Program for Development of Accelerator Driven Systems in India

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Abstract

A roadmap for developing accelerator driven systems (ADS) in India was prepared in 2001. The first phase of the activities under the program began with the commencement of the tenth plan in 2002. This involves the development of a 10 MeV (upgradeable to 20 MeV), 30 mA proton linear accelerator, the setting up of a lead bismuth eutectic (LBE) loop for target and coolant studies and a reactor physics program of developing necessary codes, compiling nuclear data, conceptual design studies of the sub-critical reactor and experimental activities. Actual ADS reactor design and development activities will be taken up in a later phase.

Presently, India has a reactor running on HEU fuel viz., APSARA. There is a plan for refurbishing and converting its core to LEU. An advanced high-flux research reactor based on LEU is also planned. Preliminary studies have been initiated to investigate the feasibility of coupling such a pool type reactor with an accelerator based neutron source and operated as an ADS.

The paper gives a brief outline of the roadmap and a description of the status of various activities under the program described above.

1.0 Introduction

Accelerator Driven Systems (ADS) are attracting increasing worldwide attention 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 / programs 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 as compared to uranium. However, thorium by itself is not fissile and must be first converted to fissile U-233 by neutron irradiation. 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 till such time that the k_{eff} of the system falls to a value below which it is not possible to maintain the power by increasing accelerator current .

For these various reasons, a roadmap [1] for developing accelerator driven systems (ADS) in India was prepared in 2001. The first phase of the activities under the program began with the commencement of the tenth plan in 2002. This involves the development of a 10 MeV (upgradeable to 20 MeV) 30 mA proton linear accelerator, setting up of a lead bismuth loop for target and coolant studies and a reactor physics program of developing necessary codes, compiling data, conceptual design studies of the sub-critical reactor and experimental activities.

Independent of this roadmap, there has been a program of refurbishment and core conversion [2] to low enriched uranium (LEU) of APSARA, the only reactor in India using high enriched uranium (HEU). In addition to this, plans are also being drawn up for the development of a high flux research reactor using LEU. In this connection, the possibility of such a reactor being operated in a sub-critical mode is being examined, which could thus serve as a demonstration ADS, in addition to the purposes for which it was originally conceived. In the following section we present an outline of the roadmap for ADS development. This is followed by a description of the activities being carried out in the tenth plan. We then present a description of the APSARA reactor, and the program for its conversion. Finally, we give our comments on the possible development of a LEU research reactor which also doubles up as a demonstration ADS.

2.0 Road map for development of ADS in India

A Co-ordination Committee for Accelerator-Driven Sub-Critical Reactor Systems (ADS) was constituted in December 1999. The committee discussed many technical aspects related to the development of such systems in India with particular regard to our objective of utilizing thorium fuel cycle in the generation of nuclear power and prepared a roadmap for development of ADS in India, extending over a period of about 15 years. The roadmap focuses on the development of the required technology needed for ADS. The most important component of this will be development of a high energy and high current proton accelerator, which is by no means trivial even for any advanced technology organization in the world. Hence, concerted efforts will be needed in our country towards development of accelerator physics and technology to be ultimately able to meet the requirements of ADS. The other important technological areas covered in the roadmap are development of spallation target and materials. The roadmap is based on avoidance of need for any new reactor technology development the demonstration ADS. This means that basically it will draw details in engineering configurations from technological experience in pressure tube type heavy water reactor (PT-HWR) for thermal ADS and FBTR/PFBR for fast ADS. However, considerable work will have to be done in the neutronics design of a sub-critical reactor coupled to an intense spallation neutron source, which will involve development of new computer codes as well as nuclear data files.

The roadmap envisages the development of ADS in several stages. The first stage involves reactor physics experiments on zero power sub-critical systems using facilities such as the Purnima sub-critical facility and the AHWR critical facility, under construction, and an already available 14 MeV neutron generators. The second stage involves development of demonstration ADS in MW(t) fission power and driven by neutrons from spallation target modules with LBE target and low to high fission power [~ 1 to several MW(t)] in two sub-stages. The first of these will be driven with a lower proton beam energy of ~120 MeV proton beam and the next with ~350 MeV beam and each up to 5 mA cw / average current. These sub-stages will serve to gain experience and establish feasibility of stable operation and dynamic behaviour of ADS reactor. In both cases the fission power can be dissipated at below 100^0C. These sub-critical reactors can be utilized as research reactors with their respective range of applications in isotope generation and fuel/material tests etc.

The final stage will be a prototype ADS reactor with full energy (0.8 - 1 GeV) proton beam and operating with fast or thermal neutron spectrum, or fast-thermal one-way coupled sub-critical reactor, for electrical power generation and thorium as bulk fuel. Various methods of providing start up fissile species for this ADS can be considered at an appropriate design phase. Table 1 gives a summary of these various stages.

Table 1. Stage-wise configurations of ADS for Indian ADS programme

Device	Experimental	For DEMO-A	For DEMO-B	For Prototype	For serial design
Accel. (Type & Energy)	400 KeV D-T, 14 MeV neutron generator	~ 120 MeV SSC/linac	~ 350 MeV SSC/linac	0.8-1.0 GeV SSC/linac	1.2-1.5 GeV SCRF Linac
Accel. (Av. cw beam current)	10^9-10^{10} n/sec.	2-5 mA	2-5 mA	12-15 mA	>30 mA (Ideally, ~100 mA)
Target material	D-T type generator	Lead-bismuth eutectic (LBE)	LBE (with fast booster zone..)	LBE	LBE (Lead, if possible)
Target coolant	N. A.	LBE	LBE	LBE	LBE (Lead, if possible)
Beam Window design	N. A.	RAFM steel like T91	W-Rh/RAFM like T91/HT-9	Windowless/window	Windowless
Hybrid Reactor (HR)	Sub-critical, zero power facility.	Light water, pool type	Thermal D_2O mod., LW coolant; Fast LBE coolant.	Thermal with fast- booster zone	Exclusive fissile breeder or dedicated EA
Fuel in HR	Nat U or, U+Th	LEU+Th	Nat. U+Th/U+PMA	F: U+Pu, T: U+Th	F:Th+Pu/^{233}U)
Design K_{eff} of HR	0.9-0.98 (variable)	0.97 max.	0.9 - 0.97 (max.)	0.97overall max.	0.6-0.8 (breeder)/0.98 (EA)
HR Fuel form	Metallic	Metallic, alloy with Al/Zr	Oxides	MOX	Nitride or metallic?
HR Fuel cladding	Al	Aluminium	Zircaloy / SS	F:HT-9/CrMo, T:Zr+Nb	HT-9 or Russian steel
Reactor coolant	N.A.	Light water	light water/LBE	F: LBE, T:D2O	Lead
Heat/reactor application	N. A.	Throw away heat, RI, n-beam applic.	Throw away heat, RI, n-beam, high flux neutron irradiation	Power generation (EA)	Breeder with or without feeding to grid
Reactor power	Low power. Watts?	up to 1 MW(t)	~ up to 40 MW(t)	~ 700 MW(t)	~1500 MW(t) max. for EA
Approx. Schedule from start	3-4 Yrs.	7-8 Yrs.	10-12 Yrs.	15 Yrs.	20 Yrs.

Abbreviations: RI- Radio-isotope generator; PMA-Plutonium & Minor Actinides; RAFM- Reduced Activation Ferritic-Martensitic steel;

2.1 Roadmap for Accelerator Development

The accelerator sub-system that forms a part of ADS based nuclear power plant has to be reliable, rugged and stable over long periods of time in order to provide un-interrupted high-energy and high power proton beam to the spallation target. The broad specification of the final accelerator system needed for building a prototype of an ADS based nuclear power plant of 750 MW(t) corresponds to a proton energy of 0.8-1.0 GeV and beam current of at least about 5 mA with CW mode of operation. In order to achieve this challenging goal in our country, a roadmap consisting of a two-phase programme of accelerator development activities has been suggested with initial efforts being put on both cyclotron and linac routes. The first phase comprises of three types of activities, namely:

(i) Designing and building of a cyclotron up to about 350 MeV, with an intermediate injector of a 70-100 MeV stage,

(ii) Designing and building of a Linac with beam energy up to 70-100 MeV with normal/super- conducting operation and

(iii) Development of different types of superconducting niobium cavities and establishment of cryogenics and superconducting RF technologies.

The phase-I development programmes lasting about 8-10 years will lead to the phase-II programme in terms of adopting either or both of the above routes to achieve the final ADS prototype accelerator system.

A first stage of cyclotron/linac development of 70-100 MeV beam energy and 5 mA beam current is suggested keeping in mind end uses for R&D studies related to ADS. The 350 MeV second-stage cyclotron will be utilized to establish a DEMO facility for ADS in studying the neutronics, target technology and reactor coupling concepts. Each of the above high power proton accelerators can also serve as driver accelerator for production of Radioactive Ion Beams. Thus, the present roadmap has intermediate milestones with well-defined end use at each stage.

In the phase-II, development of a pulsed Linac of about 500 MeV and above will find applications such as a spallation neutron source and for research on muon catalyzed fusion studies. The next stage in phase-II will be to achieve a high energy and high power CW accelerator as per the required final specifications for a full-scale ADS prototype.

The roadmap recommends pursuance of R&D for both the types of driver accelerators, that is separated sector cyclotron and linear accelerator (linac), and envisages that the designated technical group/s will bring out detailed technical aspects in the form of Conceptual Design Reports (CDRs) for the above three phase-I activities. These CDRs can then form basis of cost estimation, infrastructure and resources allocation, siting etc. for the proposed X plan projects on the high power accelerator programmes.

2.2 Roadmap for target development

The spallation target module that forms an interface between the high power proton accelerator and the sub-critical core of an ADS based nuclear power plant will be subjected to beam powers of about 10 MW. Most of the beam power is deposited in small volume so that the peak power density can be as large as a few kW/cm^3. In addition, the target and beam window will be subjected to radiation damage due to intense proton beam and fast neutron flux requiring that the construction materials are able to cope with these large fluences of radiations. Development of suitable target, window as well as structural materials require considerable R&D involving all aspects such as

1. Development of codes to simulate neutron yields and spectra, and spallation products.

2. Recoil cascade simulation programs to simulate radiation damage.
3. Thermal hydraulics and materials development.
4. Studies of window and windowless configurations.
5. Choice and development of materials for targets, windows, structural materials etc.

In order to achieve this goal, a roadmap consisting of a two-phase programme of activities has been suggested with initial efforts being put on code development, thermal hydraulics and materials developments. The phase-I comprises of three major activities, namely:

- Basic R&D studies including spallation data generation, CFD codes for thermal-hydraulics, material development, and setting up an experimental Heavy Metal (HLM) loop facility.
- Design and fabrication of a target module for proton beam power of few hundred kW that will be tested in an appropriate accelerator beam (~100 MeV and few mA current) and installed in demonstration ADS having fission power up to ~1 MW.
- Design and fabrication of a target module (beam power of ~ 1 MW; 350 MeV and few mA) for ADS reactor having fission power of tens of MW.

The phase-II development programme will involve testing and integration of target module in Demo ADS-B reactor and development efforts resulting in prototype target module for high power proton beam (~1GeV and few mA). This target module will be designed and fabricated for integration with the sub-critical reactor in the prototype ADS.

3.0 Status of tenth plan activities

The roadmap envisages a program of ADS development over a period of about fifteen years covering three five year plan periods. ADS activities began with the commencement of the tenth plan in 2002.

3.1. Reactor Physics and Nuclear Data Studies on ADS

The tenth plan program at BARC for Reactor Physics of ADS includes development of accurate computer simulation codes, compilation of necessary nuclear data for this purpose, carrying out experimental and numerical tests regarding the adequacy of the codes and conceptual design studies of ADS.

3.1.1 Development of Computer Codes

We have developed codes [3,4] for carrying out fuel burnup simulations based on the Monte Carlo method and the quicker multi-group transport theory method for this purpose. 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. The codes have been tested by analysing the IAEA ADS benchmark [5], and by analyzing PHWR lattices with U and Th clusters. It is observed that while the agreement with published results and with one another is good for thermal reactor systems, there is considerable variation in the various (fast) benchmark results and also between our two code systems. More studies are necessary to understand these differences. Further development of these codes is being carried out to include fueling operations (insertion, removal, or shuffling of fuel assemblies) and more extensive benchmarking.

3.1.2 Experimental Studies

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 labs, BARC. The existing 14-MeV neutron generator in this laboratory produces a continuous source of $3x10^9$ n/s. Efforts are on to increase its strength by increasing the deuterium ion beam current, accelerating voltage and also 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 300 rods give a k_{eff} of 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 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 [6] 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. A new theory of Reactor Noise in ADS has been developed in BARC [7], which takes into account the non-Poisson character of the ADS source, and this can be tested in the facility.

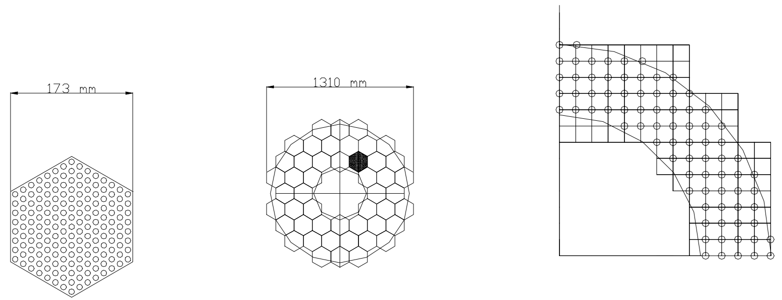
3.1.3 Conceptual Design and Fuel Cycle Studies

In view of many advantages for thorium utilization using ADS reactors, the 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 at BARC [8] and independently in Russia [9] is being studied. A schematic of the design is shown in Fig.1. The inner core is a fast Pb /LBE cooled and mixed oxide (MOX) (initially with Pu-Th and later with U233-Th) 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 U233-Th MOX.

The thorium burner concept, proposed by us [10] 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 studying various means to achieve this such as optimization of the k_{eff} and use of a target with a larger spallation yield.

The one-way coupled fast-thermal ADS reactor described above can also be used for this purpose. 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.



Fuel pin distribution in the hexagonal bundle

Hexagonal fuel bundles in the Fast zone

Fuel bundle distribution in Thermal zone

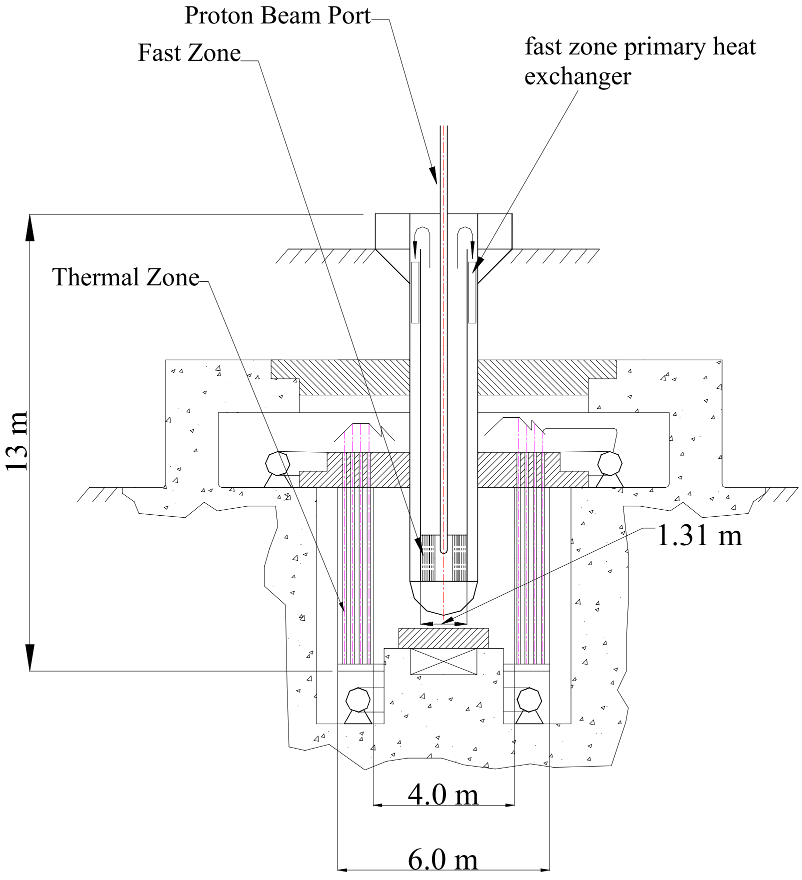


Fig. 1. Schematic of the 750 MW fast-thermal ADS

3.2 Accelerator sub-system:

The accelerator for ADS has stringent demands in terms of high current (tens of mA) and high energy (1 GeV) required for efficient spallation reaction. One of the most challenging parts of such a CW proton accelerator is the low-energy injector, typically up to 20 MeV, because the space-charge effects are maximal at lower energies. With this challenge in mind, a 20 MeV, 30 mA cw proton linac is being built at BARC [11]. The schematic of the 20 MeV linac is shown in Fig 2.

This linac will consist of an ECR ion source followed by a RFQ accelerator, which accelerates the proton beam from 50 keV to 3 MeV. The beam from the RFQ will then be accelerated to 20 MeV using the DTL structure. The beam from the ion source will be transported to the RFQ using the Low Energy Beam Transport (LEBT) line with minimum emittance growth and loss of beam current and from the RFQ to the DTL using the Medium Energy Beam Transport (MEBT) Line.

The beam dynamics in the RFQ and DTL depends on the interplay of many input parameters. After a detailed study an optimum design has been obtained. The RF power (including beam power) needed for RFQ and DTL are 450 kW and 1.36 MW respectively. The parameters of the RFQ and DTL are given in Tables 2 & 3. Based on the detailed thermal analysis its cooling system has been designed in order to maintain the frequency shift within +/- 100 kHz. The fabrication of prototypes of these systems has been taken-up.

The linac for accelerating proton beams from 50 MeV to 1 GeV will be of super-conducting type. Design and development of superconducting cavities for this energy range is also in progress. Depending upon the experience gained during these developments the 20-50 MeV section of the accelerator could either be normal conducting or superconducting type.

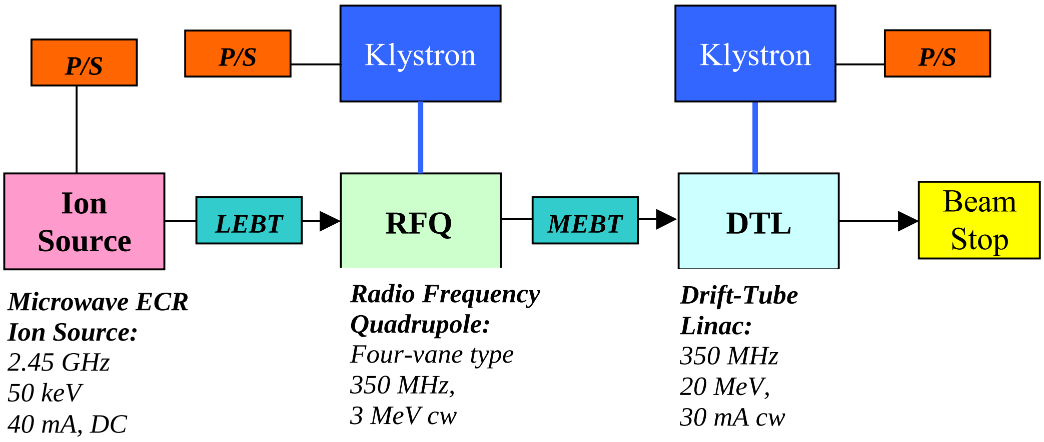


Fig. 2: Schematic of the 20 MeV high current proton accelerator

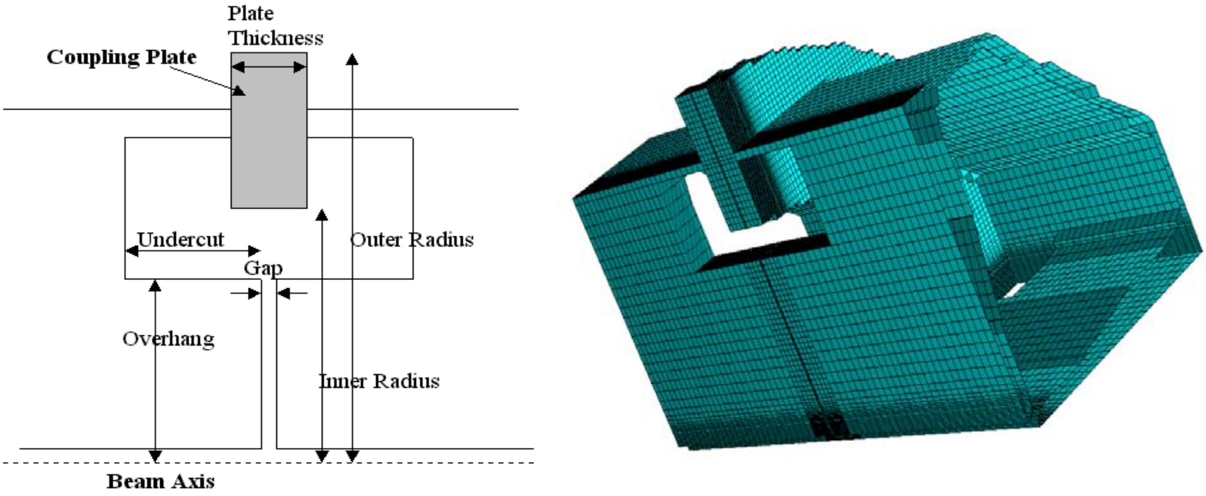


Fig. 3: Longitudinal profile and MAFIA model of coupling cell

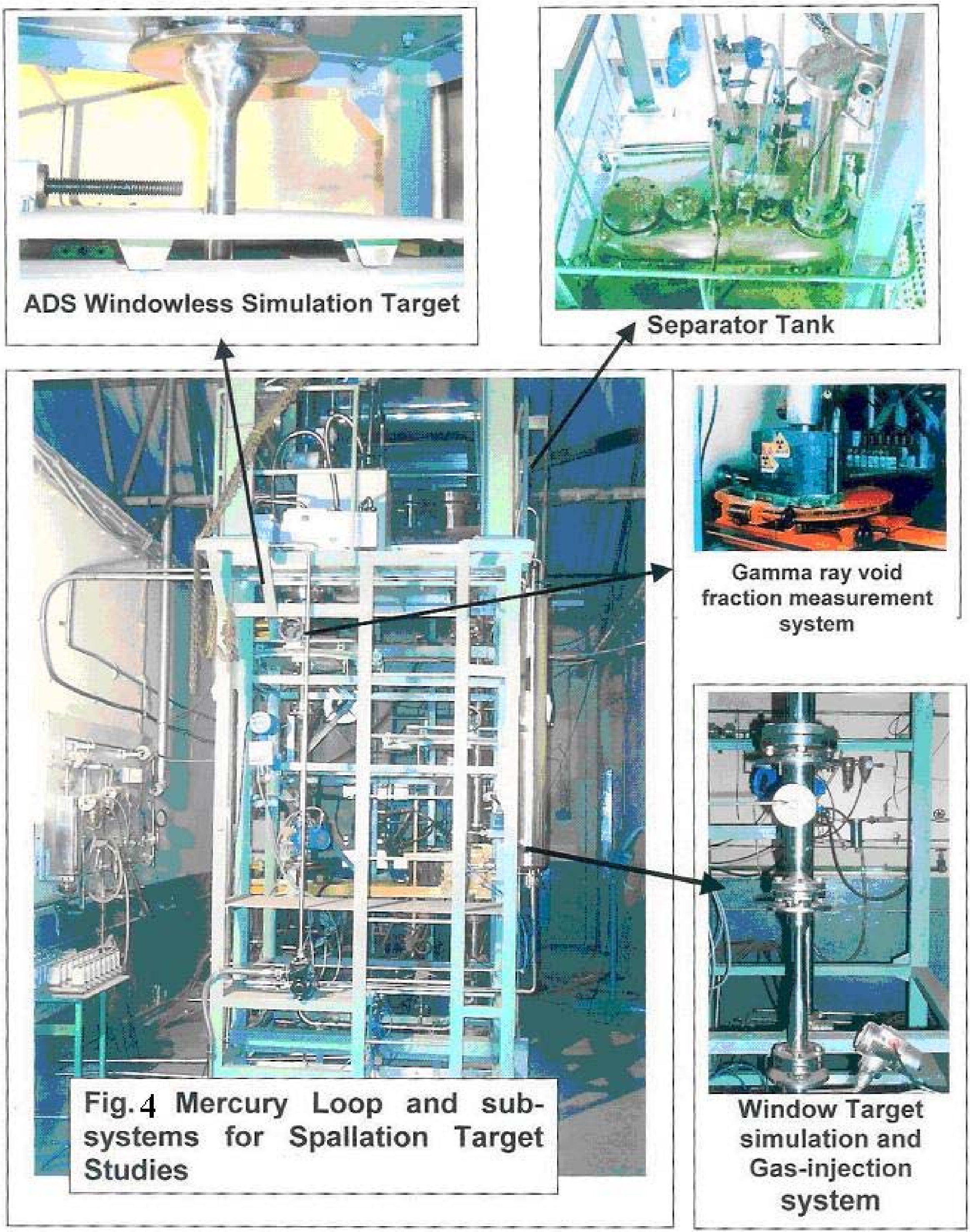
Table 2. Parameters of the RFQ

Parameter	**Value**
Frequency	350 MHz
Energy	50 keV/3 MeV
Input current	30 mA
Transverse Emittance	0.02/0.0216π cm-mrad
Vane Voltage	81.5 kV
Synchronous Phase	-30°
Length	3.62 m
Total RF power	430 kW
Peak Surface field	32.8 MV/m
Average aperture R_0	3.66-4.37 mm
Transverse Focusing parameter B	4.8-3.3
Maximum Modulation	1.96

3.3 Spallation Target sub-system:

3.3.1 Development of Computer Codes & validation

Typically the target loop consists of spallation region, riser, downcomer, expansion tank/separator tank, gas-injection system (for gas driven loop), heat-exchanger, window/ free surface region etc. We are developing codes for complete loop design (including 2-phase flow region for gas-driven target system) and detailed 2-D/3-D CFD codes for spallation region of the flow. Computational codes for target loop based on buoyancy driven and gas driven have already been developed. Presently two-dimensional CFD codes are being developed for flow and thermal analysis near the spallation region. The heat generated by the spallation, both in the window and target based on FLUKA code for 1GeV proton beam has been integrated with CFD codes.



ADS Windowless Simulation Target

Separator Tank

Gamma ray void fraction measurement system

Window Target simulation and Gas-injection system

Fig. 4 Mercury Loop and sub-systems for Spallation Target Studies

Table 3: Parameters for DTL geometry.

Input Parameters	**Value**	**Unit**
Energy	3 - 20	MeV
Cavity Diameter (D)	54	cm
Drift Tube Diameter (d)	11	cm
Diameter of Aperture (A)	1.6	cm
Corner Radius (Rc)	1.5	cm
Nose Radius	0.5	cm
Stem Diameter	2.0	cm
Axial Electric Field (E0)	1.38-3.00	MV/m

Output Parameters	**Value**	**Unit**
Peak Electric Field (E_{max})	6.54-12.71	MV/m
Energy Gain per Unit Length (W/ΣL)	1.81	MeV/m
Total Length of DTL	9.51	m
Avg. Effective Shunt Impedance (ZT^2)	52.4	MΩ/m
Beam Power	510	kW
Total RF Power	1.36	MW

3.3.2 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 UVP (ultrasonic velocity profile 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 are 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. The photograph of the facility is shown in Fig.4. The facility has already been charged with 650 kg mercury and experiments will be shortly commenced.

3.3.3 LBE loop for thermal hydraulic simulation studies

An LBE facility to study the intense heat deposition on the target window is currently being set up. The geometry and flow rates of the loop will be similar to that of a typical target. The maximum flow rate will be 125 kg/s and the loop will be operated at 225^{0}C and 400^{0}C respectively. Both pump and gas driven circulations will be incorporated in the facility. The plasma torch will simulate the thermal load on the window due to 1 GeV proton beam of few mA current (tens of kW of heat in the window). Design of the loop is in progress.

3.3.4 Lead-Bismuth-Eutectic (LBE) Buoyancy loop for corrosion studies

An LBE loop has been set up to study corrosion of SS and other container materials for LBE. The circulation is based on buoyancy. The loop is 6m in height and operates with hot leg at a maximum temperature of 550 ^{0}C and cold leg at 350 ^{0}C. The loop consists of riser and downcomer legs, corrosion testing chambers both in the hot and cold legs, air-cooled heat exchanger, expansion tank, dump tank etc. The maximum flow rate generated under optimum temperature difference will be ~ 2 kg/s. The velocity of the liquid metal in the corrosion test section will be ~0.5m/s. Both tensile as well as charpy tests will be carried out in the loop. It is proposed to expose the samples up to 4000 hours. Presently, the loop has already been installed and experiments will be commenced soon.

4.0 The APSARA facility and its conversion to LEU

4.1 The APSARA reactor

APSARA [12] is a pool type research reactor having a design power of 1 MW(t) of the MTR type. Its core is an assembly of HEU (93 %) fuel elements installed in an Al grid plate in a 7x7 square lattice. The grid plate is suspended from a movable trolley supported on rails on top of the pool. Thus the core can be positioned anywhere in the pool. Each fuel element consists of a number (12) of U-Al plates clad in Al, arranged parallel to one another and fixed in a box. In addition to the main fuel elements there are some partial elements and control elements which have fewer plates. The control elements have two Cd control rods in a 10 fuel plate box. The four control elements are used for power control, various reactivity loads such as power coefficients, Xe, and experimental loads, and for burnup compensation. Fig. 5 shows the core layout and a typical fuel element.

APSARA is the first reactor built in India (indeed in Asia) in 1956 and was the starting point of the nuclear energy program in India. It has been extensively used for material irradiation and testing, beam line research and operator training. Three types of cores have been irradiated. The initial and reload I cores had an enrichment of 46% and 80% respectively. As the reactor has been in service for a long time, a plan for refurbishment and modification has been drawn up.

4.2 The Modified APSARA reactor

Apart from the use of LEU, a number of major modifications [2] in the core have been proposed. The 7x7 lattice is rounded off by removing three assemblies at each of the corners to give 37 locations instead of the 49 in the original core. A heavy water reflector is proposed to increase the volume over which flux would be available for irradiation and the beam lines would be placed in this region. Modifications in the fuel element design include 18 plates instead of the earlier 12. The fuel used will be uranium silicide instead of the U-Al alloy because of its high density of about 4 gm per cc. The support mechanism for the core is altered. The coolant flow direction is reversed from top to bottom, primarily to reduce N^{16} activity. A delay tank has been provided. Initially the core would consist of Pu assemblies together with existing HEU which have not reached their targeted burnup and finally it will be fully converted to LEU.

5.0 LEU based reactor as a demo ADS?

As per the roadmap, the first demonstration (demo A) reactor will be having a 1 MW thermal power and will be driven by an accelerator of about 100 MeV neutrons. Since a PB /LBE target was visualized, the size of the target required a displacement of a several central assemblies from the modified APSARA reactor and the resulting k_{eff} was too low to be of much use. Thus the initial studies concluded that a straightforward conversion of the modified APSARA reactor to run as a sub-critical mode was not feasible and a redesign of the facility would be necessary. However, the ideal of having a common facility which could be run as a critical facility and later as a demo ADS continues to be an attractive one.

Another interesting idea considered was the possibility of using the 20 MeV tenth plan LINAC accelerator to drive a low power reactor. Since the energy of the beam is 20 MeV, a Be target would have to be used. With a k_{eff} of about 0.96, a power of 10-100 kW would be possible. However, due to space constraints, the new accelerator building could not be located near the APSARA reactor. This building is closer to the AHWR critical facility building and the possibility of using the beam of this accelerator to drive the sub-critical AHWR core is being considered. Since the beam power is expected to be rather high for driving the facility, power reduction through pulsing is being examined.

6.0 Summary and Conclusions

In view of the Indian perspective on utilization of thorium fuel in nuclear power generation, ADS provides an alternate route, which is also relevant for incineration of long-lived radioactive waste from the uranium fuel cycle. All aspects of ADS subsystems are being pursued for development of relevant technologies. Reactor physics studies currently focus on devising an optimum ADS configuration including one-way coupled fast-thermal system requiring low beam power from driver accelerator. In target system development programme, the thermal hydraulics and materials compatibility studies are in progress. A low-energy, high average beam current proton linac programme is in advanced stage to build a 3 MeV RFQ and further accelerator section including 20 MeV drift-tube linac (DTL). Work on linac construction has progressed to set up necessary infrastructure in BARC, which consists of a building with adequate shielding, RF (electrical) power and low conductivity cooling water systems.

The first demonstration ADS (demo A) having a power of about 1 MW, driven by a proton accelerator of about 100 MeV, is planned to be a pool type reactor employing LEU as fuel, as per the roadmap. There is already a program for converting the existing HEU facility into one using LEU and also for constructing a higher flux reactor based on LEU fuel. Further studies will be required to determine whether the demo A can be planned around these systems or will ultimately require an independent facility based on LEU.

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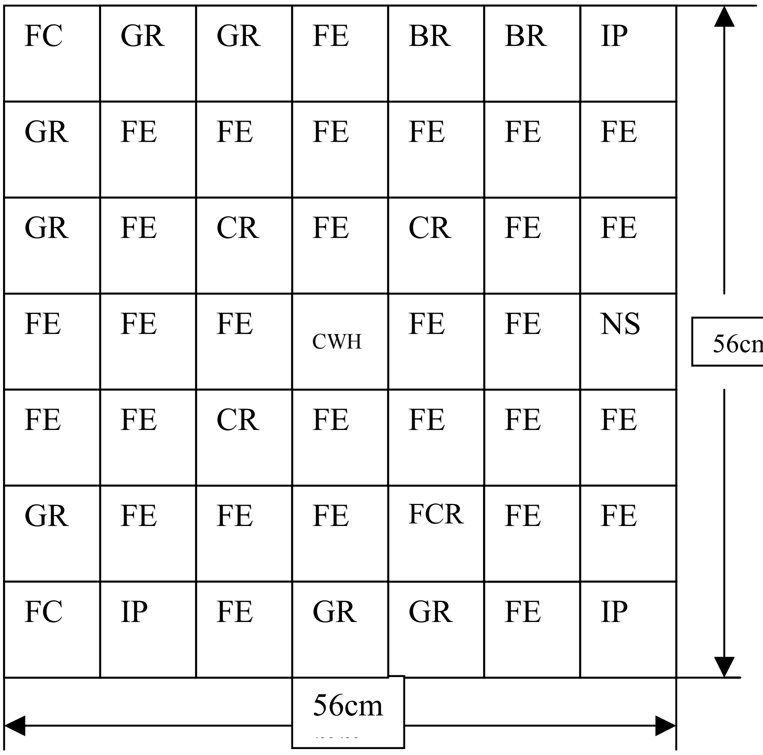
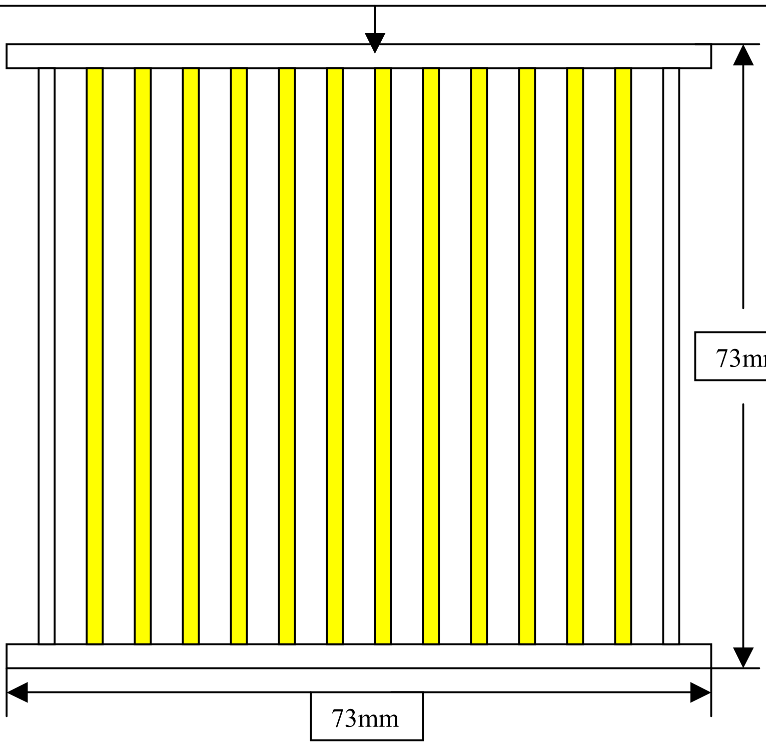
Fig. 5 Core layout of the APSARA reactor and a typical fuel element



FC	GR	GR	FE	BR	BR	IP
GR	FE	FE	FE	FE	FE	FE
GR	FE	CR	FE	CR	FE	FE
FE	FE	FE	CWH	FE	FE	NS
FE	FE	CR	FE	FE	FE	FE
GR	FE	FE	FE	FCR	FE	FE
FC	IP	FE	GR	GR	FE	IP

Core layout having: fuel element (FE), graphite reflector (GR), control rod (CR), source (NS), fission counter (FC), BeO reflector (BR), irradiation position (IR), central water hole (CWH) and fine control

A fuel element having 12 fuel plates (yellow) clad in Al and inert Al plates at the ends



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