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The VVERs at KudanKulam

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Abstract

A Nuclear Power Project is being set-up at KudanKulam in the state of Tamil Nadu, India in collaboration with the Russian Federation. The project comprises of two units each of 1000 MWe VVER type reactor. The design of the plant and supply of all the major equipment is in the scope of the Russian Federation while development of infrastructure and project construction is in Indian scope of works. The VVER (Version V-412) reactor that is under construction at KudanKulam site is an advanced PWR, which incorporates all the features of a modern PWR as per the current Russian, Western and IAEA standards. The KudanKulam site in the southern Indian state of Tamil Nadu was one among the several sites evaluated by the Site Selection Committee, which cleared KudanKulam site for setting up an installed capacity up to 6000 MWe. The design, construction and operation of the plant meets the regulatory and licensing requirements of Russian regulatory body “RTN” as also India’s Atomic Energy Regulatory Board. The supply of the equipment from the Russian Federation is on schedule and the project construction work by various Indian agencies is also ahead of schedule. The two units of KudanKulam Nuclear Power Project (KKNPP) are scheduled to achieve first criticality in the year 2007–2008. The paper discusses various design features, project construction and management aspects.

1. Introduction

Nuclear Power Corporation of India Limited (NPCIL) is constructing a Nuclear Power Project at KudanKulam in collaboration with Russian organization—Atom Stroy Export (ASE). The design of this reactor was assigned to Atom Energo Proekt (AEP), as a nodal agency, the nuclear reactor being designed by Gidropress. The KudanKulam site is located along the coast of the Gulf of Mannar, 25 km northeast of Kanyakumari in Radhapuram Taluka, Tirunelveli Kattabomman district of Tamil Nadu. The nearest town is Nagercoil, which is about 35 km west of KudanKulam village. The civil construction work has commenced since March 2002 and it is expected that both units will achieve first criticality in the year 2007–2008.

1.1. Background

In order to increase the nuclear power share without affecting the indigenous nuclear power programme basically comprising of pressurized heavy water reactors (PHWRs), the Department of Atomic Energy (Government of India) was pursuing for setting up of nuclear power plants with external technology and funds. Thus as an addition to the indigenous program, a second line of light water reactors has been introduced. The introduction of large unit size of 1000 MWe capacity will give momentum to faster growth of nuclear power and supplement energy potential for electricity generation. It not only widens the options but also enables access to external funding. It was against this backdrop that the Government of India entered into an agreement in November 20, 1988 with the Government of erstwhile USSR. This was followed with a supplement to the Inter Governmental Agreement (IGA), signed in June 1998 between the Indian and Russian Governments, with an objective to set-up 2×1000 MWe (VVER) power station.

The KudanKulam Project is being implemented on a technical co-operation basis. The Russian organizations are responsible for the design, supply of equipment, material, machinery including nuclear fuel, construction supervision, training of Indian personnel for operation and maintenance, commissioning and operations of the plant till final takeover by NPCIL.

NPCIL on its part is responsible for land acquisition, setting up of infrastructural facilities, civil construction, electrical and mechanical erection of the plant and commissioning under

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Russian supervision. The Russian side will also supply a training simulator for establishing a training center in India.

1.2. Site selection

The Site Selection Committee of the Department of Atomic Energy after considering several aspects including the guidelines set by the International Atomic Energy Agency (IAEA) has chosen the KudanKulam (KK) site. Several factors related to the nuclear safety as also the social, economical, logistic and environmental were considered. The site is located in low seismic area, zone-II as per the Indian Standards of Classification. It has no active faults in the vicinity and provides preferable foundation conditions to build the nuclear power plant. The site is free from severe cyclonic activities and has low potential of Tsunami effects.

2. KudanKulam-VVER

2.1. Salient features of VVER

VVER is an acronym for "*Voda Voda Energo Reactor*" meaning water-cooled, water moderated energy reactor. This type of reactor uses 3.92% enriched uranium as fuel. The VVER reactors belong to the family of the pressurized water reactors (PWRs), which is the predominant type in operation, world over. The advanced 1000 MWe design of VVER (VVER-1000) has many variants in different countries, which are derived from the basic VVER model V-392. The models of these plants have some modifications based on the client–country requirement (Information, 1998; KK-Proj. Tech. Assign., 1998). The VVER reactor that is under construction at KudanKulam site is an advanced PWR, i.e., VVER NSSS model Version V-412, which incorporates all the features of a modern PWR as per the current Russian, Western and IAEA standards (Seminar, 1998).

The KK-VVER has a 3 year fuel cycle. This reactor requires annual refueling of one-third of the core, i.e., approximately 55 fuel assemblies. The reactor plant consists of four circulating loops and a pressurizing system connected to the reactor with each loop containing a horizontal steam generator, a main circulating pump and passive part of emergency core cooling system (accumulators). The loops are connected with the reactor pressure vessel assembly by interconnecting piping. The reactor plant also consists of a reactor protection and regulation system, engineered safety features, auxiliary system, fuel handling and storage system, etc. (KK-PSAR, 2002). Some of the main parameters of the KK-VVER are given in Table 1.

Table 1
Main parameters of KK-VVER

Reactor thermal power	3000 MW
Electrical	1000 MWe
Number of circulating loops	4
Working pressure in primary circuit	15.7 MPa
Rated coolant temperature	
At reactor inlet	291 °C
At reactor outlet	321 °C
Coolant flow rate through reactor	86,000 m^3/h
Main coolant pump head	0.64 MPa
Steam generator (horizontal)	4
Steam pressure	6.27 MPa
Steam flow	408.33 × 4 kg/s
Pressurizer	1
Normal steam volume	24 m^3
Normal water volume	55 m^3
Reactor coolant pipe, diameter	850 mm
Reactor pressure vessel	SS clad low alloy steel
Diameter (inside)	4134 mm
Total height	11185 mm
Number hexagonal fuel assemblies	163
Reactor internals (core barrel, core baffle) and protective tube assembly	Austenitic SS
Numbers of control rods	121
Life time	40 years
Containment	Double with primary steel lined
Turbo-generator	1000 MWe (3000 rpm)

2.2. Nuclear steam supply system

2.2.1. Reactor coolant system

The primary purpose of the reactor coolant system (RCS) is to transfer the heat generated in the reactor core to the steam generators where steam is produced to drive the turbine-generator. The schematic of the RCS is shown in Fig. 1. The borated demineralized water coolant of the RCS also acts as a neutron moderator and reflector and as a solvent for the neutron absorber used in chemical shim control.

The RCS pressure boundary provides a barrier against the release of radioactivity generated within the reactor and is designed to ensure a high degree of integrity through out the life of the plant. The reactor coolant system, of the water-cooled water moderated power reactor VVER-1000 comprises of reactor pressure vessel, four reactor coolant loops and the pressurizing system connected to one of the reactor coolant loops. Each reactor coolant loop contains a primary coolant pump, a horizontal steam generator and primary coolant pipelines. The pressure vessel forms the anchor point of the RCS; the steam generators and reactor coolant pumps are mounted with flexibility to accommodate thermal expansion. The pressurizer, connected to the hot leg of one of the circulation loops by the surge line serves to maintain the pressure in the reactor coolant system and to compensate for short time changes in coolant volume.

The coolant in the primary circuit is kept under pressure to keep it sub-cooled during plant operation. The thermal–hydraulic design of the RCS rules out nucleate boiling in the fuel assemblies and also guarantees optimum selection of steam generator size and reactor coolant pump power. The sub-division of RCS into a number of loops make it possible to continue operating the reactor system on three or two loops at correspondingly reduced power in the event of failure of one or two reactor coolant pumps.

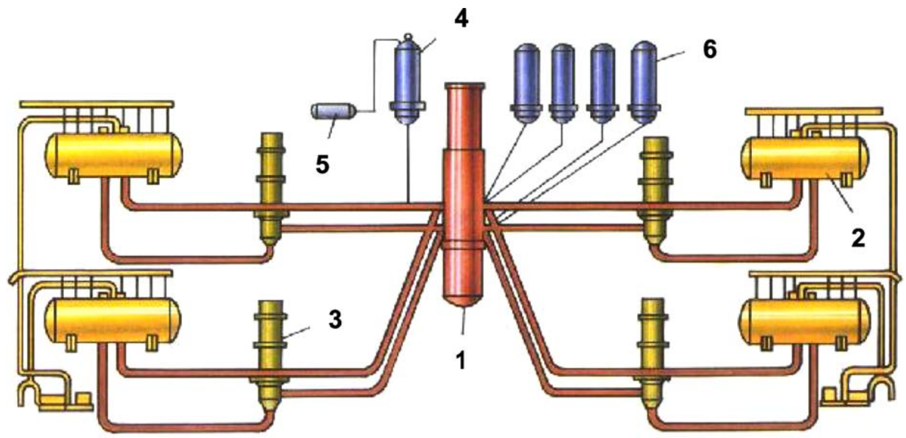

Fig. 1. Reactor coolant system.

2.2.2. Reactor pressure vessel

The reactor vessel is designed to contain the vessel internals and fuel assemblies of the core. The reactor along with control rod drive units has an overall height of 19 m and a diameter of 4.5 m. It is a vertical cylindrical container made of high purity and high strength 200 mm thick low alloy ring forging, welded together. The pressure vessel has no weld joints in the core region and the inside surface has an austenitic stainless steel clad. It has a detachable top cover and sealing elements. The upper part of the reactor vessel has nozzles in two planes. In the upper plane, there are four reactor coolants outlet nozzles and in the lower plane four reactor coolant inlet nozzles. Each nozzle corresponds to one coolant loop. The reactor vessel houses the core barrel which in turn houses all core components including the fuel assembly. The core barrel has perforations at the bottom, which allow circulating water to enter the reactor core and perforations at the top for exit of hot water from the core. All core components are made of austenitic stainless steel.

The reactor with the top cover is kept in a concrete pit inside the containment. On the top of the vessel, the head assembly containing control rod drive mechanism is mounted which is bolted to the vessel flange with 54 studs. The vessel is supported on the concrete through collars on the outer surface of the vessel below the nozzle region. Bellow-seals welded to the vessel flange seal the concrete pit. The entire outer surface of the vessel is covered with a thermal insulation. The cut-away view of the reactor pressure vessel with its internals is shown in Fig. 2.

2.2.2.1. Reactor internals. The reactor internals are used essentially for reactor coolant channeling, shielding the vessel against irradiation from the core, support and hold down the fuel assemblies, securing the irradiation specimen and mechanical guiding of control assemblies and instrumentation lines.

2.2.2.1.1. Core barrel. The core barrel is a cylindrical vessel with perforated elliptical bottom. Fuel assemblies are fixed in the specified locations at the bottom of the core barrel. The barrel also directs the coolant to a uniform flow. The top of the barrel is supported on the reactor vessel flange. The vessel is prevented from vibrating at the bottom by eight splines on the reactor vessel inner surface inserted into the slots on the barrel. On the upper side of the barrel, holes of 180 mm diameter are provided on the side for coolant outlet flow.

2.2.2.1.2. Core baffle. This is placed inside the core barrel in the core region. It provides spacing for peripheral assemblies and acts as a shielding for neutron flux to protect the reactor vessel. It consists of five forged rings connected mechanically. Bottom ring is secured to the core barrel collar. Vertical splines on the inner surface of the barrel mate the slots on the basket outer surface. Vertical holes are provided for ensuring cooling of the core baffle.

2.2.2.1.3. Protective tube assembly. Protective tube assembly (PTU) is designed to align the fuel assemblies in position, to prevent them from floating up, to incorporate the in-core monitoring system, to protect the control rod drives from coolant stream and to provide a uniform outflow of coolant into the core barrel and reactor vessel. It consists of two plates joined by a perforated shell with tubes for control rod assemblies and monitoring system. It is secured in the upper position on the core barrel flange. The bottom is mounted on the heads of fuel assembly.

2.2.3. Reactor core

One hundred and sixty-three fuel assemblies are arranged in a hexagonal lattice pattern within the reactor core with the help of stainless steel supporting structure. Each fuel assembly has 331 locations out of which 18 locations are for control rods, one location for instrumentation tube and balance 311 locations have got enriched uranium dioxide fuel pellets contained inside Zr–Nb tubes. The fuel is uranium-enriched up to 4.1% and are arranged in a hexagonal grid. Fuel pellets have central coaxial hole. The schematic of a fuel rod and the fuel assembly is given in Fig. 3. Stainless steel spacer grids are located with interval of 255 mm along the core height. The spring loaded upper block assembly keeps the fuel assemblies in their position. Loading and unloading of fuel is achieved with the help of specially designed fuelling machine positioned above the reactor.

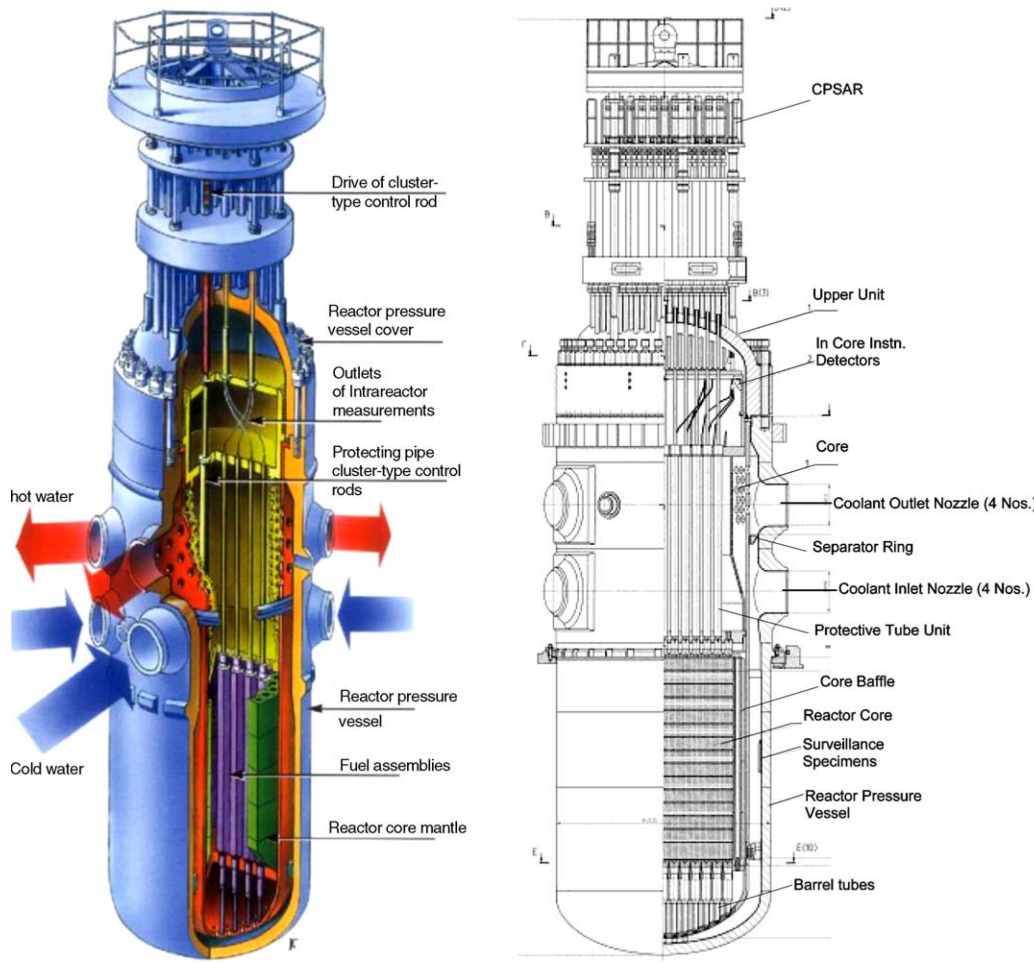

Fig. 2. Reactor pressure vessel and its internals.

The arrangement of fuel assemblies with the burnable absorber rods in the core for the 1st cycle is given in Fig. 4.

The reactor core and the fuel rod data are given in Table 2.

2.2.4. Control protection system absorber rod (CPS-AR) system

In KK-VVER 121 absorber rods can be inserted into the core through the guide tubes provided in the top of the core. One control protection system absorber rod (CPS-AR) is a cluster of 18 absorbing elements arranged in the way as shown in Fig. 5. One CPS-AR can be inserted in one fuel assembly.

CPS-AR consists of a gripping cap and individual suspension springs for each of the 18 absorbing elements. The gripping cap consists of a steel bush with console ribs connected to it. Absorbing elements pass through the holes provided in the ribs. The suspension springs are installed on the upper tips of the absorbing elements on both sides of the ribs. The CPS-AR cap has a receptacle for bayonet engagement with the control rod drive extension shaft and a through groove for fixing the pin to avoid inadvertent turning of the extension shaft leading to disengagement.

The absorbing material is vibro-compacted powder of boron carbide (B_4C), but is substituted at the bottom up to a height of 30 cm with dysprosium titanate ($Dy_2O_3TiO_2$).

2.2.4.1. Electromagnetic control rod drive system. The control rod drive system is designed to provide step-by-step motion of the control assemblies within the reactor core to:

- automatically maintain a preset reactor power level;
- change the reactor from one power level to another;
- provide coarse control of reactivity (shim);
- terminate the chain reaction rapidly making the reactor shut down.

The main drive unit includes:

- Thimble: which houses the interior and exterior parts of the drives and is designed to operate in the conditions of the primary circuit.
- Shaft with square teeth with a 20 mm pitch.
- Electromagnet assembly: consists of three electromagnets, i.e., pulling, locking and registering mounted rigidly on the outside of the thimble. The movable poles of the pulling and

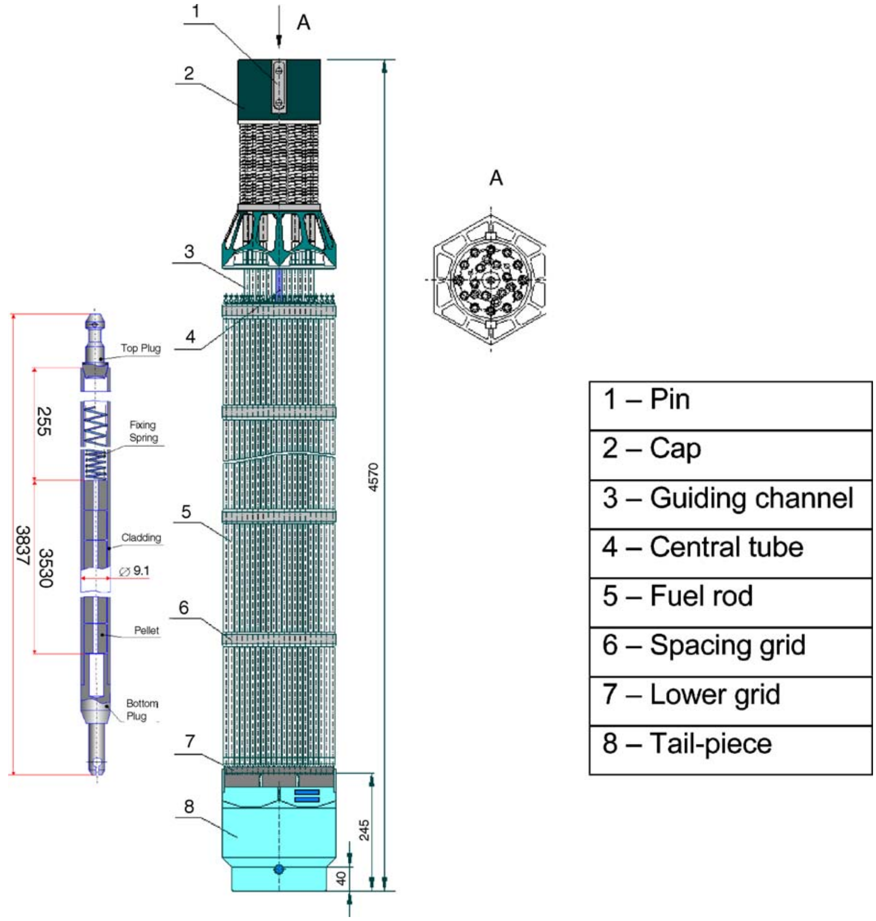

Fig. 3. Fuel rod and fuel assembly.

locking units are arranged in the external pipe. The movable catch of pulling and retaining catch of locking unit are arranged in lower portion of a bearing pipe.

2.2.5. *Pressurizer*

The pressurizer serves to build up and maintain the necessary pressure of 15.7 ± 0.3 MPa in the reactor coolant system. It is a vertical cylindrical vessel with hemispherical top and bottom heads. The reactor coolant system pressure is controlled by the use of the pressurizer, where water and steam are maintained in equilibrium by electric heaters and water sprays. Pilot operated safety valves are mounted on the pressurizer and discharge to the bubbler tank.

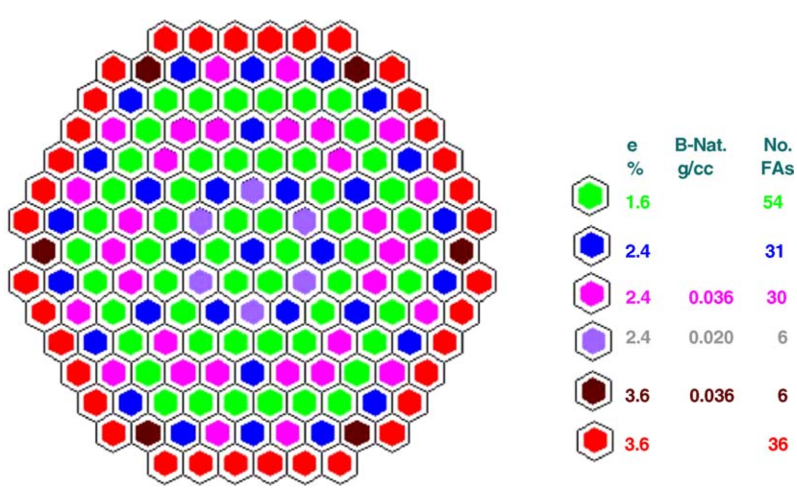

Fig. 4. Arrangements of fuel assemblies and burnable absorber rods in the core (1st cycle).

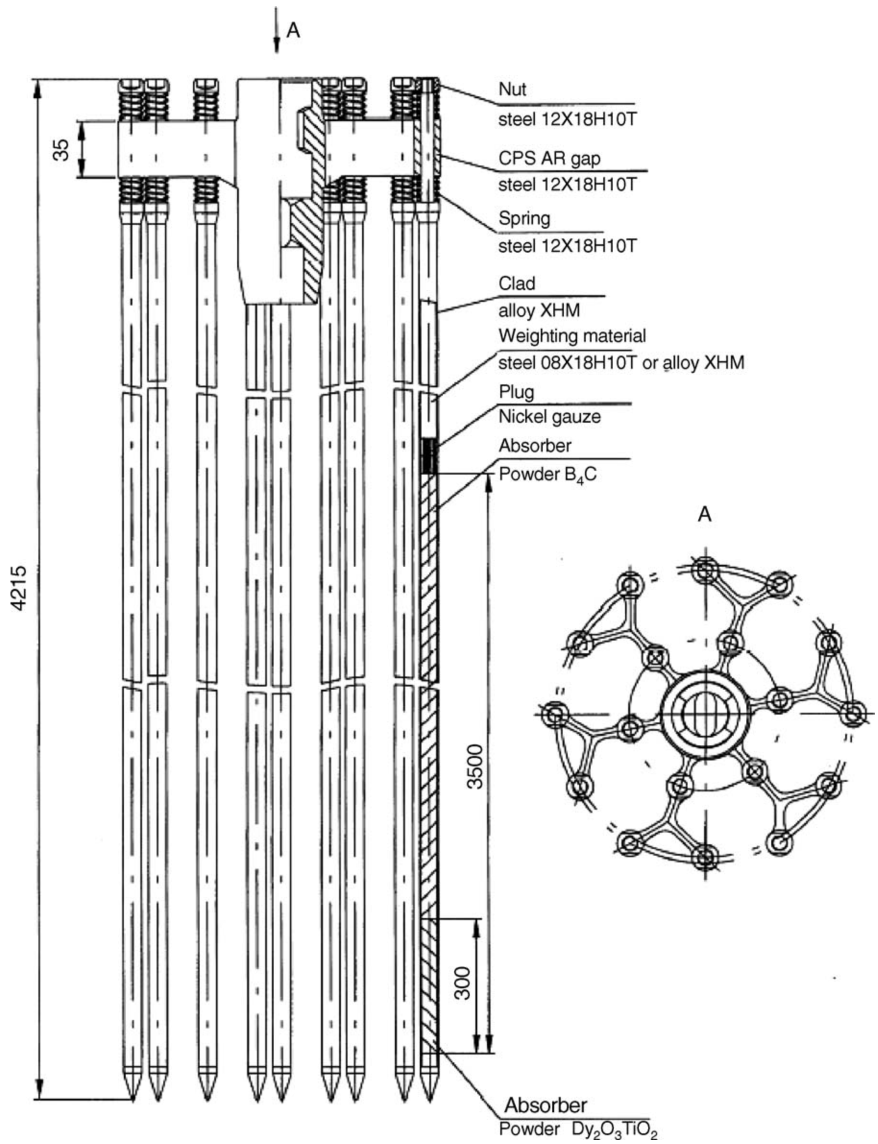

Fig. 5. Control protection system absorber rod (CPS-AR) arrangements.

2.2.6. Steam generator

The steam generators produce steam at conditions (pressure, temperature and dryness) required for the operation of the turbine by transferring heat from the primary coolant to the secondary side feed water. The VVER-1000 steam generators are shell and tube type horizontal heat exchanger with built in moisture separators. The horizontal steam generators have large evaporation surface, and hence the advantages of low steam velocities, leading to effective moisture separation from steam using simpler moisture separator design. The steam generator layout is designed to cool the reactor during re-fuelling by natural circulation. The pressure boundary of steam side of steam generator is made of forged steel and dished ends and accommodates heat transfer surface and other internals.

The primary side of the steam generator comprises of inlet and outlet manifolds called primary collectors. Heat transfer surfaces in the form of U-shaped stainless steel (Ti stabilized) tubes emanate from the inlet primary collector (hot header) and terminate at the outlet primary collector (cold header). The steam generator shell also accommodates feed water distribution system and a separate nozzle for emergency feed water supply. The schematic of the steam generator is given in Fig. 6.

2.2.7. Main circulating pump

The reactor coolant pumps circulate the reactor coolant in the closed loops through the reactor pressure vessel, the reactor coolant piping and the steam generators. The reactor coolant pump is a single stage, centrifugal unit driven by 1000 rpm 6 kV-induction motor with 6.8 MW rating. It has a vertical shaft with the rotor mounted above the pumps. A flywheel on the shaft above the motor provides additional inertia to give suitable coast down characteristics.

2.2.8. Reactor auxiliary system

In order to fulfill the complete range of function the reactor system is provided with reactor auxiliary systems, which support

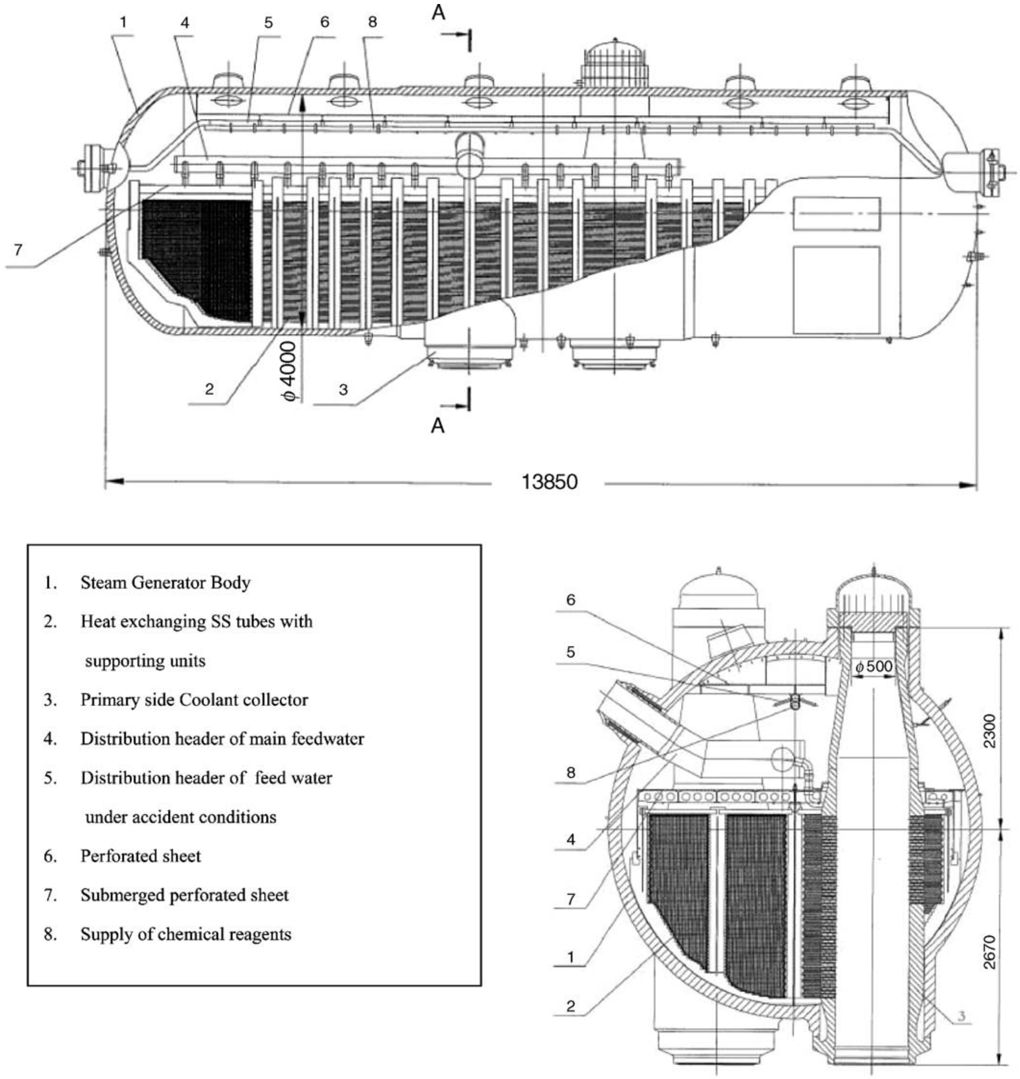

Fig. 6. Steam generator.

the reactor coolant system by performing a wide range of functions. The main auxiliary systems are discussed in the following sub sections.

2.2.8.1. Reactor chemical and volume control system. Primary function of reactor chemical and volume control system is to regulate the boric acid concentration in the primary coolant to control long term reactivity changes resulting from the change in reactor coolant temperature between cold shut down and hot full power operation, burn up of fuel and burnable poisons, build up of fission products in fuel and xenon transients, etc.

2.2.8.2. Residual heat removal system. The residual heat removal system functions as the long term heat sink for the reactor. It removes decay heat during the second stage of a planned plant cool down. At the first stage, residual heat is removed by way of steam release from steam generator to turbine condenser.

2.3. Secondary side systems

The secondary circuit is a non-radioactive circuit. It consists of the steam generation section of the steam generators, the main steam lines, the turbine, the auxiliary equipment and the associated systems of de-aeration, reheating and feed water supply to the steam generators.

2.3.1. Turbine system

The turbine system is designed to operate at 3000 rpm on saturated steam in conjunction with the VVER-1000 reactor having a thermal output of 3000 MWt. The rated output at the generator terminal will be 995 MWe based on cooling water temperature of 32 °C and a steam dryness of 0.995.

The turbine consists of one double flow high-pressure turbine and three low-pressure double flow turbine. The turbine is capable of stable operation between the frequency ranges of 47.5 and 51.5 without any time limit. The turbine has an electro-hydraulic governing system backed by a mechanical hydraulic system.

Table 2
Core structural parameters

Specification	Magnitude
Equivalent diameter of core	316.0 cm
Height of core in cold condition	353 cm
Fuel assemblies pitch	23.6 cm
Face to face size of fuel assembly	23.4 cm
Number of fuel elements in fuel assembly	311
Spacing of fuel elements	12.75 mm
Number of non-fuel tubes in fuel assembly	20
Number of absorber rods	18
Number of spacer grids in fuel assembly within the core	15
Weight of spacer grid	0.55 kg
Material of non-fuel tubes for absorber	Zr + 1% Nb
Material of central tube of fuel assembly	Zr + 1% Nb
Material of burnable absorber rod	CrB_2 in aluminium matrix with boron content of 0.20, 0.036, 0.05 g/cm^3
Material of spacer grid	Zr + 1% Nb
Density of absorber in burnable absorber rodsr	2.8 g/cm^3
Number of fuel assemblies	163
Number of fuel assemblies with BAR in	
1st cycle	42
Stationary cycle	18
Number of fuel assemblies containing absorbing rods of the control and protection system	
1st cycle	85
Stationary cycle	103
Number of absorber elements in control and protection system rods	18

Modern features like stress evaluator, on line performance monitoring system, moisture separator have been incorporated in the turbine system.

2.3.2. Secondary circuit

Steam generated in the steam generator passes through the high-pressure turbine. Between the high-pressure and the low-pressure turbine, moisture is removed in a moisture separator and the steam is reheated in a re-heater section of the moisture separator. The exhaust of turbine is condensed in the steam condenser, cooled by seawater. The liquid condensate from the condenser with the help of condensate extraction pump is pumped through a set of low-pressure heaters to the deaerator. The deaerator tank takes care of non-condensable gasses and ensure sufficient water inventory. Feed water with the help of boiler feed pumps pushes the water through the heater to the steam generator. The schematic of the feed water cycle is given in Fig. 7.

3. Electrical system

The KudanKulam Nuclear Power Station (NPS) consists of two 1000 MWe Turbo-generator sets to the supply electrical power to the southern region grid. The NPS electrical system can be broadly classified into the following sub-systems.

3.1. The generator

A VVER-1000 consists of a single set generating 24 kV. The generator has the capability of working at full load at 5% voltage and frequency tolerance. The stator of the generator is built up from three parts and the rotor is a single forging. The stator is cooled by water-cooled and the rotor is cooled by hydrogen, which in turn is cooled by water. The voltage regulator maintains the voltage from the generator automatically.

3.2. Main power output system

The main power output system is designed for safe evacuation of nominal electrical power generated at KudanKulam Nuclear Power Station, to the regional grid without impairing the stability of the station, in case of loss of any transmission line. It also ensures the availability of normal and reserve start-up power to the station.

The main power output system consists of 400 and 220 kV systems interconnected by means of two three-phase interconnecting auto-transformers (ICT). The 400 and 220 kV system comprises indoor type SF6 Gas Insulated Switchgear (GIS) to avoid the effects of saline atmosphere.

Standard switching schemes, i.e., "One and a half circuit breaker scheme" for the 400 kV systems and "Two non-sectioned main and a transfer bus scheme" for the 220 kV systems are adopted. The 400 kV GIS is connected to regional grid through three double circuit transmission lines, and the generator through the generator transformer (GT) and the generator circuit breaker (GCB). These will also ensure the availability of power to the station auxiliaries through the unit auxiliary transformer (UAT) for normal start up and shut down of the station. In addition two 220 kV single circuit lines are connected to the 220 kV GIS to provide reserve source of power to the NPS auxiliaries through the reserve station transformer (RST) for start up, when the 400 kV grid supply is not available. During normal operation of the NPS, these 220 kV lines can also be used for evacuation of power.

3.3. Station auxiliary power supply system

The station auxiliary power supply system is designed to supply power to the auxiliaries required for normal operation of the NPS as well as those required during anticipated operational occurrences and design basis accidents. The auxiliary power system has various voltage levels to feed various type and size of loads as given below:

- 6 kV, 50 Hz;
- 380 V/220 V, 50 Hz;
- 220, 110, 48 and 24 V DC supplies.

The plant loads of the NPS have been classified according to the degree of reliability required for its supply and are divided into three groups.

The Group-1 includes loads that require highest degree of reliability of the electrical supply and does not allow interruption

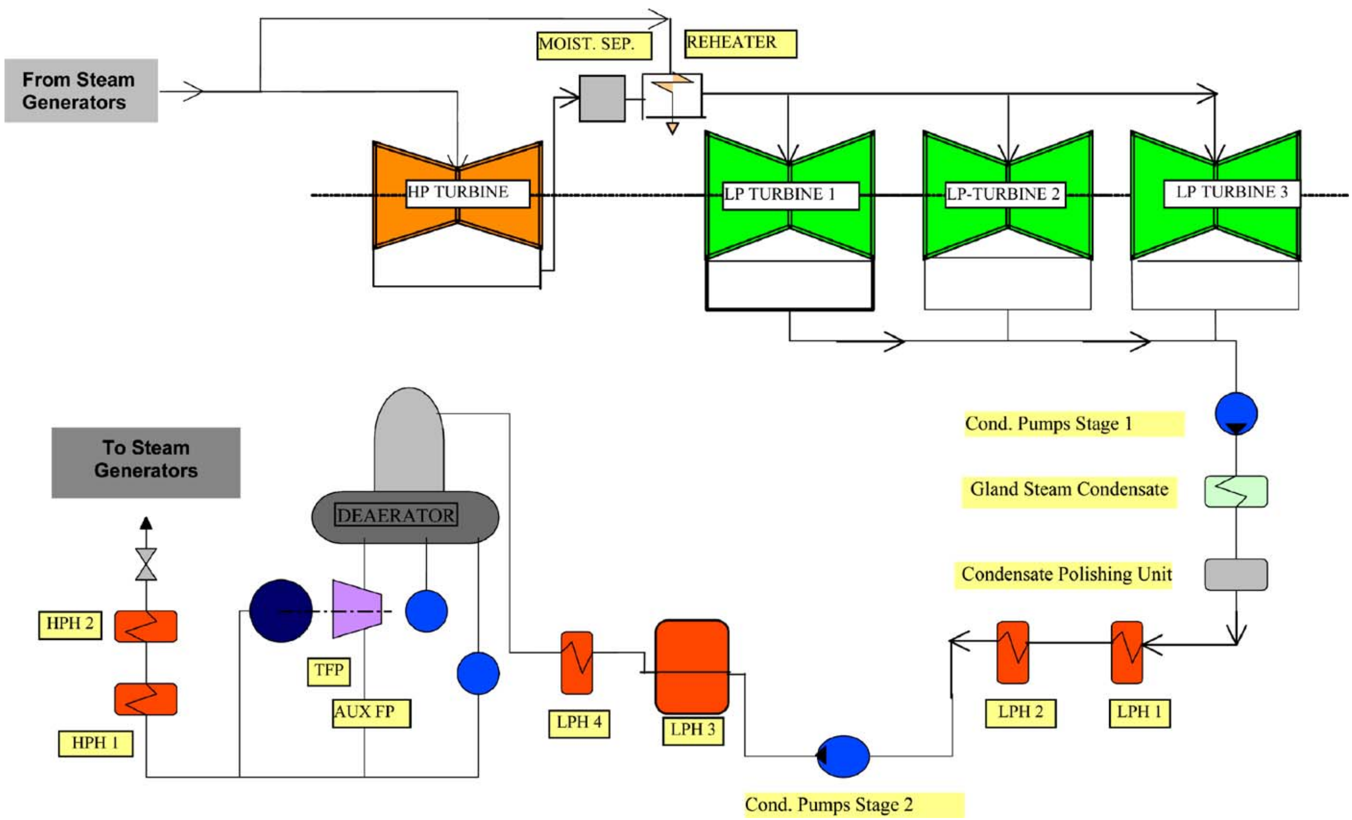

Fig. 7. Feed water cycle.

in the power supply for more than a fraction of second under all conditions. This group is supplied power from 380 V/220 V, 50 Hz networks or 220/110/48/24 V DC networks whose main source of power is from the battery banks in case of loss of grid supply and until automatic restoration by standby onsite D.G. sets.

The Group-2 includes loads requiring reliable electrical supply, which can tolerate an interruption up to 10 min and either requires power even after activation of the reactor emergency protection or to ensure preservation of basic equipment/system in the event of power outage at the station. In the event of the loss of normal and reserve source of power from the grid/TG, these loads are backed up by standby source of power from onsite diesel generator sets, ensuring that the load is taken up within 15 s after receiving the start pulse.

The Group-3 includes loads, which require power for generation of power at the NPS but do not require high reliability of electrical supply when unit is shut down and thus can tolerate interruption of power for long duration without affecting safety of the NPS. The station auxiliary power supply system can be further classified into the following sub-systems, as per their functional requirement during normal operational states and/or after accident conditions.

3.3.1. Normal power supply system

The normal operation system caters to those loads which are required for the normal operation of the station within specified operational limits and conditions including shut down, power operation, shutting down, starting up, maintenance, testing and re-fuelling, excluding the safety systems and the systems important to safety.

The first group of this system is normally supplied power from the second group through rectifier and inverter and is backed by battery banks up to a period of 30 min, in case of unavailability of the second group sources till restoration of the second group standby sources.

The second group of this system is normally supplied from 400/24 or 220 kV sources through the third group buses, and as an alternative from its own onsite standby D.G. sets if the normal sources are not available.

The third group of this system is normally supplied from 400/24 kV system through the GT/UAT, and in case of non-availability of these sources, it is automatically supplied from 220 kV system through the reserve station transformer.

3.3.2. Emergency electric power supply system

The emergency electric power supply system (EEPS) is designed to ensure the availability of power supplies to safety systems and systems important to safety, that are essential for safe shut down of the reactor, containment isolation, reactor core cooling and are otherwise essential in preventing significant release of radioactivity to the environment under:

- anticipated operational occurrences and
- accident conditions.

The EEPS has 4 × 100% independent, redundant power supply distribution trains corresponding to the similar safety systems trains.

The second group of this system is normally supplied power from 400/24 or 220 kV sources through the third group buses of normal power supply system and as an alternative from its own onsite standby D.G. sets if normal sources are not available.

The first group of this system is normally supplied power from the second group of this system through rectifier and inverter and is backed by battery banks up to a period of 30 min, in case of unavailability of second group sources till restoration of second group standby sources.

4. Instrumentation and control

The instrumentation and control system (I&CS) in KudanKulam Nuclear Power Plant is based on the latest and proven state of art technology, having hard wired as well as computerized control system. The I&CS for reactor protection system, safety system, etc., are hardware system, working on two out of three logic. The instrumentation and control system for the plant control, the safety display parameters, the man machine interface with the computerized operated simulation system and the event sequence recorder are some of the systems integrated in the distributed control system (DCS). This system is based on latest state of art digital technology using the advanced computers.

5. Safety features of VVER

The design features for the KudanKulam plants have been extensively negotiated. These include:

- Compliance of all the regulatory requirements of India. Its designs have to be licensed by our independent regulatory body.
- Capability to operate with high performance, reliability and safety within Indian grid conditions.
- Latest design features that meet international safety requirements.
- Basing the plant on the most reliable and safe PWR technology, which uses ordinary water for cooling and moderation purposes.
- Verification of the designs by Indian engineers who will also over-see the quality of equipment, witness necessary inspection and testing during manufacture and also participate in construction and commissioning.

5.1. The general design concepts of safety systems

The VVER reactor that is under construction at KudanKulam site is an advanced PWR, i.e., VVER NSSS model Version V-412, which incorporates all the features of a modern PWR as per the current Russian, Western and IAEA standards. The general design concepts of the safety systems in the KK-VVER are:

- The safety systems are designed on fail-safe principle and are capable to function under loss of power supply.
- Each active safety system has four trains 4 × 100%, i.e., each capable to perform completely the intended safety function except few like emergency boron injection system which has 4 × 50% capacity.
- The number of the safety trains are chosen proceeding from the consideration that one train may not be available due to single failure criteria, another may not be available due to maintenance and the third may be knocked out because of a postulated initiating event.
- Each active safety system is backed up by passive safety system and each is capable to perform the intended safety function.
- The safety system trains are completely segregated in terms of physical location, layout and source of motive force.
- The design of control safety systems are such that a failure in the system causes actions directed to ensure safety.
- The safety system actuates on demand automatically and operator actions to disable an automatically actuated safety system are blocked in the first 30 min to exclude personnel error.
- All safety systems are supplied with power from independent sources (dedicated diesel generators), designed in accordance with the requirements of the protective safety systems.
- The core damage frequency (CDF) of the nuclear power plants as per the Russian regulatory requirement is less than 10^{-5}/reactor-year. However, the safety approach adopted in the design of "KudanKulam" NPP resulted in a calculated CDF of 10^{-7}/reactor-year. This approach involves different principles of operation of safety systems (active and passive) and minimizes common-cause failures. Some of the active safety system functions are combined with normal operation functions, with a view to increase functional reliability. In such cases, the design provides fulfillment of safety functions with minimum number of changes of valves positions.

5.2. Engineered safety features

The engineered safety features are provided to mitigate and limit the consequences of abnormal conditions including accident condition. This task is accomplished by making the reactor sub-critical, cooling and maintaining the level in the core, limiting the rise of fuel temperature, containing the radioactivity release from the core and safeguarding various system from over pressure. The KudanKulam-VVER-1000 incorporates advance engineered safety features apart from standard safety features of PWR'S.

5.2.1. Emergency core cooling system

The emergency core cooling system provides core cooling under a wide ranged of postulated accidents involving leaks of primary system. In the case of loss of coolant accident (LOCA), borated cooling water is injected into the reactor core to remove the decay heat and to preserve core integrity. The emergency core cooling system comprises of the following sub-systems:

(i) high-pressure emergency injection;
(ii) high-pressure accumulator injection (passive system);

(iii) low-pressure accumulator injection (passive system);
(iv) low-pressure emergency injection and long-term recirculation.

5.2.1.1. High-pressure emergency injection system. The high-pressure emergency injection system is designed for performing the function of high-pressure emergency core cooling system during an event of loss of coolant accident. In case of LOCA, this system provides borated water (with concentration of 16 g/kg) at an injection pressure of 7.89 MPa into the primary circuit from the spent fuel-cooling bay.

This system has four independent physically separated trains. Each system train includes the emergency boron injection pump, pipelines, valves, heat exchanger, etc. The heat exchanger is shared by the corresponding train of the high- and low-pressure injection systems, containment spray system and high-pressure emergency boron injection system.

This system draws borated water from the spent fuel-cooling bay through suction line of low-pressure injection system and utilizes the same shared heat exchangers with other systems. The pump has a recirculation loop, which is normally open, and as the flow gets established during a LOCA the recirculation line gets closed. This high-pressure injection system in case of a LOCA injects into the main coolant inlet pipelines and the rated capacity of the pumps are 214 m^3/h. In case the 500 m^3 of spent fuel bay water available for ECCS injection gets over the suction is automatically switched over to the containment sump.

5.2.1.2. High-pressure accumulator injection system. The high-pressure accumulator injection system (passive core cooling system) is intended for quick supply of borated water into the reactor core for cooling and filling during a loss of coolant accident. This system automatically starts injecting borated water when the primary circuit pressure falls below 5.89 MPa during a LOCA. It consists of four independent physically separated trains. This system is riding over the primary system at all times during normal operation. They are isolated from the effect of the high-pressure primary system in normal operation by the two check valves in series. The accumulators are each of 50 m^3 capacities filled with borated water (16 g/kg) and are maintained at around 55 °C by specially provided electric heaters. The accumulators are Nitrogen pressurized to 5.89 MPa. During the injection as the accumulator level goes below a preset level the quick acting isolating valves isolate the accumulators, so that the nitrogen ingress into the reactor coolant system will be avoided.

5.2.1.3. Low-pressure accumulator injection. This additional system for core passive flooding is designed to supply borated water of concentration of 16 g/kg, into the reactor core in order to remove residual heat during a LOCA accompanied with a station blackout. There are eight low-pressure accumulators (Fig. 8), each of 120 m^3 capacities and divided into four trains, each train containing two hydro-accumulators. In the upper part, these hydro accumulators are connected to cold lines of main coolant pipes through NB50 lines with installed special check valves and electrical operated gate valves. These check valves are pre-adjusted to open in case the primary circuit pressure reduces below 1.5 MPa. In such cases, the pressure in the accumulator increases to the primary pressure and the injection takes place because of the hydrostatic head. The outlet from the accumulators is connected to the safety injection nozzles, which helps in injecting coolant directly to the reactor pressure chamber and reactor collection chamber. Design envisages six-step flow profiling during the tank discharge. The system design envisages decay heat removal for 24 h when the system operates together with passive heat removal system (PHRS) and for 8 h without PHRS operation.

5.2.1.4. Low-pressure emergency injection and long term recirculation system. The low-pressure emergency injection and long term re-circulation system is designed to remove the residual heat release from the core following an accident for an extended period of time. Additionally, it also serves as the second stage of planned cool down of the primary coolant system. The system comprises of four independent trains. Each train comprises of a heat exchanger, pump, pipes and valves. In case of a LOCA, when the reactor coolant system pressure falls below 2 MPa two of these trains inject borated water into both reactor

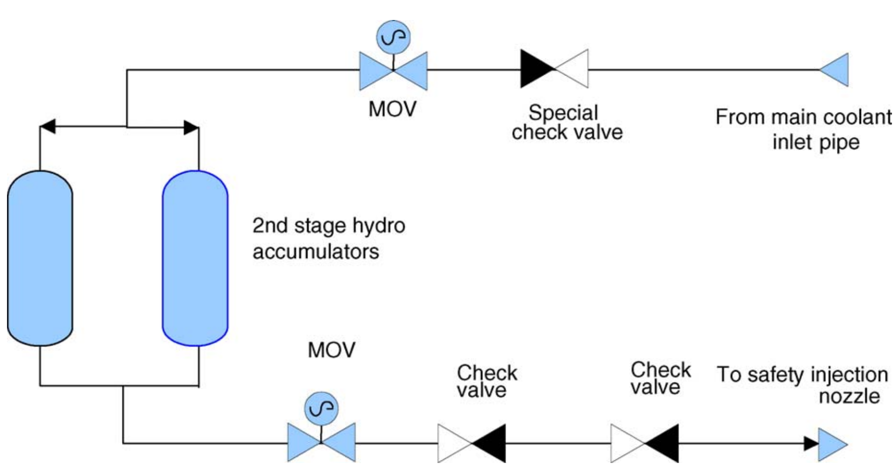

Fig. 8. Low-pressure hydro accumulators.

upper and lower plenum and the other two trains inject into the corresponding inlet and outlet main coolant pipe-lines.

This system draws borated water from the spent fuel-cooling bay (16 g/kg of borated water) through suction line and in case the 500 m^3 of spent fuel bay water available for ECCS injection gets over the suction is automatically switched over to the containment sump. The pump has got a re-circulation loop, which is normally open, and as the flow gets established during a LOCA the recirculation line gets closed.

The same trains of low-pressure emergency injection are manually operated in a closed loop during the second stage of planned cool down of the reactor coolant system.

5.2.2. *Steam generator emergency cool-down and blow-down system*

The steam generator emergency cool-down and blow-down system is intended to provide residual core heat removal and reactor cool-down in emergency condition due to loss of power supply or loss of heat removal through the secondary side. Under normal operation it is also used for the blow down of the steam generator for the steam generator water purification purposes. It has four independent trains and in case of loss of power supply to the station, all the system pumps are actuated as per the sequential loading programme after restoration of the emergency power. When the steam generator pressure reaches 7.35 MPa, the valves on the steam lines to heat exchanger open automatically. The re-circulation pumps pump cooled condensate back to the steam generator. The control valve in the pump discharge provides automatic maintenance of the steam generator pressure at a level of 6.67 MPa. The system operates in closed loop and does not need any additional source of water.

5.2.3. *Passive heat removal system*

The passive heat removal system (Fig. 9) removes the core residual heat in the event of non-availability of the normal heat removal system on account of complete loss of normal and emergency AC power supply (station blackout condition).

The system consists of four independent cooling circuits, each one connected to individual steam generator. In design of PHRS, finned tube air heat exchangers, placed outside the reactor building containment, are used for rejecting core heat to the outside atmosphere. The heat exchangers are connected to the secondary side of steam generators such that the steam from the steam generators is condensed in the heat exchangers and condensate returns back to the steam generator water volume, conserving secondary side water inventory. The heat exchangers are chimney like structures located on the top of reactor building annex (RBA). Higher elevation of the heat exchangers, relative to the steam generators, ensures a reliable natural coolant circulation in the steam/water circuit.

Heat exchanger shell is in form of a rectangular housing wherein lower and upper parts are connected to air ducts. The upper air duct is in form of a chimney. The cool air enters through the lower air duct. The dampers are installed in air ducts at the heat exchanger inlet and outlet. On the tube side, heat exchangers are connected with the steam generator by means of pipelines. Under the condition of the reactor plant operation, the system is in warmed up state. The valves on steam/water path are normally open and are closed only for maintenance of heat exchangers.

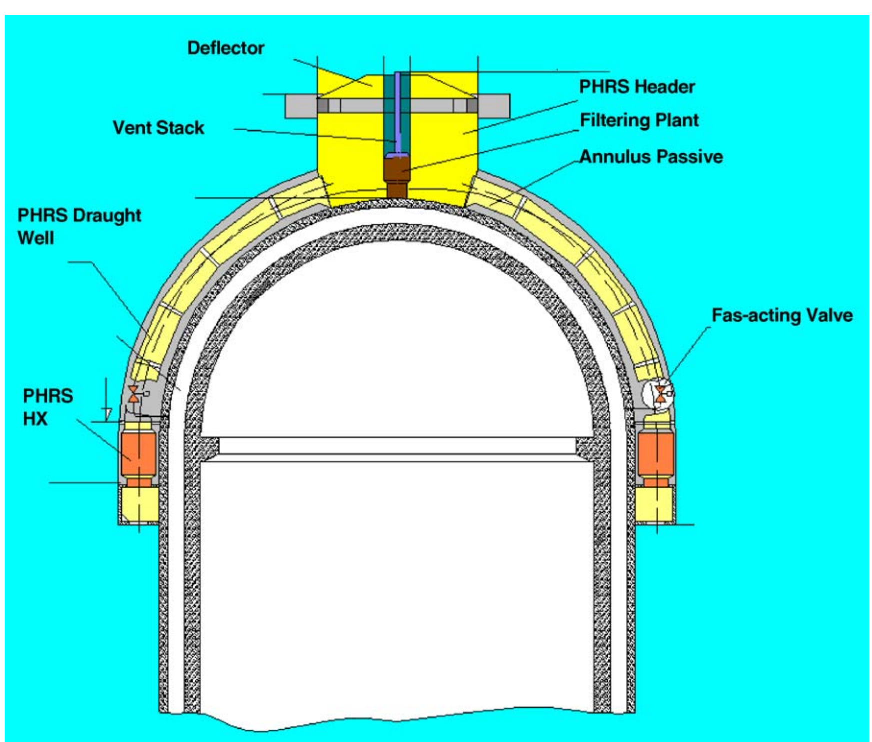

Fig. 9. Passive heat removal system (PHRS).

The dampers on the air path are kept closed through electro magnetic actuators. With loss of power supply, actuator solenoid is de-energized and gates opens under the action of its own weight. Due to air heating and consequent density difference between the shell inner and outer air, air flows through the shell by natural draft and slowly design flow is established thus removing the decay heat.

5.2.4. *Quick boron injection system*

The quick boron injection system is intended to bring the reactor to a safe shut down state by injection of highly concentrated boric acid solution in the event of failure of reactor protection system. The system comprises of four high concentration boron (40 g/kg) tanks, each located across each reactor coolant pump set. On sensing the failure of the reactor protection system, the solenoid valves across the tank opens and the tank becomes part of the reactor coolant system volume. The boron solution from the tanks is flushed automatically into the reactor coolant by the primary coolant pumps.

5.2.5. *Localizing systems*

5.2.5.1. Containment. The reactor building (RB) has double containment. The primary containment is a pre-stressed reinforced concrete, lined with carbon steel, and sealed enclosure which houses main equipment of nuclear steam supply system (NSSS). The containment performs the following functions:

- It acts as final barrier against release of radioactive fission products in the event of an accident.
- Acts as biological shielding and protects site personnel against radiation under normal and accidental conditions.
- Protects NSSS equipment against external hazards.

The inner containment is made of pre-stressed concrete with a spherical dome designed for internal pressure and temperature effects during accidents and lined on the inside with 8 mm thick carbon steel sheet. The outer containment is of reinforced cement concrete (RCC). In the space between primary and secondary containment vacuum is maintained to prevent any leakage to the environment. To ensure plant safety and prevent release of radioactivity to the environment, the primary circuit is housed inside the inner containment.

5.2.5.2. Containment isolation system. The containment isolation system ensures containment leak tightness in the case of an accident that is likely to cause a release of radioactive fission products from the reactor core. The purpose of containment isolation system is to maintain overall integrity of the containment by isolating the normal operating system, which penetrates the reactor building.

Each line that penetrates the reactor building and is a part of the RCS pressure boundary or connects directly to the containment atmosphere is provided with two isolation valves. Under accident conditions these isolation valves and dampers get closed.

5.2.5.3. Containment spray system. The containment spray system removes the heat released into the reactor containment in the case of a break in the coolant pipeline inside the containment. Through condensation of the steam produced in the case of an accident, the containment spray system limits the temperature and pressure peaks to values at which containment integrity is assured and confines the radioactive fission products released during primary system leak, thus assuring protection of the plant environment and the population. The addition of chemicals to the spray water reduces fission product concentration (in particular iodine) in the containment atmosphere and neutralizes some of the boric acid to limit its reaction with metal surfaces and consequent hydrogen production.

The spray water is drawn into each independent channel of the reactor building containment and is cooled by the residual heat removal (RHR) system heat exchangers, before entering the pump suction. The containment spray system consists of four trains and each train terminates with an open ring under the dome of the containment on which nozzles are arranged to provide most even coverage of the entire containment.

5.2.5.4. System of vented containment. The system of vented containment helps in limiting the containment pressure to the design limit under condition of hypothetical accident (which have potential to exceed pressure in the containment beyond design value) by control release of steam–gas mixture in a planned manner.

The system comprises of a pressure-relieving device, which bursts open at a pre determined containment pressure to relieve steam–air mixture along with radioactive products out of the containment. This steam air mixture is relieved through pipelines into a scrubber filter, which removes the radioactive products to a high level of efficiency. The filtered air is purged out through a moisture separator into the outside atmosphere.

5.2.5.5. Annulus passive filtering system. The annulus passive filtering system is designed for controlled removal of steam–gas mixture from the containment annulus (secondary containment volume) and maintaining a negative pressure during a SBO condition with/without LOCA. The creation of negative pressure prevents the uncontrolled release of radioactivity to the atmosphere through the secondary containment. There are four independent trains each having four heat exchanging modules. Thermal energy of the PHRS outlet, air draught is utilized in the system for its passive operation.

5.2.5.6. Combustible gas control system. The system of the hydrogen concentration control within the containment is designed to avoid the formation of the explosive mixtures inside the containment by maintaining the volumetric hydrogen concentration in the air mixture below the safe limits, thereby protecting the containment integrity under all conditions including the design basis accidents and the beyond design basis accidents. This is achieved by providing: (i) hydrogen control system and (ii) hydrogen monitoring system. These systems include installation of catalytic hydrogen re-combiners (at 101 locations) and monitoring units (at 54 locations) at a large number of locations inside the reactor building.

5.2.5.7. Core catcher. The core catcher is meant for retention of the solid and liquid fragments of the damaged core, parts of the reactor pressure vessel, and reactor internals under a beyond design basis accident condition resulting in core melting. This prevents melt spreading beyond limits of the containment. Under highly improbable conditions of core melt and breach of the reactor pressure vessel the molten core will come to the core catcher. In the core catcher, the molten core will interact with the sacrificial materials forming an eutectic mixture and the over all temperature of the molten mass will be reduced.

Special arrangement is made to spray water on the corium surface at a later phase of the accident for the crust formation for minimizing the radiological consequences. The reactor pit water around the core catcher will cool the core catcher vessel along with the corium. The sacrificial material also contains gadolinium oxide in its composition such that the molten mass will always remain sub-critical.

5.3. Automatic fire fighting system

Automatic fire fighting system is designed to detect fires, control equipment and valves to automatically extinguish fire using water sprinklers and transmit information to the operator.

In the reactor building, the cable rooms, shafts, area of primary coolant pump oil tank and other normal operating oil systems constitute major fire hazards.

The automatic fire fighting system has four independent channels (4 × 100%) each of which is fully capable of performing its assigned tasks. Each system consists of tank, pump and group of valves. The passive components of the system, the feed, and distribution pipes, and sprayers are common for all four channels.

The water supply tanks for this system are replenished by water from the main firewater storage reservoir. In case of failure of this supply, it can be fed from critical load water supply system. Capacity of each tank is selected in such a way that its fire extinguishing capacity is 15 min for a room of maximum volume.

6. Civil engineering features of KudanKulam reactors

The KudanKulam NPP is being constructed in the state of Tamil Nadu, India and is situated near to the tourist center of Kanyakumari on the shores of Gulf of Mannar. The twin units of the plant along with its ancillary structures are laid out within an area of 600 m × 600 m and this area is referred to in this paper as the Nuclear Island. The original topography of the plant site had a gradual declining slope towards the seashore. Therefore, the plant area had to be graded, and the minimum general formed safe grade level has been maintained at +7.50 m (MSL) near the pump house. This safe grade elevation was arrived at after an analysis for the worst flood effects that could possibly occur at the site. This grade level is gradually increased to +9.50 m (MSL) towards the northern end and the elevation of +13.0 m (MSL) at the switchyard area forms the highest elevation in the layout.

6.1. Layout of the main plant

The general layout of the main plant buildings and structures are shown in Fig. 10.

While finalizing the main plant layout, several aspects were considered. Some of these aspects are enumerated:

(a) The layout is based on independent operation of each unit. The units share common facilities only for the reasons of economy without affecting the safety.
(b) A mirror image arrangement has been avoided.
(c) The orientation and location of the buildings are optimized from the topographical consideration and minimum groundwork point of view.
(d) The separation of buildings is based on seismic class, safety class and radiation zoning considerations.
(e) The compactness of the layout considering aspects such as convenience in operation and maintenance of the plant systems and fast movement of operation and maintenance (O&M) personnel.
(f) The ease of construction of the units in a phased manner.
(g) The provision of providing effective drainage system to protect the site against flooding.
(h) The location of the auxiliary buildings and structures (common plant structures) in between the power units to share these facilities.
(i) The provision for construction of additional units in future in the adjacent area.

6.1.1. The special features of the layout

Certain features stand out in the finalized layout of the main plant structures. They are:

- The compact placement of reactor building (UJA), reactor auxiliary building (UKC) and turbine building (UMA) reduces the cost of piping and cable laying.
- Most of the Class-I safety systems are housed inside the UJA and most of the Class-II safety systems are housed either in UJA or UKC.
- All equipments, which can eject missiles during operation or accident conditions, are housed within the accident localization areas and surrounded by reinforced concrete wall barriers.
- All Category-I buildings and structures are designed for air shock wave impact effects.
- The UJA outer containment structure is designed for air crash effects, air shock wave effects and impact effects due to vent stack collapse.
- All the building foundations including their basements are protected from the ingress of sub soil water and aggressive chemicals by provision of hydro insulation.
- Special provisions are made to drain out sub-soil water by providing drainage lines and drainage wells at the level of foundations. The ground water drainage system is provided

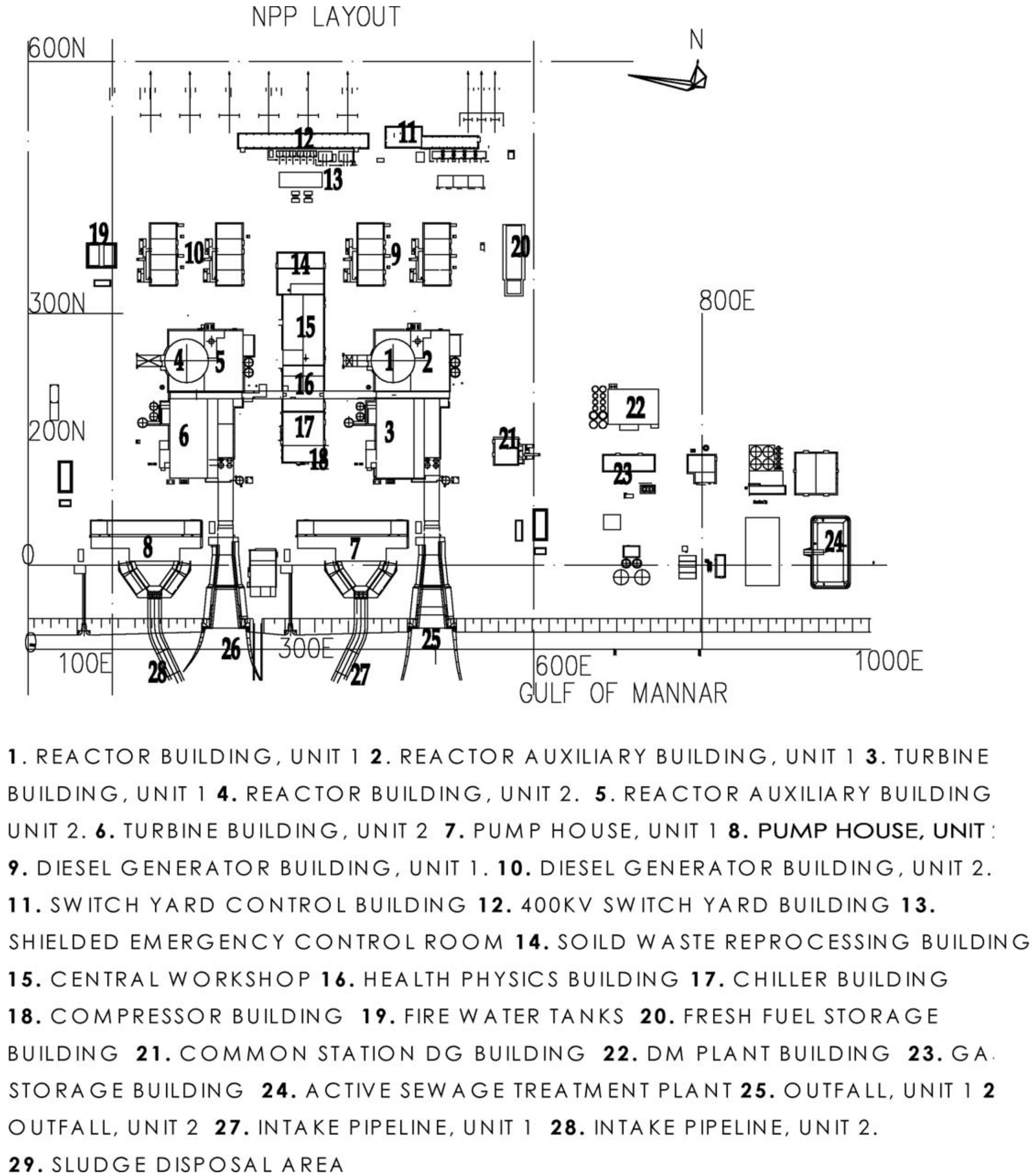

Fig. 10. Plant layout.

to rule out the flooding of underground cable tunnels and to reduce ground water table in the nuclear operating zone. The drains are provided at several levels along the side of the tunnels and around main buildings.

6.2. Arrangement of buildings and structures

The central area of the site is occupied by the reactor and turbine buildings (Units 1 and 2).

6.2.1. Reactor building—UJA

The reactor building accommodates basic and auxiliary equipment. It houses a complex of systems and components necessary for normal operation, emergency cooling down and maintaining the reactor in a safe state.

The UJA is a double containment concrete structure that confines the accident isolation area. The outer containment structure is of reinforced concrete and the inner containment is of pre-stressed concrete. The inner containment is hermetically sealed using a 6 mm thick steel liner, which provides the necessary leak tightness. Two annex structures join the outer containment on opposite sides. A transport portal (UJG) structure is located on the western side of the reactor building. This structure is utilized for the transport of heavy equipment.

A cross section of the reactor building is shown in Fig. 11.

6.2.2. Reactor auxiliary building—UKC

The reactor auxiliary and main control room building (UKC) adjoin the reactor building on the eastern side. The steel vent

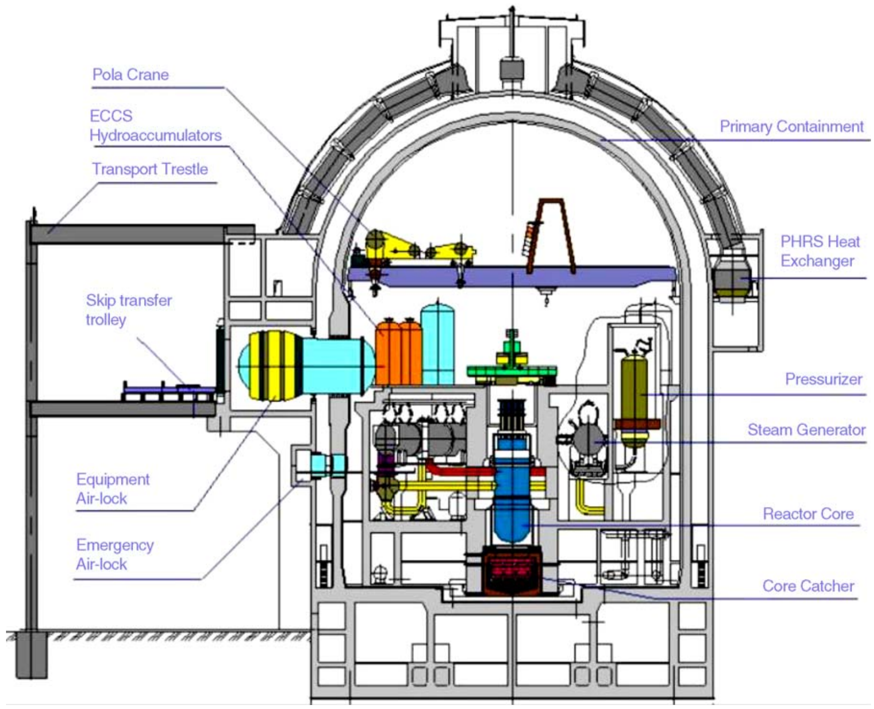

Fig. 11. Reactor building cross section.

stack (1UKH) is located on the UKC building and rises to a height of 100 m above the ground elevation.

At the eastern side of the UKC building, two demineralized water tanks each with a capacity of 630 m^3 are located. Two 400 m^3 tanks for filling and making up the refueling pond which is used for boron water storage for the main safety systems are located in the UKC building.

6.2.3. Turbine building—UMA

The turbine building houses the systems and equipment of the secondary side related to the electric power generation. It is located to the south of the UJA building at a distance of 9.0 m and is oriented radially from it. On the eastern side of the turbine building, the normal operation power supply building (UBA) is located. On western side of the turbine building, the turbine and generator (T&G) oil building (UMV) is located. Near the T&G oil building, the turbine building emergency oil discharge tank (UMW) is located.

The unit auxiliary transformers and generator transformers structures (UBF) with rolling tracks for transformers (UBJ) are located on the site adjacent to the normal operation power supply building.

6.2.4. Emergency power supply and control buildings—UKD

The emergency power supply and control buildings (1–4UKD) are located to the north of the reactor building and have an underground intermediate diesel fuel storage facility. These buildings house the diesel power generators, which provide the necessary electrical power during abnormal operating conditions in the plant. The emergency power supply and control buildings are separated from each other in the general layout to avoid their simultaneous destruction in case of a missile impact.

6.2.5. Pump houses—UQC, UQA

Towards the south side of the turbine buildings, the main cooling water pump houses (UQA), the pump houses of essential services cooling water (UQC), the seawater supply channels (UPN) and the chlorination plant building (UPK) are located. The pump houses of essential services (1UQC) of the first subsystem of the safety systems are physically separated from the pump houses of essential services (2UQC) of the second subsystem of safety systems and thus provide the required redundancy in case of an emergency.

The UQA and the UQC buildings houses the seawater pumps that are utilized for circulation of sea water to cool the heat exchangers of the power units. In the UQA building, the heat exchangers of the cooling water circuit of normal operation are located and in the UQC structure, the heat exchangers of the essential services are located.

The seawater is led to the fore bay of the pump house through an intake structure having fish protection facilities (UPX) and metallic screens.

6.2.6. Common buildings—UKS, UKU, USV, UYB

In the center of the site, between the power units, the complex of main auxiliary buildings and structures are located.

The areas in these buildings are zoned as controlled access areas and common access areas. The controlled/common access area gallery (UJY/UKY), is located between the reactor and turbine buildings and connects the auxiliary buildings and structures to the reactor and turbine buildings. The gallery is located at an elevation +7.20 m from the grade of the reactor building. The engineering utility and laboratory building (USV) which houses the facilities for repair and maintenance of I&C equipment is situated towards the southern side. It is located in the common access area between the turbine buildings. It is envisaged that this building will also contain a small mechanical workshop for repairing common access area equipment. The change rooms of the common access area are located in the USV building.

The solid radioactive waste reprocessing and storage building (UKS) is provided for processing solid radioactive waste (pressing, milling and combustion) and for temporary storage of the cemented and concentrated solid radioactive wastes. The building is a controlled access area and is situated towards the northern end of the site.

The controlled access area of the central workshops (UKU) is located to the south of the UKS building. This is utilized for repair and maintenance of the equipment installed in the controlled access area.

Towards the south of the controlled access area central workshops, the health physics building (UYB) is located. The building incorporates controlled access area personnel facility rooms, laboratories and active laundry.

Integration of the controlled access area facilities within one zone assures strict control of personnel access to this area. All the above structures are indicated in the main plant layout (Fig. 10).

6.2.7. New fuel storage building—UFC

The new fuel storage building (UFC), the area for locating the spent fuel storage building (UFA) and the common plant diesel generator building (5UKD) are situated towards the eastern part of the site by the side of the Unit-1 structures.

The new fuel storage building (UFC) is designed for operations involving acceptance of new fuel, its storage, inspection and preparation for loading into the reactor.

6.2.8. Switch yard area—UAB, UAD and UAC

The complex of buildings and structures pertaining to the electric power output supply is situated on the terrace at an elevation +13.00 m MSL in the northern end of the site. It includes the following buildings and structures:

- 400 kV GIS building (UAB);
- 220 kV GIS building (UAD);
- Switchyard central control building (UAC).

The UAB building includes gas equipment room, ventilation centers, warehouses and auxiliary buildings for sulfur hexafluoride gas equipment. The UAD building includes gas equipment room, ventilation centers, warehouses and auxiliary buildings for sulfur hexafluoride gas equipment. Between the UAB building and the UAD building there is an open site for the coupling auto-transformers structures (UAG). The UAC building is on the western side of the UAD building.

6.2.9. Shielded control building (UZM)

On the same terrace (+13.00 m), towards the center of the site, the shielded control building (UZM) is located.

This building accommodates:

- the NPP central control point, including the central radiation automated monitoring system;
- the standby control panels of Units 1 and 2;
- a local crisis center;
- the computers and communication equipment.

6.3. Safety aspects considered in the development of layout

6.3.1. Radiation zoning and contamination control

All of the buildings and structures of the NPP are subdivided into the following areas:

- controlled access area, where the personnel can be exposed to radiation;
- common access area where the personnel are not affected by radiation.

The controlled access area is located to the north of the controlled/common access area gallery, whereas the common access area is located to the south of the controlled/common access area.

The rooms in the controlled access area are further subdivided into the following categories:

- Non-attended rooms where the process equipment and associated communications are accommodated. During operation condition, personnel cannot access these areas.

Non-attended rooms include the rooms that accommodate the reactor coolant circuit, active purification filters, liquid waste treatment equipment, active pipelines, etc.

- Periodically attended areas where the personnel can stay for a limited time during operation condition where radiation levels are less.

Periodically attended rooms include instrumentation and health monitoring room, active sampling rooms, a number of pipeline corridors, pump rooms, etc.

- Continuously attended rooms where the personnel can stay continuously during the entire working shift.

Continuously attended rooms include radiation monitoring stations, workshops, laboratories, etc.

For radiation monitoring of the buildings and premises of nuclear Island, the radiation monitoring system is used.

6.4. Movement of personnel, equipment, fuel, etc., within the layout

Motor vehicles can enter the territory of the Nuclear Island through two motor vehicle entrances. The main entrance is placed on the western side of the Nuclear Island where the infrastructure buildings and structures are located. The second entrance is arranged on the eastern side of the Nuclear Island, which will be considered the main entrance during the period of Unit 2 construction, while Unit 1 is under operation.

The total area of the plant is divided into common access areas and controlled access areas. Entry to the dirty and clean areas is planned in such a manner that passage through separate galleries is required for entering the clean areas and dirty areas.

For accessing the common access area, the personnel first enter the engineering utility and laboratory building and from there go to common access area gallery (UKY). Through this gallery, the personnel enter the turbine building and via the staircases and elevators to go to various floors of the turbine building, normal operation power supply building and T&G oil building.

For accessing the controlled access areas, the personnel first enter the health physics building and via the transportation and pedestrian corridor (UJY), enter the controlled access area central workshops and the adjacent radioactive waste reprocessing and storage building.

The passage from the controlled access area gallery to the reactor building of Units 1 and 2, and the reactor auxiliary building is provided at elevation of +7.20 m. Through this passage, the personnel can enter the controlled access area of the reactor auxiliary building and from there to the reactor building. All transport operations including fuel and equipment is carried out through the transportation lock, located in the reactor building.

The gallery of the controlled/common access area rules out non-authorized personnel movement and provides a high standard of sanitary conditions and comfort in the tropical climate.

The controlled/common access area gallery and corridors of the health physics building, the central workshop and the solid radioactive reprocessing and storage buildings are also designed for transport of contaminated equipment and waste weighing up to 5 tonnes.

6.5. Protection against missiles

The NPP layout is based on the principles that ensure enhanced safety of the NPP against missile impacts. The reactor building and the fresh fuel storage building are designed to withstand impacts of light aircraft and other lighter missiles, generated by man-made or natural phenomena. The reactor building is also designed to withstand the fall of the steel vent stack, located in the reactor auxiliary building.

Other buildings and structures of Category-I are located at a distance from each other and houses mutually redundant safety systems. The redundant safety system are segregated and housed in separate buildings in such a manner that an impact event cannot damage all the redundant trains of a safety system.

6.6. Transport

The motor roads, by which the cargoes are delivered to the erection sites, are designed as two lane roads with a minimum turning radius of 22 m. A network of motor roads and access roads has been designed in line with operational and fire safety requirements. The main roads are 7.0 m wide with camber at the center. However, along the perimeter of the terrace where the main buildings are located, the road width is increased to 8.0 m. Contaminated equipment heavier than 5 tonnes is transported from the reactor building through the transport portal to the repair workshops in the controlled access area with specialized motor vehicles along the shortest routes.

7. Use of Indian construction materials in civil construction

The civil engineering design of the KKNPP is carried out as per Russian standards, norms and design practices using Indian construction material as far as possible. As the civil construction work was under the scope of the Indian side, special efforts were put to find out equivalent Indian materials satisfying the specifications of the Russian designers.

7.1. Equivalent Indian materials used in construction

7.1.1. Concrete

As the prime construction material is concrete, an equivalent grade of concrete to be used in the construction was worked out between the Indian and Russian sides. The Russian design organization (AEP) suggested B-30 grade as per their SNiP standard for all the concrete structures of the NPP. B-50 grade of concrete was suggested for the hermitic pre-stressed concrete inner containment structure.

NOTE:

B	compressive strength criteria
30	compressive strength of a prism $6'' \times 6'' \times 6''$ made out of the concrete mix to be used at works with a 95% probability of achievement expressed in megapascals

The other design parameters stipulated to be met are as follows:

E	static modulus of elasticity of concrete
ω	unit weight of concrete
R_{bt}	tensile strength
R_{bn}	normative compression strength
R_b	design compression strength

Additionally, the designers specified an impermeability grade for the concrete. This is a special feature and is included in all the concrete grades as an additional parameter. To site an example, W6 grade of impermeability implies that a concrete sample of size 150 mm wide does not leak through the width under a hydrostatic pressure of 6 kg/cm^2 kept for duration of minimum 48 h.

7.1.2. Reinforcement steel

Two grades of reinforcement steel are produced in India. They are classified as Fe 415 and Fe 500 grade. In order to draw a material equivalence, the yield strength, rupture strength and other chemical composition of these grades were compared with that of Russian grade steels classified as AIII and A 500 S. The Indian steel grades were found acceptable and are being used in the construction.

7.1.3. Ingredients of concrete

The characteristics of the various ingredients of concrete required as per Russians norms were studied using available local ingredients, such as sand, water, cement, aggregate, etc. It was ensured that the concrete mix ingredients satisfied all the Russian requirements.

7.2. Reinforced concrete design philosophy

The reinforced concrete design of civil structures was carried out as per Russian standards and practices. The design philosophy for reinforced concrete as per Russian standards has the following special features.

(a) The Russian concrete design code SNiP 2.03.01-84 contain tables of design strength of concrete (both compression and tensile) for each grade of concrete for both the limit state, i.e., limit state of strength (Group-I) and limit state of serviceability (Group-II).
(b) The design strength of concrete applicable for limit state of strength (R_b) and limit state of serviceability (Rb_{ser}) for each grade of concrete is specifically indicated in the tables of the design code.
(c) The shear design concept is different from that of the Indian and International concept. In the International and the Indian concept, the shear strength at a vertical section of a beam is checked with the strength of the concrete at this section plus strength of the shear reinforcement available at the section. In contrast to this, the Russian design concept checks the strength of concrete and shear reinforcement in a shear span assuming cracking due to shear always takes place in an oblique way. This concept gives a higher shear capacity for the section.
(d) The design resistance in concrete (R_b) is further multiplied with operational environmental factors (γ_{bi}) taking into account type of loading, duration of loading, etc.

8. Important construction features

The entire civil construction of KudanKulam NPP was agreed by both sides to be executed as per the construction norms and procedures prevalent in India. Nevertheless, the Russian side included various advanced systems of construction not yet executed out in India. Some of the important construction features of KKNPP are as follows.

8.1. The 55C15 pre-stressing system for the inner containment (IC)

The 55C15, pre-stressing system has been designed by M/s. Freyssinet, France. In this system, each pre-stressing tendon consists of 55 numbers of steel strands, 15.7 mm in diameter. Each strand is composed of 7 plys and has a sectional area of 150 mm^2. Each strand is housed in a HDPE sheath filled with grease. The schematic layout of the tendons in the RB is shown in Fig. 12.

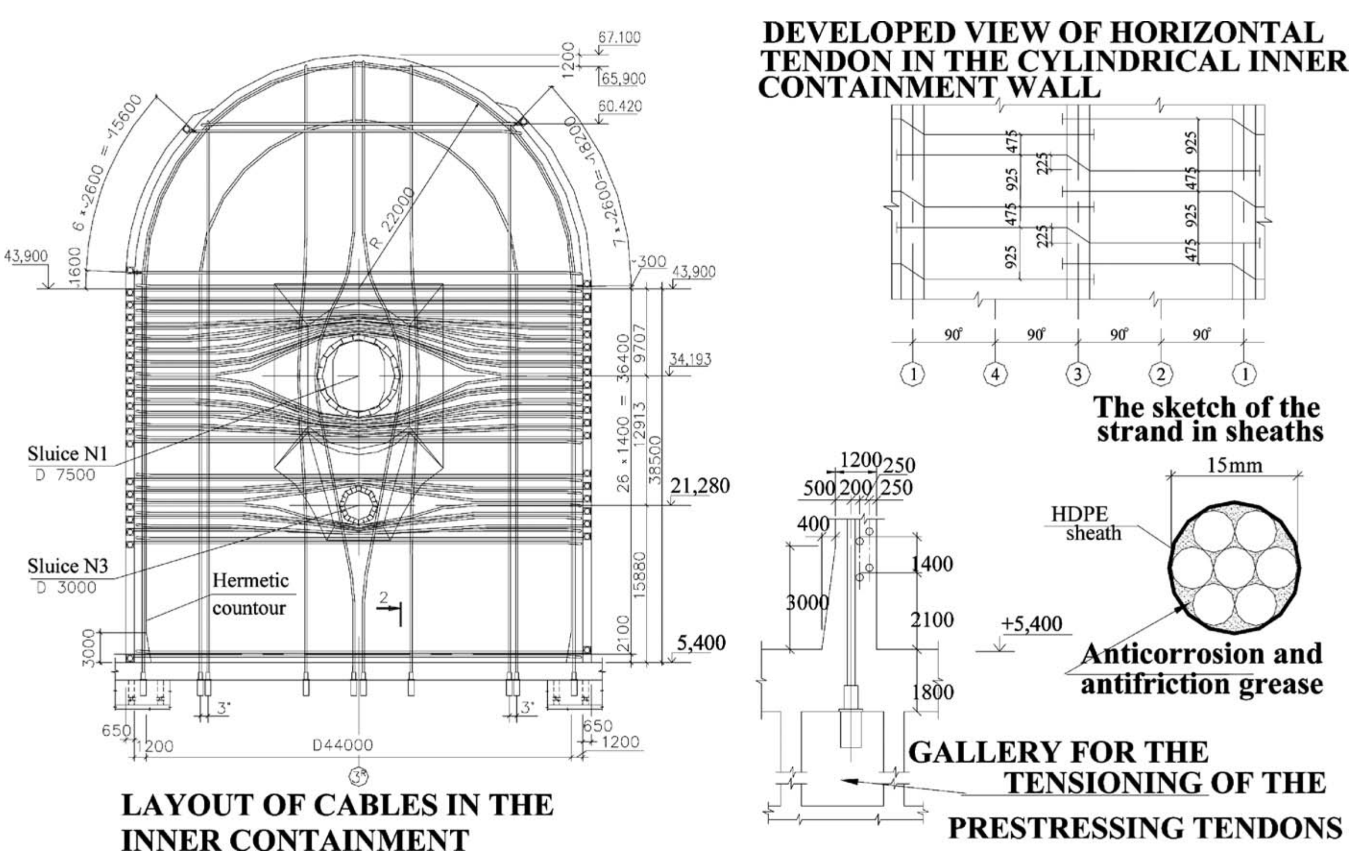

Fig. 12. Pre-stressing cable layout.

The pre-stressing anchoring force applied at the anchorage at the time of stressing is about 1100 tonnes. Fifty-five individual strands will be threaded into a flexible dross-batch sheath of 200 mm diameter (for horizontal tendons) or 219 mm diameter steel pipe (for vertical U tendons), which are left embedded in the concrete section. The duct is grouted with cement grout for added corrosion protection of the steel strands.

8.2. Provision of in-service inspection of the inner containment

The following measures are incorporated to establish the surveillance requirements of the pre-stressed concrete inner containment.

(i) Tendon dynamometer to measure the pre-stressing force in the tendons.
(ii) Vibrating wire strain gauges to measure internal concrete strains and deformations.

8.3. Provision of hermitic liner in floor as well in wall of inner containment

A steel liner 8 mm thick for the inner containment floor slab and a 6 mm thick steel liner for the wall and dome are provided to ensure the required leak tightness to the inner containment under the postulated accident conditions.

8.4. Provision of breakwater dyke in the open sea off KudanKulam

The seawater cooling system for KudanKulam Project requires about 3,00,000 m^3/h per unit of sea water supply for condenser cooling operation, essential cooling and other non-essential cooling loads. The design intake seawater temperature was considered as 32 °C and permissible outlet temperature of the discharge water in the sea was 39 °C. For meeting the requirement of the huge quantity of water, satisfying the temperature limits, a water dyke (UZQ) 800 m × 250 m was designed in the offshore about 400 m away from shore (0–0 line). The main advantages of this dyke are:

(1) To receive cooler water at a depth of 5–10 m below the sea water level.
(2) To ensure sediment free water supply to the intake pipelines.
(3) To reduce the under sea pipeline length which in turn reduces the maintenance costs.
(4) To segregate the hot outlet water from the cold inlet water.

8.5. Special features of construction of intake structures

Reinforced concrete caisson structure (UPA) is to be placed in the mouth of breakwater dyke (UZQ) as shown in Fig. 13. This structure consists of three massive boxes like structures having interconnected walls for allowing entry of water into the dyke through the central part. The size of central water inlet structure is about 46 m × 15 m in plan and is 12.45 m in height. The sizes of the adjoining caissons are 36 m × 15 m × 12.45 m. The central caisson has five numbers of water passages of size 5.2 m × 6.0 m. Adjoining caissons flanks the central caisson. All these structures are to be constructed within a dry dock area. The dry dock area has been created between the shoreline and the intake structures through construction of a temporary dyke using bunds made of earth and rock fill. Once all the three caisson structures are ready, they will be floated by cutting the bunds of the temporary dyke and allowing the seawater to enter the dry dock area and then towing them to the final location. The salient construction features of these caissons are as follows:

(i) The design takes care of the floatation of the caissons by adjusting their gross weight and the buoyancy.
(ii) Floating and tugging the caissons to their final positions using winches and tug boats.
(iii) Sinking and placing the caisson to its exact location.

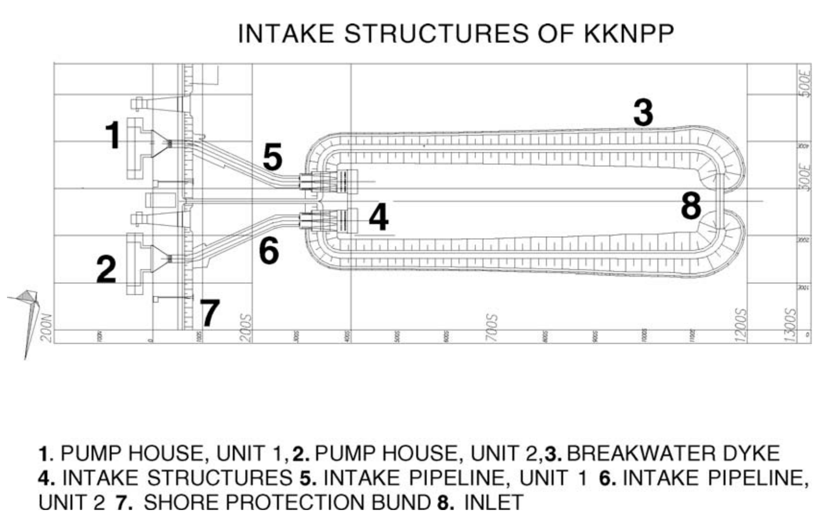

Fig. 13. Intake structure at KK-NPP.

9. Project management strategy

The project management strategy for the KudanKulam Project was planned well in advance keeping the following prime objectives in view:

(1) Reasonable and comparable project cost, with a tariff competitive enough to ensure the salability of the produced power.
(2) Optimum utilization of the available national infrastructure and experienced manpower.
(3) Optimum utilization of the Russian state credit extended for the Project.
(4) Optimum gestation period.

The following advance steps are taken to meet the objectives:

- To assess the techno-commercial viability of the project, a detailed project report (DPR) was prepared jointly by the NPCIL and ASE, based on a Technical Assignment, which stipulated the technical requirements and parameters for the NPP.
- A preliminary safety analysis report (PSAR) was elaborated, which facilitated the regulatory clearances for the construction of the project.
- Also, as a part of DPR, development of project management documentations was taken up. The documentations covered division of scope, project cost estimates, construction schedules, equipment lists and sources, economic viability studies, construction management and format for the Techno-Commercial Offer.
- Development of the site infrastructure.
- Site grading and excavation for the main plant buildings.

On completion of the DPR, which established the technical viability of the project, a Techno-Commercial Offer was submitted by the Russian side for the project, which was negotiated to arrive at an optimum cost of the project and financial closure was achieved. The financial sanction for the project was obtained from the Government of India in December 2001.

9.1. Major obligations of the sides

The obligations of the Russian side include complete design, detailed engineering and designer's supervisions for the construction of the project; supplies of all main plant equipment, instrumentation, training simulator, fuel and mandatory spare parts. The commissioning of the systems and plant will be carried out by the Indian manpower under technical supervision of the Russian specialists. The Russian side will also assist in planning and project management, quality management and training of the Indian manpower. The side will also be responsible for procurement of some of the equipment of the plant from third countries.

The Indian side is responsible for carrying out infrastructure design; review of the plant design and obtaining regulatory clearances required for construction of the plant. The Indian side is also responsible for overall project management and quality management of the NPS, construction of the main plant and infrastructure buildings, erection of all plant equipment and systems, commissioning of the plant and operation of the station (after the provisional takeover).

9.2. Development of project management documentation

During the DPR preparation, elaborate documentations on the project management were developed jointly by the experienced Indian and Russian specialists. As a result, complete project implementation plans, including milestone network schedule and detailed Level-1 networks schedule, were ready to be annexed to the Techno-Commercial Offer. The documentation on the organizational set-up, project interface control, equipment list, project monitoring, detailed project cost break-up, cost control methodology and economic viability were also developed beforehand. As a result of this clear-cut division of scope and the interfaces were made available for the scope of works of NPCIL and Russian side. The advance preparation of the project management documentation not only shortened the period for preparation and submission of the Techno-Commercial Offer, but also facilitated quick negotiations and agreements during TCO and Russian contracts. The documentation also helped in speedy approval of the financial sanction from the Government of India and thus provided a head start to the project.

9.3. Pre-project activities

As a prudent project management strategy, NPCIL initiated the process of land acquisition immediately after the Government of India decided to locate the project at KudanKulam. For smooth interaction with the local landowners and the Government, the state officials from the Tamil Nadu state were deputed for the land acquisition process. This expedited the process of land acquisition. The site surveys and the collection of the input data required for the detailed design were carried out in parallel.

The development of the site infrastructure facilities like the approach roads, administrative office buildings, concrete testing laboratory, telecommunication facilities, construction power supply and lighting, water supply, residential quarters and associated facilities like school, recreational facilities, bank, shopping mall for the project personnel, etc., were taken up well in advance with prior approval from the Government. This not only facilitated in taking up the main plant construction works immediately after the construction contracts were awarded, but also helped to boost the morale of the project construction personnel by having good working environment right in the beginning of the construction stage of the project.

Also to reduce the effective gestation period of the project construction, the pre-project activities of the site grading and leveling as well as the pit excavation works for the main plant were taken up in advance. This facilitated advancement of the start of main plant construction (first pour of reactor building concrete) by 2 months.

9.4. Construction planning

While carrying out the construction planning the following major differences in the construction management methodologies were experienced by the sides:

- Russians stationed at construction site had been constructing the plants using in house specialized manpower. The approach, while facilitates the smoother coordination and relatively longer periods to the designer, manufacturer and erectors by parallel working, necessitates the recruitment of large in house manpower. The Indian on other hand maintains an optimum in-house manpower for construction management and plant operation, sub-contracting the works. This approach necessitates advance availability of the information on the volume of works on equipment and working documentation, for award of the contracts and for planning and preparatory works.
- Large, in house, construction workshops are maintained by the Russian at plant site to handle the fabrication works during construction. The sub-contractors at the Indian Sites handle the jobs.

The major gaps between two diverse construction management methodologies, followed in the Russia and India, were bridged through elaborate deliberations. A mutually agreed Level-2 schedules containing about 13,000 activities, for the Project was agreed fusing the Indian capabilities with the Russian construction sequences. Primavera Project planner has been used for preparation of the network.

The Level 2-project schedule encompasses the design, supplies, construction and commissioning activities for all the phases of the project (from pre-project up to commercial operation).

9.5. Contract management

To ascertain the smooth cash flows, the entire scope of Russian works was divided into eight contracts, within the overall agreed cost of the Russian scope. The supply contracts also provides for phasing out the preparation of the lists, the tech specs and ordering of the supplies, using contract supplements. The following contracts have been signed:

(a) preparation of the detailed project report (including PSAR);
(b) elaboration of working documentation (detailed engineering);
(c) supply of equipment with long manufacturing cycle (LMC) equipment;
(d) supply of balance of plant (BOP) equipment;
(e) supply of the equipments from the third countries;
(f) deputation of Russian specialists at site (for supervision);
(g) training of Indian operation and maintenance personnel;
(h) contract for supply of fuel.

The contracts have adequate provisions, for the benefit of the owner, to maintain control over the quality, manufacturing progress, delivery schedule and payments. The provisions of incentives and penalties are also included in the contracts to stimulate the progress and discourage the non-performance.

In order to avoid repetition of the efforts, in preparation of the contracts, the general terms and conditions of the contracts were compiled as a separate annex and attached as common annex to all the contracts.

The delivery schedules are kept in line with the requirement worked out from the Level-2 network of the project. In order to provide the required lead time for manufacturing of the critical equipment like reactor pressure vessel (RPV), steam generator, turbine, generator, etc.; the contract for supply of the long manufacturing cycle equipment was the first to be signed and orders were placed well in advance.

The items required to be erected during the first phase of the combined construction (along with the civil construction) like hermetically and biologically sealed doors, embedded parts, liner plates, core catcher vessel, cooling water pipelines, etc., were also ordered within the Contract for the supply of LMC equipment.

9.6. Mega-package approach for the construction contracts

The Indian scope of construction and erection works of the plant has been distributed into 12 major mega packages, and has been sub-contracted. These mega-package contracts cover the total scope of civil construction works including the supply of construction materials (in case of civil contract packages), arranging the construction and erection equipment, erection of the equipment, quality control and quality assurance and construction management at site. With this approach, the leading contractors in the construction field with requisite experience and capability and high standard of performance are participating in the tendering and contracts are awarded at a highly competitive cost of construction.

This strategy also helped in optimization of the in house manpower for procurement, quality control and construction management at site.

9.7. Project monitoring

The project progress is being monitored through a multi-tier system:

(i) *At Governmental and Board of Directors level:* The monitoring and decision making is being carried out through a Joint Coordination Committee (JCC), consisting of the Deputy Minister level and other high ranking officials from the Federal Agency for Atomic Energy of Russian Federation, the Department of Atomic Energy of India, ASE and NPCIL. The JCC reviews the progress of works on a quarterly basis. NPCIL and ASE's Board of Directors also review the progress of the project on regular basis.
(ii) *At NPCIL Corporate level:* Project Management Services (PMS) group, stationed at the NPCIL headquarter in Mumbai, is the nodal agency, which integrates, processes and analyses the progress inputs on design, supplies and con-

struction being received from the Russian organization and Project Site. Various management information reports are generated and issued by the PMS to cater the varying needs of the different agencies, including the JCC, Indian Governmental agencies and in-house. The PMS also carryout Financial planning and monitoring.

(iii) *At site management level:* The construction works are being monitored on daily basis at working level and on weekly basis at higher management level for adherence to the construction schedules stipulated as per the contracts. At site level for all the major activities Level-3 networks are prepared jointly with the Russian specialist deputed at site. Level-4 schedules are prepared by the contractor and approved by the executing engineer level for close monitoring of the construction works.

9.8. Quality management

The quality management for the project is based on the corporate level quality manual. The overall quality assurance program (POKAS-O), elaborated jointly by Indian and Russian sides, meets the stringent requirement of Indian regulatory and statutory requirements. Based on this framework the individual contractors develop separate quality assurance program POK(S) for their respective scope of works and obtains the approval from the NPCIL, before implementation. The process quality control during construction and erection is the responsibility of the mega-package contractors. The highest quality standards and the strong organizational strength of the mega-package contractors help in fulfilling the stringent quality requirements of both the Russian standards and the Indian mandatory requirements in all the construction works.

In order to maintain the quality of works by the contractors an in-house Concrete Technological Testing Laboratory (CTL) equipped with state of the art testing equipment and facilities have been established at site, which is being utilized by various contractors. This not only saves cost of testing the materials outside but also saves time for unhindered works at site.

9.9. Shipment, transportation and warehouse management

The equipment for the project manufactured in the Russian manufacturing plants and third countries are being transported by sea route from St. Petersburg port in Russian Federation and other third country ports via Tuticorin port in India, which is nearly 150 km from KK-site. A multimodal comprehensive contract with the total scope of sea transportation (on FOB incoterms basis), unloading, custom clearance, inland transportation, warehousing and delivery at the erection point has been awarded to a consortium of leading firms in the field. The shipment of cargo is based on last in first out (LIFO) principle.

The warehouses constructed by NPCIL are handed over to the warehouse contractor for storing the transported equipment. The entire warehouse management and issue of the material to the erection contractors is also carried out by the warehouse contractor.

This strategy of entrusting single point responsibility has helped to ensure the timely delivery of the equipment to site in safe condition. With the start of full bulk cargo shipment, the time required for transportation of the consignments from the manufacturing plants to the site has been considerably reduced.

For the transportation of the over dimensional consignments, which cannot be transported to the site by road, a jetty has been constructed at the site to bring the consignment via sea using barges.

9.10. Financial management

The project is being financed through two sources: soft term State credit for the supplies and services from the Russian Federation and the equity funding from the Government of India. The planning of the annual fund requirements for the Project is carried out by the PMS group at headquarter, on the basis of the scheduled and expected deliveries from the Russian side and estimation of the fund requirement of the Project Site. Indian Government, through union budget, approves the Project Budget and allocates equity funds. Annual Financial plans, if required, are adjusted within the approved budget allocations.

The financial operations for the project are carried out at two places. At headquarters in Mumbai, the payments in respect of all the contracts with Russian organization (ASE) are processed. The accounting of the soft term State credit extended by the Russian Government is done thorough the Controller of Aids Accounts and Audit (CAA&A), under the Ministry of Finance, Government of India. Payments of all the construction and erection contracts are being handled at Project Site. The funds for the site operations are transferred from the NPCIL's headquarter to site, based on the weekly fund requirement schedule. The idling of funds is minimized by these means.

The valuation of the assets and capital work in progress are done at site. Valuation of the supplies from the Russian Federation is also done at site, as and when the items are received at site.

The normal routine works like maintenance of the infrastructure facilities, office equipment maintenance and medical services are done through outsourcing thereby reducing the overhead expenditure and minimizing the total cost of ownership (TCO).

The entire financial operations are computerized and transactions are carried out almost on same day. The computerization of the financial operation has helped in elimination of the manual accounting errors, and minimizing the personnel.

9.11. Organizational set-up

For management of the project, organizational set-up have been established at three places by the Indian side:

- *Headquarters at Mumbai:* To cater the functions of design reviews, obtaining regulatory clearances, Russian contracts management, corporate project planning and monitoring, financial management and training coordination.

- *Project Site at KudanKulam:* To cater the functions of the construction management, commissioning and operation of the Plant.
- *NPCIL Representative Office at Russian Federation:* To coordinate design reviews and carry out quality assurance functions.

The Executive Director (LWR) who reports to Chairman and Managing Director of NPCIL heads the project. The construction management at Project Site is the responsibility of the Project Director, KKNPP who reports to Executive Director (LWR). All the mega-package contracts and the procurement functions are managed and controlled at site by the Project Director. The Project Director does site level project monitoring and liaison with other external agencies for the project at site.

A team of design specialists is deputed at Moscow for coordination of the design works and first level review of the detailed engineering documentation before forwarding to headquarters. This has reduced the time and cost of correcting and issuing the revisions of the working drawings.

The quality assurance wing of NPCIL is also established at Moscow and St. Petersburg for ensuring the quality of the equipment being manufactured in Russian manufacturing plants for the project.

9.12. Human resources management

The human resources for the implementation of the project are a mix of experienced engineers and specialist drawn from NPCIL's existing projects and stations as well as newly recruited supervisory and technical staff. The total manpower strength has been reduced to optimum using the following strategy:

1. Execution of the construction through mega-packages.
2. Outsourcing the services like transportation, drawing office and reprographic services, IT management, maintenance of the township and guesthouses, etc.
3. Advance recruitment and utilization of the operation and maintenance manpower for the quality assurance and construction management.

The design coordination and construction teams are primarily experienced engineers from NPCIL's other sites and headquarters. Since the routine works are out-sourced, the effective number of project construction personnel is kept to a minimum.

For the operation and maintenance of the plant, a core team of engineers is selected from NPCIL's existing stations and is given a comprehensive training in the VVER reactor operations. In the first phase in-house training is given on the basic VVER systems and processes. In the second stage, on-the-job and simulator based training is given at operating VVER stations in the Russian Federation.

10. Environmental impact

Nuclear Power Corporation of India Limited has acquired the land within the 2 km radius from the main plant. About 40% of 2 km radius areas to be acquired lie in the Gulf of Mannar. The balance portion is mostly barren lands and without any habitation. The radiological impact on the site will be very much lower than the stipulated regulatory requirements. The environmental clearances have been obtained from State and Central Government statutory authorities. The activity will not in any way affect the marine life nor curtail the fishing activities of the fishermen living nearby. Nuclear reactors provide clean power and there is no release of gases like sulfur dioxide, carbon monoxide and carbon dioxide. This will also not affect the Vivekananda Rock Memorial, located nearby. The requirements of fresh water are very small and will be drawn from the Pechiparai Reservoir. The fresh water requirements will thus not affect the drinking water and agricultural needs of the local population.

The environmental laboratory will be set-up and managed by Health Physics Division, Bhabha Atomic Research Centre. Its findings will be reported directly to the Atomic Energy Regulatory Board (AERB) and other environmental authorities.

11. Conclusions

The VVER-412 units being set-up at KudanKulam in collaboration with the Russian Federation are advanced pressurized water reactors meeting international safety, quality, manufacturing and construction standards and practices. The project also meets the Indian and Russian regulatory requirements.

Civil engineering design and construction for KudanKulam Project has opened a vast sea of knowledge, which are going to be used for design and construction of various civil structures.

The project has introduced a new technology to India where Boiling Water Reactors and heavy water reactors are already under operation and the construction of first prototype fast breeder reactor has just commenced.

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