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Accelerator-driven sub-critical reactor system (ADS) for nuclear energy generation

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Abstract. In this talk we present an overview of accelerator-driven sub-critical reactor systems (ADS), and bring out their attractive features for the elimination of troublesome long-lived components of the spent fuel, as well as for nuclear energy generation utilizing thorium as fuel. In India, there is an interest in the programmes of development of high-energy and high-current accelerators due to the potential of ADS in utilizing the vast resources of thorium in the country for nuclear power generation. The accelerator related activities planned in this direction will be outlined.

Keywords. High-energy accelerator; energy generation; radioactive waste elimination.

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1. Introduction

If we examine all possibilities by which electricity generation can be expanded, the nuclear power appears to be an inevitable option. As of now, fission chain reaction is the only way known to produce nuclear power, while the naturally occurring uranium and the man-made plutonium are the two key elements that are serving as nuclear fuel. Nuclear power presently constitutes about 17% of the total electric power generation in the world from about 430 operating reactors. Although this figure of global nuclear energy generation appears modest, the share of nuclear electricity in several countries is much higher, ranging from 30 to 70%.

It appears that hesitations in further developments of nuclear power are primarily due to the environmental concerns arising from the nuclear waste disposal schemes involving long-term geological storage of commercial reactor waste. For future growth of nuclear power, it will be necessary to satisfactorily address the troublesome issue of disposal of the nuclear waste, in particular, long-lived transuranic elements (TRU), e.g. Pu, Np, Am, Cm etc. and fission products (FP), e.g. ^{129}I, ^{135}Cs, ^{99}Tc, ^{93}Zr, ^{107}Pd etc. The TRU constitute about 1% of the nuclear waste mass, but TRU radiotoxicity (RT) is about 20000 that of the fission products after 1000 years. Hence, considerable reduction of the source radiotoxicity (RT) can result from incineration of TRU. Consequently, incineration of TRU and transmutation of FP can make its disposal in geological repository environmentally acceptable.

While the incineration of minor actinides (MA) Np, Am, Cm etc. is particularly required, it appears difficult to achieve this in the critical reactors. Considerations of the available delayed neutron fractions and negative temperature feedbacks needed for the safe reactor operation impose severe constraints on the fuel types that can be used in its core. For this reason, it becomes difficult to design critical reactors that are suitable to burn, in particular, these long-lived minor actinides. Also neutron economy considerations make it difficult to transmute the long-lived fission products (LLFP) in the critical reactors. Consequently, in the recent years there has been considerable upsurge of interest in the concept of accelerator-driven sub-critical reactor systems (ADS). This is primarily due to the fact that in ADS, plutonium as well as the long-lived minor actinides can become substantial part of the nuclear fuel and incinerated for energy generation without concerns on the criticality related safety issues.

Ideas on the use of high intensity accelerators in nuclear energy development have been proposed many decades ago (see, for example [1–3]). But, current interest in the use of ADS has been stimulated particularly by the papers by Bowman [4] and Rubbia *et al* [5], which demonstrate that a commercial nuclear power plant of adequate power can also be built around a sub-critical reactor, provided it can be fed externally with required intensity of accelerator-produced neutrons.

There have been a number of international seminars, conferences and IAEA sponsored meetings on the subject and a recent summary of the international activity on this topic can be found in [6]. In Europe, USA and Japan, the interest in the ADS – also called hybrid reactor systems – has been largely stimulated by the fact that a sub-critical core is ideally suited to safely incinerate the long-lived transuranics and the fission products, which constitute the troublesome component of nuclear waste for disposal in deep geological repository. Hence the term accelerator transmutation of waste (ATW) has become synonymous with the accelerator-driven sub-critical reactor systems (ADS).

The nuclear waste disposal is certainly an urgent and important issue to be tackled to ensure further growth of nuclear power, particularly in countries already having a large nuclear power programme. ATW is, therefore, quite relevant for further growth of nuclear power. However, for developing countries like India, where the nuclear power programmes are presently at a rather low level, economic exploitation of nuclear power is considerably more dependent on an efficient utilization of the nuclear fuel resources in the country. For India, which has abundant reserves of thorium, ADS is relevant because one can also exploit its potential to design hybrid reactor systems that can produce nuclear power with the use of thorium as the main fuel. The ^{232}Th–^{233}U fuel cycle has the added advantage that it minimizes the production of troublesome long-lived actinide waste. The ADS-based thorium burners may need only small and limited quantities of uranium and plutonium fuel to serve as starter seeds. In general, the additional degree of freedom provided by the external neutron source in ADS can enable one to design reactor systems which primarily burn thorium fuel as well as make a more efficient use of the uranium fuel. Therefore, ADS seems to have the potential to provide an additional route to an efficient and economic nuclear power generation with the available uranium and thorium resources.

2. Brief description of ADS

Figure 1 shows a schematic of the principal elements of ADS concept. In ADS, high-energy proton beam strikes a heavy element target, which yields copious neutrons by (p,xn) spallation reaction and therefore, a spallation target as a source of neutrons can

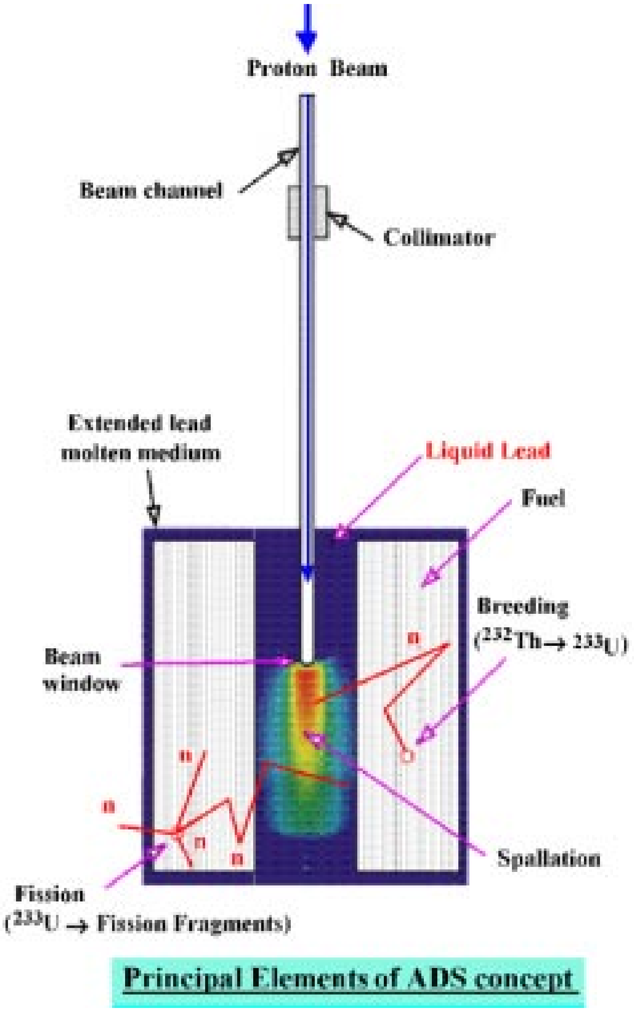
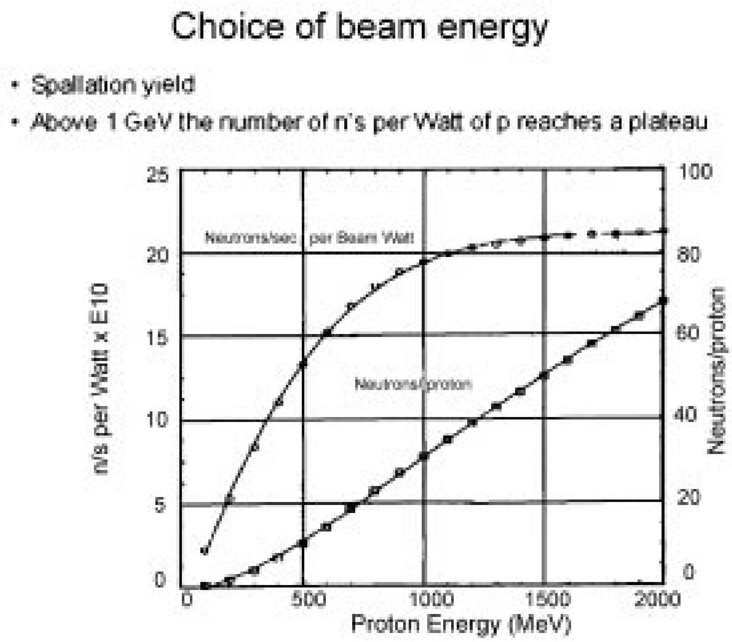


Figure 1. Schematic diagram showing elements of an ADS configuration to utilize thorium as fuel.

drive self-terminating fission chains in a sub-critical core. Except for a high energy tail, the spectrum of these neutrons emanating from the target surface is not very much different from that of fission neutrons. In general, each energetic proton can yield 20–30 neutrons at proton energies around 1 GeV in high Z target materials.

The major sub-systems of ADS are:

(i) High power proton accelerator – 1 GeV, $\geq$10 mA current.
(ii) Spallation target – heavy element (Pb, W, U...), for $\geq$10 MW beam power.
(iii) Sub-critical core – fast neutron system, thermal neutron system or a combination of fast and thermal neutron system.



Choice of beam energy

- Spallation yield
- Above 1 GeV the number of n's per Watt of p reaches a plateau

Figure 2. Calculated yield of spallation neutrons from thick lead target at various energy of accelerated proton beam. Above 1 GeV, the neutrons per watt of incident proton beam reach a plateau (taken from European TWG report on ADS, March 2001).

The thermal power of the ADS will depend on the value of the effective multiplication factor, k, of the multiplying fuel (sub-critical) core of the medium surrounding the spallation target and the strength of the primary neutron source. The energy (or power) generated by fission in the multiplying fuel core is many times more than the energy (or power) of the incident proton beam.

The power gain G, as discussed in [7], being the ratio of total fission power and the incident beam power, can be written as:

$$\begin{aligned} G &= \frac{k}{1-k}\cdot\frac{\text{Average energy released in fission per emitted fission neutron}}{\text{Average energetic cost of production of spallation neutron}} \\ &= G_0\cdot\frac{k}{1-k}. \end{aligned} \tag{1}$$

For protons of energy 1 GeV and a lead spallation target, the value of G_0 is about 2 which has been experimentally verified [8].

The average energetic cost of spallation neutron has been calculated for different proton beam energy and the target nuclei combinations. In a typical case of a thick target of pure lead, both the neutrons per proton and the neutrons/s/W of the proton beam power at different incident particle energy are shown in figure 2. From this, it is seen that proton beam energy of about 1 GeV would be required. Above this proton energy, there is only marginal neutronics gain but below this there is a sharp fall.

Figure 3 illustrates that ADS can feed a net electric power to the grid. In this illustration, the proton beam of 13 MW ($E = 1$ GeV, $I = 13$ mA) impinges on a heavy metal spallation

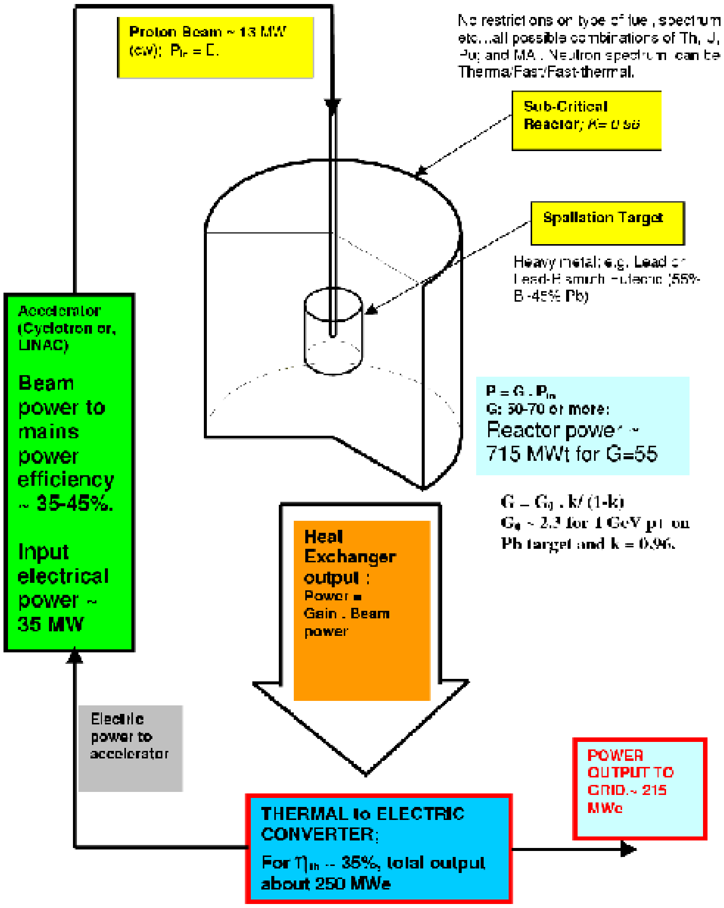


Figure 3. Schematic of accelerator-driven sub-critical reactor system for nuclear energy generation.

target, and the resulting neutrons enter the core of a sub-critical reactor to produce fission power. As an example, if the power gain is 55, it can result in an output electric power of 250 MWe, out of which 35 MWe is fed back to run the accelerator and 215 MWe is fed to the grid. Increasing the power gain or the input accelerator power or a combination of both can generate larger electric powers.

In order to drive ADS with a relatively lower power accelerator, the concept of using a booster has been proposed [9]. In the neutronics studies carried out at Trombay [10], it has been shown that we can circumvent this high beam current requirement by designing a suitable two-stage energy amplifier. Such a two-stage system (figure 4) consists of a fast sub-critical reactor (booster) which is one-way coupled to a thermal sub-critical reactor. This is achieved by installing a thermal neutron absorber shield between the two cores as well as by keeping the two cores at a distance so that the fission neutrons of the thermal core do not interact with the fast booster core.

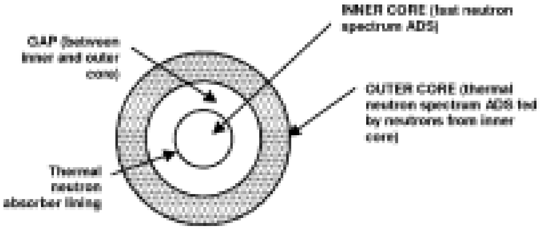


Figure 4. A schematic of fast-thermal one-way coupled ADS.

3. Spallation target and acceleration in ADS

In order to realize these attractive features of ADS, considerable R&D and technology development will be needed in the coming years, particularly to develop the required high-power accelerator and spallation target systems. Two severe operating conditions of the spallation target are the very high volumetric heat deposition rate and irradiation by high fluence of energetic protons and neutrons. Regarding the former, the peak power dissipation density in the target volume can be of the order of a few kW/cm^3. Use of heavy liquid metals like lead and bismuth serves both as spallation target and heat removing media. The problems associated with irradiation damage like swelling, cracking/embrittlement and other degradations are easily avoided in such a target. However, these and corrosion/erosion issues need to be resolved with new and better materials for liquid target container and process equipment.

But, in the practical realization of the ADS, the most challenging task is the development of a high energy ($\sim$1 GeV) and high current ($\geq$10–15 mA) proton accelerator, which is reliable, rugged and stable in order to provide uninterrupted beam power to the spallation target over long periods of time. Presently, accelerators of continuous wave type, as well as high repetition (pulse) rate types are being evaluated for ADS applications [11]. Even though charged particle accelerators have been used as tools of front-line research for more than half a century, proton accelerators developed so far have a beam power which is at least one order of magnitude less than that needed for ADS. Therefore, the ADS and some other applications of high power proton beams, such as for rare ion beams (RIB) facility and spallation neutron source for research and material irradiation testing are the driving force for intense R&D to develop such accelerators.

To summarize, some of the most important technological challenges for these two subsystems in ADS are as follows:

(a) *High power spallation target*:

- Has high spallation neutron yield at 1 GeV proton beam (neutron/proton$\sim$20–40).
- Has capability to dissipate very high heat flux without vaporizing (heat flux of the order $\sim$1 kW/cm^3).
- Withstands irradiation and thermal effects along with its container.

(b) *High-power proton accelerator for $\geq$10 MW (cw) beam power that is*:

- Robust and reliable for year-round uninterrupted operation. That is, its availability is $\geq$99%.

- Operates with minimum beam loss in accelerator channel for limiting activation of components and their hands-on maintenance (beam loss $\leq$ 1 nA/m).
- Having high (electrical) conversion efficiency from mains to beam power ($\eta \geq 40\%$).

3.1 *International scenario on accelerator development programmes*

(i) USA: Earlier as ATW/APT. Now AAA (advanced accelerator applications) aiming for having accelerator-driven test facility (ADTF) within 10 years from 2001 and full technological demonstration plant in further 10 years.

(ii) Europe: Under extended technical working group (ETWG) planning by 9 European countries for a demonstration X-ADS. Also, some countries in Europe have undertaken individual ADS programmes, e.g.,

> Italy: under its TRASCO (transmutazion scorie) programme and, industrial project undertaken by ANSALDO for EC.
>
> Belgium: under MYRRHA project as extension of ADONIS (accelerator-driven operated new irradiation system) programme for radioisotope production.
>
> France: its CNRS/IN2P3 institutes are spearheading waste incineration R&D with spin-off of its TRISPAL activities directed now for ADS as part of GEDEON.
>
> Germany: activities under FZK in the yet un-named programme.

(iii) Japan: Under its OMEGA (option making extra gains of actinides and FP), that is the extension of its earlier actinides burner reactor (ABR). Now, under Joint KEK-JAERI project.

(iv) Russia: Undertaken several study projects in ITEP/ISTC against the EC/US funding.

(v) Korea: Under its HYPER (hybrid power extraction reactor) programme.

(vi) China: Proposed as CIAE+IHEP project under an un-named ADS programme.

3.2 *Types of accelerator for ADS*

Basically, there are two types of proton accelerator systems for application to ADS – separated sector or orbit proton cyclotron and proton linear accelerator (LINAC). Both these high-intensity accelerator systems do not require new scientific principles to evolve but need consolidation of technologies already in application at somewhat less demanding levels. The basic characteristics of these two types, which need developments in varying technology regimes, can be summarized as follows:

Cyclotron is an inherently continuous wave (cw) beam current accelerator – the type that is ideally required for ADS reactor. Since the beam orbits during acceleration of protons are wrapped up, the machine systems occupy space of typically the same size as nuclear reactor complex. But the limitation in performance of this type of proton accelerator comes from the maximum beam current. Designs of separated sector cyclotrons have been proposed to achieve a 10-MW beam power, but this is generally seen as upper limit for a cyclotron. The cyclotron can work as fixed energy machine, up to 1 GeV without needing too large electromagnets, but, with little freedom to change either beam energy or too much of current.

The high-energy proton LINACs built so far have been designed for pulsed beam current operation and thus, have duty-cycle in the range 0.2–10%. LINACs have modular configuration and amenable to be upgraded in both the energy and beam power. At the present technological level, it seems feasible to achieve proton energy of 1 GeV or more and produce as much as 100 mA beam current from this type of accelerator. However, for conserving the electrical efficiency in respect of input electrical power, it is necessary to utilize the superconducting rf cavities at liquid helium temperature in most part of the accelerator. However, that adds to the technological complexity in machine systems. A shortcoming with LINAC is its requirement of long length, from 500 m to 800 m, for 1 GeV energy of accelerated protons.

4. Indian programme on accelerator for ADS

Realizing the vast potential of high-intensity proton accelerators for ADS and other equally important applications, a programme has been evolved for stage-wise development of systems and technologies in India. This is based on proton linear accelerator development in the first stage and cyclotron as a complementary one. This programme for the accelerator development is shown in figure 5. This is divided into three distinct technology modules involving:

(1) High current, low-energy normal conducting proton injector of 10 MeV.
(2) An intermediate energy LINAC up to 100 MeV; most likely to be of normal conducting rf resonating cavities type, but with possible change over to SC cavities in future for saving in operating energy costs.
(3) High energy, superconducting cavities type LINAC for 100 to 800/1000 MeV energy section.

At the end of each developmental stage, more than one important technological applications of the system have been shown as part of multi-purpose accelerator complex. This perspective plan of action is expected to be taken up for stage-wise funding and implementation soon.

In the implementation of Indian plans on high current proton accelerator which is primarily intended for application to drive ADS, several new and improved technological requirement will have to be dealt with. A few of these are listed below:

(1) High power rf system
    - Klystron power amplifier system
    - HV (MW) DC power supplies
    - New rf power technologies
(2) CW rf resonating structures (NC cavities)
    - Precision machining
    - Copper welding/vacuum brazing

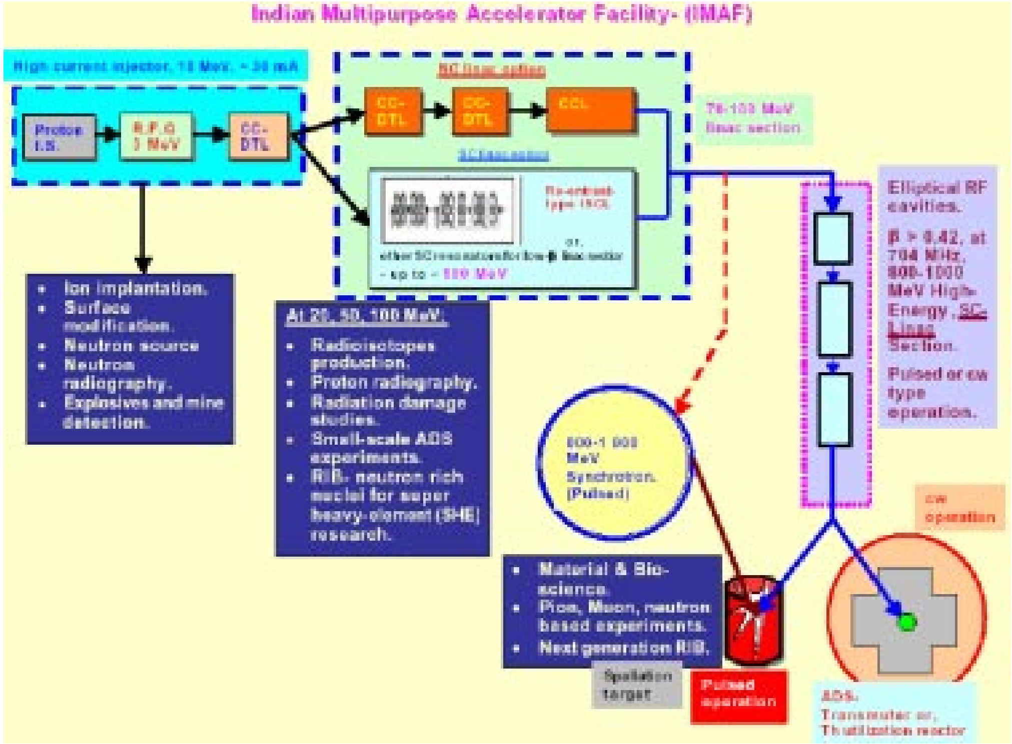


Figure 5. Schematic lay out of Indian multipurpose accelerator facility (IMAF).

  - Heat dissipation
  - Alignment and thermal stability

(3) Superconducting rf technology

  - Niobium resonators
  - Cryogenics below 4.2 K
  - Cryostats
  - rf Power couplers

(4) Surface finishing/cleaning and ultra clean-room assembly.
(5) Special high-power proton beam diagnostics – non-obstructing type.
(6) Target–vacuum interface for containment of spallation products.
(7) Reliability, efficiency, maintainability (activation effects of beam-spill).

5. Concluding remarks

Accelerator-driven sub-critical reactor systems have many attractive features for nuclear power applications. One of the most challenging component of the ADS is the high-energy and high-current accelerator capable of delivering average proton beam power of 10 MW or more. There is worldwide interest to develop an accelerator system of such a high beam power, which is at least one order of magnitude larger than the beam power of presently operating ones. Development of such high power accelerators will have several other applications in nuclear science and technology. In India, there is a programme to undertake a stage-wise development of such a high power proton accelerator and put to applications the intermediate milestone achievements.

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