CHAPTER 2

Brief description of Advanced Heavy Water Reactor and Accelerator Driven Subcritical Systems

2.1 Introduction

The nuclear waste disposal is certainly an urgent and important issue to be tackled to ensure further growth of nuclear power. More recently, there has been interest in transmuting the long-lived transuranic radio-nuclides (actinides- neptunium, americium and curium particularly) formed by neutron capture in a conventional reactor and reporting with high-level nuclear waste. If these could be made into shorter-lived radio-nuclides such as fission products, the management and eventual disposal of high-level radioactive waste would be easier and less expensive. For many years, there has been interest in utilizing thorium as a nuclear fuel since it is three times as abundant in the earth's crust as uranium. All of the mined thorium is also potentially useable in a reactor, compared with 0.7 % of natural uranium. A thorium reactor would work by having ^{232}Th capture a neutron to become ^{233}Th which decays to ^{233}U, which fissions.

India has abundant reserves of thorium compare to uranium. Therefore, Indian nuclear power has been conceived bearing in mind the optimum utilization of domestic uranium and thorium reserves with the objective of providing long-term energy security to the country [1]. Considering the large thorium reserves in India, the future nuclear systems, in the third stage of Indian nuclear power program, will be based on ^{232}Th – ^{233}U fuel cycle. There is a strong need for the development of thorium-based technologies for the entire thorium fuel cycle. The Advanced Heavy Water Reactor (AHWR) [1] is being designed in India to fulfill this need.

The concept of Accelerator Driven Subcritical Systems (ADS) [2-4] brings out 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 [5]. The ADS are seen as safer compare to normal fission reactor because it is subcritical and stop when the input current is switched off. This is because ADS burn material does not have a high enough fission to capture ratio for neutrons to enable criticality and maintain a fission chain reaction. It may be thorium fuel or actinides which need "incineration". In this way, ADS address both these issues. 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.

In view of above discussions and importance of AHWR and ADS in India, the present chapter briefly gives an overview of AHWR and ADS.

2.2 AHWR – The thorium fuelled Indian nuclear reactor

The AHWR means Advanced Heavy Water Reactor and it is being designed by Dr. R. K. Sinha and Dr. Anil Kakodkar [1] of Bhabha Atomic Research Centre, Mumbai, India. The AHWR is a 300 MW_e, vertical, pressure tube type, heavy water moderated, boiling light water cooled natural circulation reactor. The fuel consists of $(Th–Pu)O_2$ and $(Th–^{233}U)O_2$ pins. The fuel cluster is designed to generate maximum energy out of ^{233}U, which is bred in situ from thorium and has a slightly negative void coefficient of reactivity. A distinguishing feature which makes AHWR unique, from other conventional nuclear power reactors is the fact that it is designed to remove core heat by natural circulation, under normal operating conditions, eliminating the need of pumps. In addition to this passive feature, several innovative passive safety systems have been incorporated in the design, for decay heat removal under shut down condition and mitigation of postulated accident conditions.

2.2.1 Evaluation of the AHWR

Thorium is a fertile material and has to be converted into ^{233}U, a fissile isotope. Of the three fissile species (^{233}U, ^{235}U and ^{239}Pu), ^{233}U has the highest value of η (number of neutrons liberated for every neutron absorbed in the fuel) in thermal spectrum. Since ^{233}U does not occur in the nature, it is desirable that any system that uses ^{233}U should be self-sustaining in this nuclide in the entire fuel cycle, which implies that the amount of ^{233}U used in the cycle should be equal to the amount produced and recovered. Thorium in its natural state does not contain any fissile isotope the way uranium does. Hence, with thorium-based fuel, enrichment with fissile material is essential. The large absorption cross-section for thermal neutrons in thorium facilitates the use of light water as coolant. On account of its high cost and its association with radioactive tritium, use of heavy water coolant requires implementation of a costly heavy water management and recovery system. The use of light water as coolant makes it possible to use boiling in the core, thus producing steam at a higher pressure than otherwise possible with a pressurized non-boiling system. With boiling coolant, the reactor has to be vertical, making full core heat removal by natural circulation feasible. The choice of heavy water as moderator is derived from its excellent fuel utilization characteristics. Considering these characteristics, the mainly thorium fuelled AHWR, is heavy water moderated, boiling light water cooled, and has a vertical core. For the AHWR, pressure tube type PHWR technology is selected to take advantage of the vast experience gained and infrastructure developed in the country. It is desirable for the new reactors to incorporate passive safety characteristics consistent with the emerging international trends.

2.2.2 Brief description of AHWR configuration

The AHWR is a vertical, pressure tube type, heavy water moderated and boiling light water cooled natural circulation reactor [6] designed to generate 300 MW_e and 500 m^3/day of desalinated water. The AHWR is fuelled with $(Th–^{233}U)O_2$ pins and $(Th–Pu)O_2$ pins. The fuel is designed to maximize generation of energy from thorium, to maintain self-sufficiency in ^{233}U and to achieve a slightly negative void coefficient of reactivity. An emergency core cooling system injects water directly into the fuel. The reactor core of the AHWR consists of 505 lattice locations in a square lattice pitch of 245 mm. Of these, 53 locations are for the reactivity control devices and shut down systems. Reactivity control is achieved by on-line fuelling, boron dissolved in moderator and reactivity devices. Boron in moderator is used for reactivity management of equilibrium xenon load. There are 12 control rods, grouped into regulating rods, absorber rods and shim rods of 4 each. The reactor has two independent, functionally diverse, fast acting shut down systems, namely, Shut Down System-1 (SDS-1) consisting of mechanical shut off rods and Shut Down System-2 (SDS-2) based on liquid poison injection into the moderator. There are 30 interstitial lattice locations housing 150 in-core self-powered neutron detectors and 6 out-of-core locations containing 9 ion chambers and 3 start-up detectors. An automatic reactor regulating system is used to control the reactor power, power/flux distribution, power-setback and xenon override. Both for the control rods and the shut off rods, the absorber material, boron carbide, is packed in an annulus within 80 stainless steel tubes. The schematic diagram of AHWR is given Fig. 2.1.

A fuelling machine is located on top of the deck plate. The fuelling machine of the AHWR handles the fuel clusters by means of ram drives and snout drive for coupling and making a leak tight joint with the coolant channel. The AHWR has the flexibility to have on power as well as off-power fuel handling.

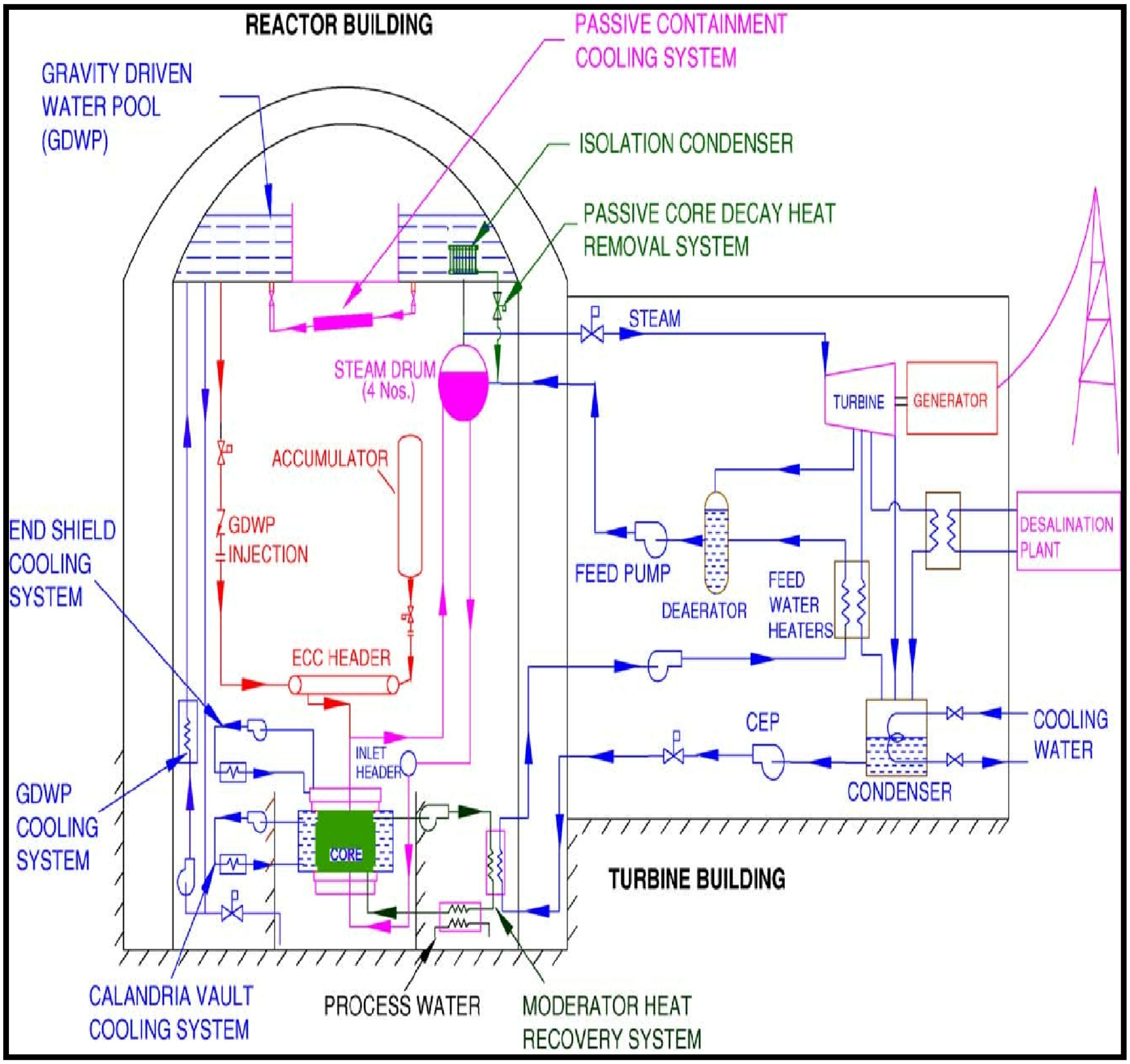

Fig. 2.1 A schematic arrangement of the AHWR [1]

2.2.3 Fuel for AHWR

The AHWR fuel has been designed to meet the requirement of thermal hydraulics, reactor physics, fuel handling and reconstitution (i.e., replacement of outer ring of irradiated $(Th–Pu)O_2$ fuel pins with fresh ones). The vertical pressure tube configuration has guided the structural design of the fuel assembly. The fuel assembly is 10.5 m in length and is suspended from the top in the coolant channel. The assembly consists of a fuel cluster and two shield sub-assemblies. These sub-assemblies are connected to each other through a quick connecting/disconnecting joint to facilitate handling. The fuel cluster is a cylindrical assembly of 4300 mm length and 118 mm diameter. The 24 fuel pins in the outer ring have $(Th–Pu)O_2$ as fuel and the 30 fuel pins in the inner and intermediate rings have $(Th–^{233}U)O_2$ as fuel.

The fuel pin consists of fuel pellets confined in a Zircaloy-2 clad tube. The fuel pin has a pellet stack length of 3500 mm and a plenum volume with a helical spring in it to keep the pellet stack pressed. The AHWR fuel cycle is a closed fuel cycle, envisaging recycle of both fissile ^{233}U and fertile thorium back to the reactor [7]. Since the ^{233}U required for the reactor is to be bred in situ, the initial core and annual reload for the initial few years will consist of $(Th–Pu)O_2$ clusters only. After reprocessing, ^{233}U is always associated with ^{232}U, whose daughter products are hard gamma emitters. The radioactivity of ^{232}U associated with ^{233}U starts increasing after separation. This poses radiation exposure problems during its transportation, handling and refabrication. Hence, it is targeted to minimize delay between separation of ^{233}U and its refabrication into fuel. In view of this, a co-location of the fuel cycle facility, comprising reprocessing, waste management and fuel fabrication plant, with the AHWR has been planned. The ^{233}U based fuel needs to be fabricated in shielded facilities due to activity associated with ^{232}U. This also requires considerable enhancement of automation and remotization technologies used in fuel fabrication. The spent fuel cluster, before reprocessing, would undergo disassembly for segregation of $(Th–Pu)O_2$ pins, $(Th–^{233}U)O_2$ pins, structural materials and burnable absorbers. The $(Th–^{233}U)O_2$ pins will require a two stream reprocessing process, i.e., separation of thorium and uranium whereas the $(Th–Pu)O_2$ pins will require a three stream reprocessing process, i.e., separation of thorium, uranium and plutonium. A part of the reprocessed thorium (45%) may be used immediately in the fabrication of $(Th–^{233}U)O_2$ pins since ^{233}U fabrication is required to be carried out in shielded facilities. The remaining thorium will be stored for sufficient amount of time for the activity to decay to a level at which, it is easier for handling with minimal shielding. The stored thorium will be subsequently used for the fabrication of (Th–Pu)O_2 fuel pins.

2.3 ADS – A new concept for nuclear waste transmutation and nuclear energy generation

In the recent years, there has been considerable interest in the concept of accelerator-driven sub-critical reactor systems (ADS). This is primarily due to the fact that in ADS, thorium 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. The main interest in the use of ADS has been stimulated particularly by the papers of Bowman [3] and Rubbia et al [4], 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.

Accelerator-driven sub-critical reactor systems have many attractive features for nuclear power applications. One of the most challenging components 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.

2.3.1 The major subsystems of ADS

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 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. A schematic of the principal elements of ADS concept are given in Figs. 2.2 and 2.3.

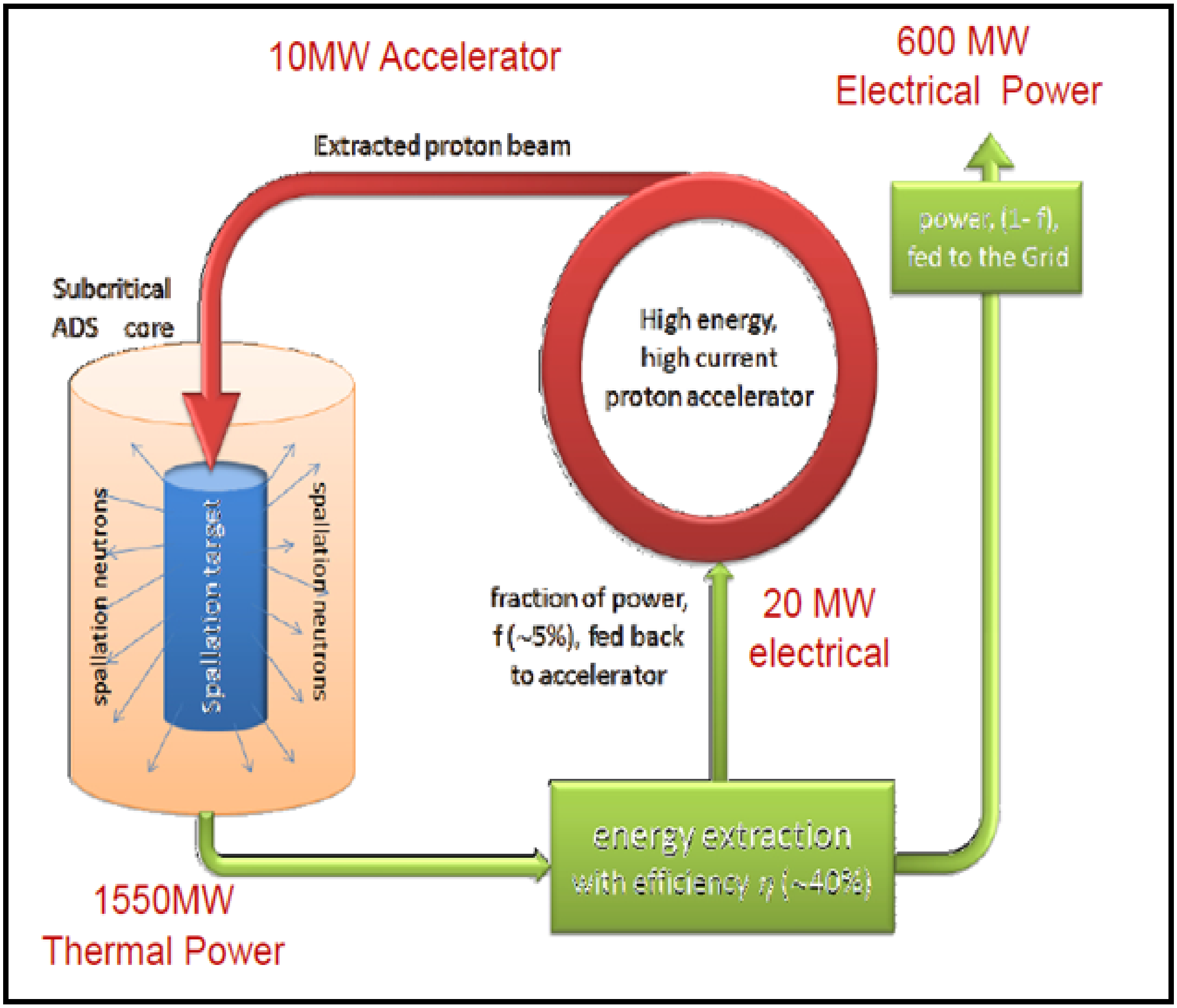

Fig. 2.2 A Schematic diagram of ADS

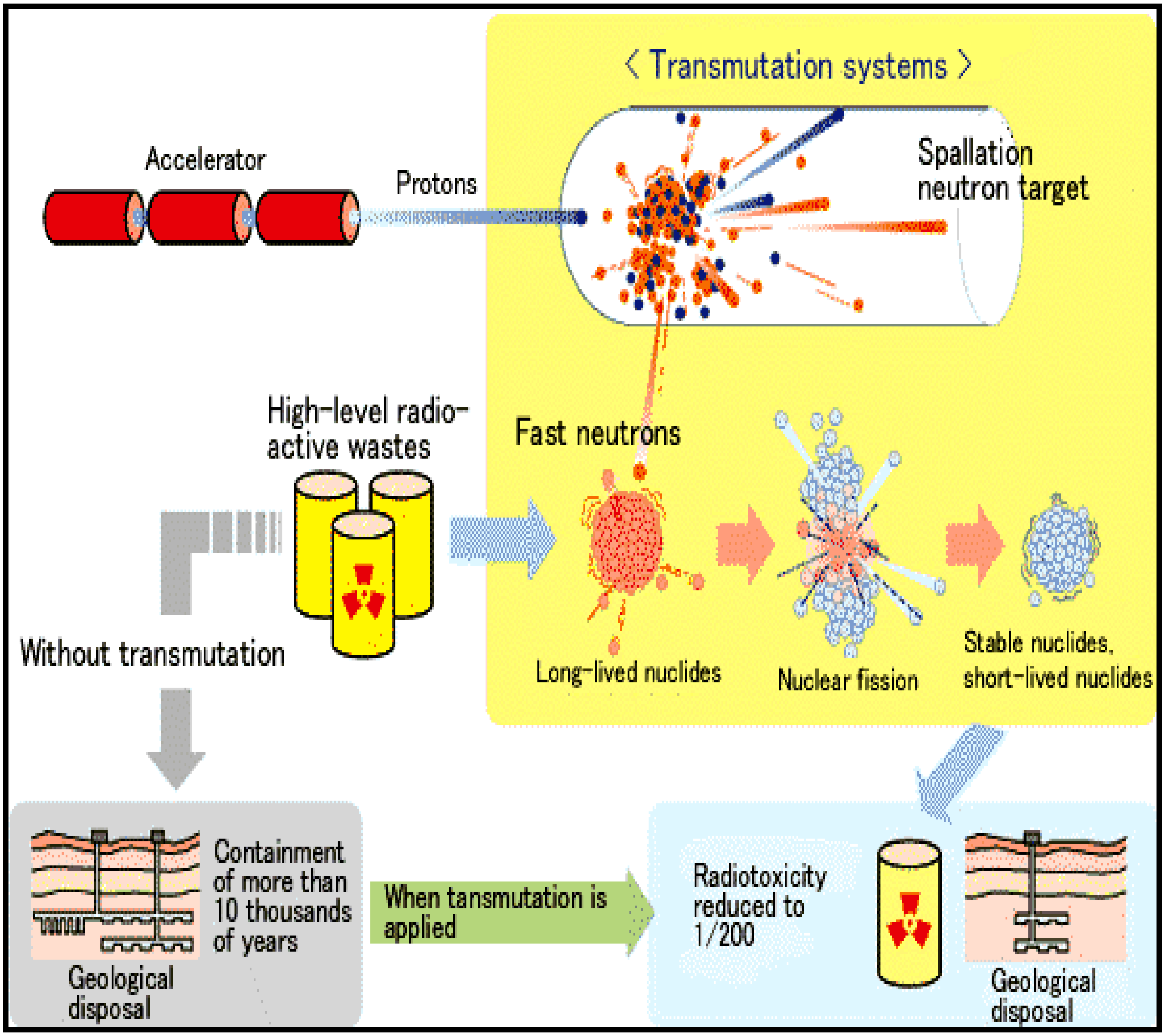

Fig. 2.3 A Schematic diagram of ADS for transmutations

The main sub-systems of ADS are as follows [5]:

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

The capability of high-current, high-energy accelerators to produce neutrons by spallation from heavy elements has been used in the structural research of such materials. In this process, a beam of high-energy protons is directed at a high-atomic target and up to one neutron can be produced per 25 MeV of the incident proton beam. (These numbers compare with 200-210 MeV released by the fission of one ^{235}U and ^{239}Pu atom). A 1 GeV proton beam will create 20-30 neutrons per proton. In principle, the subcritical nuclear reactor may be able to convert all transuranic elements (generally) short-lived fission products and yield some energy in the process. Much of the current interest is in the potential of ADS to burn weapons grade plutonium, as an alternative to using it as mixed oxide fuel in conventional reactors.

In the practical realization of the ADS, the most challenging task is the development of a high energy (~1 GeV) and high current (≥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 [8]. 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.

The thermal power of the ADS 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.

Some of the important technological challenges for these two sub-systems are as follows:

(a). High power spallation target:

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

(b). High-power proton accelerator for ≥10 MW (cw) beam power that is:

- Robust and reliable for year-round uninterrupted operation. That is, its availability is ≥ 99%.
- Operates with minimum beam loss in accelerator channel for limiting activation of components and their hands-on maintenance (beam loss ≤ 1 nA/m).
- Having high (electrical) conversion efficiency from mains to beam power (η ≥ 40%).

2.3.2 ADS as an "Incinerator"

The other role of ADS is the destruction of heavy isotopes, particularly actinides but also long-lived fission products such as ^{99}Tc and ^{129}I. In this way, the blanket assembly is actinide fuel and/or spent nuclear fuel. One approach is to start with fresh spent fuel from conventional reactors in the outer blanket region and progressively move it inwards. It is then removed and reprocessed, with the uranium recycled and most fission products separated as waste. The actinides are then placed back in the system for further transmutation by fission.

In the case of atoms of odd-numbered isotopes heavier than ^{232}Th, they have a high probability of absorbing a neutron and subsequently undergoing nuclear fission, thereby producing some energy and contributing to the multiplication process. Even-numbered isotopes can capture a neutron; perhaps undergo beta decay, and then fission. A fast neutron spectrum enables maximum fission with minimum build-up of new actinides due to neutron capture.

2.4 Summary and Conclusion

The AHWR is thorium fuelled Indian nuclear reactor. The AHWR is a 300 MW_e, vertical, pressure tube type, heavy water moderated, boiling light water cooled natural circulation reactor. In AHWR, the fuel consists of $(Th–Pu)O_2$ and $(Th–^{233}U)O_2$ pins and the fuel cluster are designed to generate maximum energy out of ^{233}U, which is bred in situ from thorium. The concept of ADS brings 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. The ADS are seen as safer compare to normal fission reactor because it is subcritical and stop when the input current is switched off. The following conclusions have been drawn from this present work.

- The development of ADS and advanced reactor programme requires significant amount of new and improved nuclear data in extended regions as well as for a variety of new materials.
- The energy produced in ADS or any nuclear reactor is due to neutron induced fission of actinides. Therefore for the design of ADS, it is necessary to have accurate knowledge of nuclear data of actinides such as yields of fission products, neutron capture cross-sections and decay data including half-lives, decay energies, branching ratio etc.
- One of the most challenging components of ADS is the high-energy and high-current accelerator capable of delivering average proton beam power of 10 MW. Therefore, there is worldwide general interest to develop an accelerator system of such a high beam power.

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