CW-RFQ FOR ACCELERATOR DRIVEN SYSTEM

A high intensity proton linear accelerator (linac) is required for typical ADS applications. It will produce a continuous wave (CW) proton beam of current of about 10 mA and energy of 1 GeV. Its low-energy section will consist of a number of components including a high intensity Radio-Frequency Quadrupole (RFQ).

The integrated thermal/structural analysis of a RFQ is crucial to its design and operation. The heat generated due to resistive losses in the copper walls of RFQ is required to be dissipated. If the RFQ is not properly cooled, this heating can cause large temperature excursions in the RFQ structure along with distortions in the vane geometry, leading to thermal strains. The thermal distortions lead to significant deformation and detuning of the structure.

The RFQ consists of four vanes and individual vanes will be made of Oxygen Free High Conductivity (OFHC) copper. A four-vane type RFQ structure and its cross section are shown in Figure.

The RFQ is 3.62 m long and it is planned to fabricate into 4 segments of 0.91 m each because single module RFQ would be very unstable due to the longitudinal Higher Order Modes (HOM) being very close in frequency to the accelerating mode frequency. Due to RF heating about 92 kW/m heat is dissipated on the inner surfaces of the RFQ and this heat is to be removed to limit thermal deformation of the structure.

The acceptance criterion is that the total frequency shift due to thermal deformation within the entire cavity should be less a ± 50 kHz. The mechanical fabrication tolerance of the structure is very tight (1/100th of mm) from beam dynamics point of view and these tolerances have to be maintained during high power operation. A cooling scheme of 24 cooling channels using water as the coolant was designed to extract the heat.

Frequency shift depends upon the thermal deformation of the vanes and is very sensitive to radial deflection of the vane tip. Hence, temperature rise of the vane tip should be minimum. The location of the channels specially the vane channel-1 should be as close to the tip as possible for efficient removal of heat. The heat transfer can be increased by higher flow rate of cooling fluid but it is limited by material erosion. Fluid temperature should be such that the over all temperature rise and the resulting detuning should be within limit.

Analysis of the RFQ has been done in two stages. In the first stage 2-D analysis has been carried out and frequency shift has been evaluated at inlet and outlet plane for various channel inlet temperatures. For 3-D analysis, the channel inlet temperature has been chosen on the basis of the minimum average frequency shift as obtained from the 2-D analysis. After doing a number of iterations, temperature distributions, subsequent deflection and frequency shift have been obtained.

Results and discussion

(a) 2-D analysis

For a typical case (channel inlet temperature of 289 K (16 °C)), temperature contour plots are shown at inlet and exit planes maximum temperature is obtained at vane tip.

The variation of frequency shift at inlet and exit plane for respective cases are shown in the Figure. There is a difference of 42 kHz between inlet and exit plane. Average frequency shift is zero for channel inlet temperature of 16.2 °C. Frequency shift is observed to closely follow the tip deflection i.e. higher tip deflection leads to higher frequency shift.

(b) 3-D analysis

Fluid temperature of 16.2 °C at channel inlet has been considered for 3-D analysis which is expected to give minimum frequency shift. Temperature contour plot is shown in Figure which shows that maximum temperature is at the vane tip.

Subsequent deflection has been obtained for reference temperature of 303 K (30 °C). Deflection at the vane tip for axial
(Uz), radial (Uy) and resultant (Usum) along axial direction is shown in Figure. The maximum deflection in Y (radial) direction is 8.1 micron at one end of the RFQ.

The variation of average frequency along axial direction is shown in Figure. It shows that the frequency shift goes to 180 kHz at the ends. The overall average frequency shift is 63.755 kHz, which is more than the prescribed limit. The average frequency shift obtained by 3-D analysis is quite different than 2-D analysis for same fluid channel inlet temperature. In order to get frequency shift very close to zero, one more case has been analyzed with considering the fluid channel inlet temperature of
16.5 °C for which average frequency shift is 1.736 kHz. Hence in 3-D analysis with changing fluid channel inlet temperature by 0.3 °C (16.5-16.2) the change in average frequency shift is 62 kHz. Hence to maintain average frequency below 50 kHz the fluid channel inlet temperature can be varied from 16.25 to 16.75 °C.