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PROTOTYPE FAST BREEDER REACTOR MAIN OPTIONS

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Abstract

Fast reactor programme gets importance in the Indian energy market because of continuous growing demand of electricity and resources limited to only coal and FBR. India started its fast reactor programme with the construction of 40 MWt Fast Breeder Test Reactor (FBTR). The reactor attained its first criticality in October 1985. The reactor power will be raised to 40 MWt in near future. As a logical follow-up of FBTR, it was decided to build a prototype fast breeder reactor, PFBR. Considering significant effects of capital cost and construction period on economy, systematic efforts are made to reduce the same. The number of primary & secondary sodium loops & components have been reduced.

Sodium coolant, pool type concept, oxide fuel, 20% CW D9, SS 316 LN and modified 9Cr-1Mo steel (T91) materials have been selected for PFBR. Based on the operating experience, the integrity of the high temperature components including fuel and cost optimisation aspects, the plant temperatures are recommended. Steam temperature of 763 K at 16.6 MPa and a single TG of 500 MWe gross output have been decided. PFBR will be located at Kalpakkam site on the coast of Bay of Bengal. The plant life is designed for 30 y & 75% load factor. In this paper the justifications for the main options chosen are given in brief.

1.0 BACKGROUND TO THE DESIGN OF PFBR

1.1 Energy Demand

The utilities in India generated 351 TWh of electricity during the year 1994-95. The cumulative installed capacity is 81.2 GWe (Coal 52.2, Hydro 28.3, Gas 5.6, Nuclear 2.3 and others 0.3 GWe). The per capita electricity generation works out to 380 KWh/a which is only 1/7th of the world average. There is an urgent need to increase the energy generation for rapid industrialisation to improve the living standard of the large population. The growth of electricity generation during the last 30 years has been on an average 8% and it is likely to continue to grow in the coming decades. See Fig 1. However, there is a gap of about 15% between demand and supply of electricity in the country. The total installed capacity is expected to be about 120 GWe by the year 2000. The efforts in increasing the installed capacity should be complemented by efforts in reducing the transmission and distribution losses (23%), improving the capacity factors of the power plants (current average 50%). India is spending Rs 190 billion/a (6 billion US $) for import of oil and this is the single largest burden on the foreign exchange reserves. This is the price being paid for lack of a clearcut policy on energy independence. The growth of the installed capacity is limited by the available financial resources. So far, generation, transmission and distribution of electricity was a Government activity. With the economic liberalisation policy started in 1991 it is being privatised - domestic and foreign. Foreign investment is increasing on a big scale in the power industry.

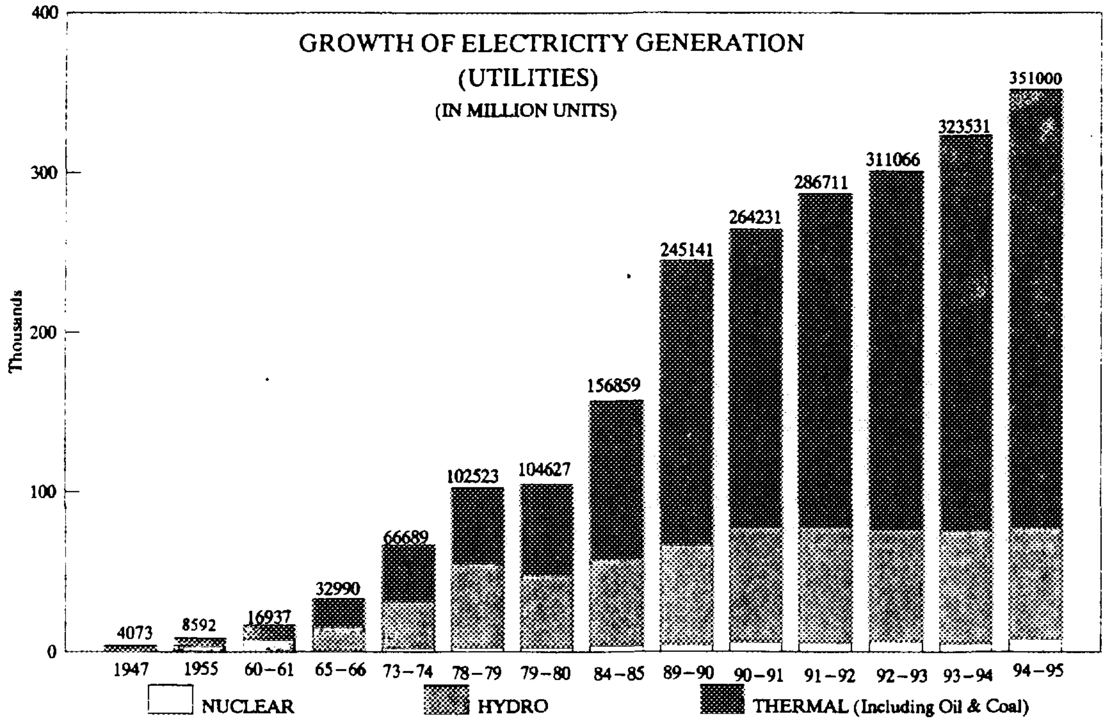

Fig 1

1.2 Energy Resources

Large energy resources available in the country are coal and nuclear energy through FBR. See Fig 2. Coal would not last for more than 50 years for a targeted electricity generation capacity of 500 GWe. Therefore, it is imperative that FBR should be introduced on a commercial scale at the earliest so that by the year 2050, dependence on coal will be very much reduced. Indigenous Uranium reserves are estimated to be about 50,000 t which can support 10 GWe PHWR and about 300 GWe FBR.

Transportation of poor quality coal (~ 40% ash) over long distances (~ 1000 Km) is going to be difficult when the generation capacity increases. Environmental concern - greenhouse effect and acid rain - is important for decreasing the production of electricity from coal. The cost of electricity produced from coal will increase at a rapid rate due to deep mining, transportation over long distances and stringent environmental requirements on the discharges. Gas and Oil cannot make important contributions in the generation of electricity, although gas is making rapid progress in the present condition because of the short gestation periods. The potential hydroelectric power is about 80 GWe at 40 % load factor while 30 GWe has been realised so far. There may be difficulties in further realisation because of the prospective sites being located in difficult terrains and related environmental concerns. Apart from being costly, the renewable energy resources like Solar, Wind, Ocean and Biomass can only make a small contribution in the total generation of electricity in the country.

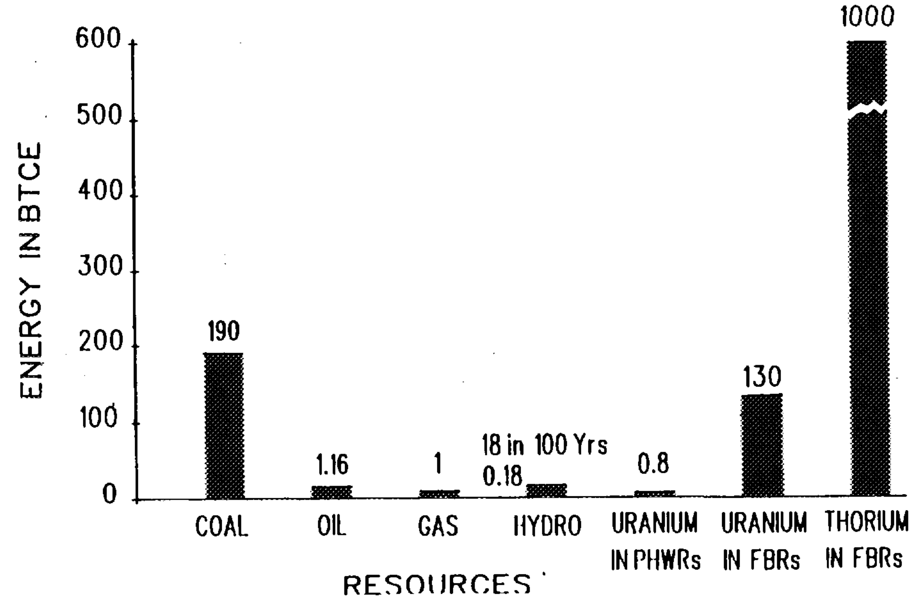

Fig 2

1.3 Thermal Reactor Programme

India is operating 10 power reactors of 200/220 MWe capacity each which have logged 110 reactor-years of operating experience (2 BWR and 8 PHWR). 4 x 220 MWe and 2 x 500 MWe PHWR units are under construction. The indigenous content of the recent reactors has been very high at 85 to 90% and the Indian industries have risen to the occasion in taking up manufacture of high quality components for the nuclear industry. In order to be economically competitive with the coal fired power stations, it is essential to reduce construction time and increase the capacity factor of nuclear power stations.

1.4 Fast Reactor Programme

India started its fast reactor programme by construction of 40 MWt Fast Breeder Test Reactor (FBTR). Most of the components of the FBTR have been manufactured by the Indian industries. The reactor attained its first criticality in October 1985 and its rated power of 10.5 MWt in December 1993 with the Mark I small core. Though the performances of the various systems have been generally satisfactory with respect to the ratings, the reliability of operation has to be increased considerably. Design and construction deficiencies were observed and the same have been removed by systematic analyses and followup actions. Generation of electricity at about 2.5 MWe is expected from the Mark I core in the coming months. 600 mm of Hg vacuum has been achieved in the condenser during commissioning test. With the change to Mark II full size core in 1996, the reactor power will be raised to 40 MWt. FBTR will be used as an irradiation facility for fuel development and to gain operating experience.

1.5 FBR Cost Competitiveness

The development of FBR was takenup very vigorously in USA, Europe and erstwhile USSR in the 60's and 70's because of the following two reasons,

- FBR is a large energy resource.
- FBR produce electricity more economically than thermal reactors.

Construction experiences of BN 600, SUPERPHENIX and MONJU have indicated that FBR are costly by a factor 2 to 3 compared to PWR and considerable cost reductions are essential for their commercialisation.

Any large power plant must fulfill the following in order to be competitive with the alternative energy resources.

- Low capital cost
- Short construction period
- High capacity factor

The components of UEC from FBR can be approximated as shown in Table I. Reduction in the Fuel Cycle Cost reduces UEC only marginally.

Table I

Capital	O & M	Fuel Cycle
75 %	15 %	10 %

Since the capital cost forms the major component in the UEC, efforts must be made to decrease the same. Large capital cost reductions have been demonstrated in the designs of AP 600, CANDU 3, EFR, BN 600 M by design simplification. The low capital cost not only reduces UEC but also decides the quantum of capacity that can be added from a given amount of finance allotted. Lower the capital cost, higher will be the growth rate.

As in any developing country, India is finding scarcity of capital particularly for power industry where the investment is large and returns are spread over a long period. The present interest rates are 12% on Government borrowing and about 18% on the market borrowing compared to about 8% in the developed countries. The high interest rate becomes one of the demanding factors for reducing the construction period. Otherwise, the Interest During Construction becomes a major investment cost and reduces the competitiveness of the project. The long gestation period in the construction of the Nuclear Power Plants is one of the eroding factors in cost competitiveness. The effect of capital cost, construction time & interest rates on UEC can be seen from the following.

Components of UEC

$$= DCC + ICC + EDC + IDC + OMC + FCC$$

$$= DCC+K_{ICC}.DCC+K_{EDC}..DCC+K_{IDC}.DCC+0.03(1+e)^{n}\,(1+K_{ICC})DCC + FCC$$

$$= DCC + K_{ICC}DCC + K_{EDC}DCC + K_{IDC}DCC + 0.04(1+e)^{n}\,DCC+ FCC$$

$$= DCC.(\,1+ K_{ICC}+ K_{EDC}+ K_{IDC} + K_{OMC}) + FCC$$

$$= DCC.\,K_{TOTAL} + FCC$$

where, DCC - Direct Capital Cost, ICC - Indirect Capital Cost, EDC - Escalation During Construction, IDC -Interest During Construction, OMC - O&M Cost, FCC - Fuel Cycle Cost, n - number of years and e - escalation rate.

The reduction in DCC would result in reduction of ICC, EDC, IDC and OMC.

2:1 Debt/Equity ratio is assumed in the calculations invloved in the following table which shows clearly the effect of construction time and interest rates on UEC.

Table II :

No of years	Interest rate = 8 % & Esc. rate = 4 %					Interest rate = 16 % & Esc. rate = 8 %				
	K_{ICC}	K_{EDC}	K_{IDC}	K_{OMC}	K_{TOTAL}	K_{ICC}	K_{EDC}	K_{IDC}	K_{OMC}	K_{TOTAL}
6	0.35	0.13	0.13	0.05	1.66	0.35	0.27	0.26	0.06	1.95
8	0.35	0.17	0.17	0.05	1.75	0.35	0.38	0.37	0.07	2.17
10	0.35	0.22	0.22	0.06	1.86	0.35	0.50	0.49	0.09	2.42
12	0.35	0.27	0.27.	0.06	1.96	0.35	0.62	0.62	0.10	2.70

Construction of a NPP takes 8 to 10 years and when compounded with the high interest rates leads to high IDC. 50% of the investment cost of the Kaiga Project (2 x 220 MWe PHWR) is due to IDC. Apart from Unit Energy Cost (UEC) consideration, the shorter construction periods make a rapid growth of installed capacity and thereby the national economy. Therefore, it is highly desirable to plan to minimise the construction period, even at the conceptual design stage. This can be done by improving the infrastructure and reducing the number of systems and components and their sizes.

By the time FBR is commercialised in India, further construction of PHWR would not be viable due to limited availability of U and the only competition for the FBR would be from coal fired power stations.

We are proposing to the government to fully finance the PFBR.

2.0 Design Objectives of PFBR

- The purpose of constructing PFBR is to demonstrate on an industrial scale techno-economic viability of an FBR Power Plant in India.
- The concepts selected for PFBR should be based on the operating experiences of FBR. Any innovative design concept is to be incorporated only after thorough research and prototype test. Atleast 4 reactors of 500 MWe capacity are likely to be built after PFBR. Therefore, the designs must be optimised and standardised so that the follow on plants will have minimum modifications.
- High breeding ratio is not an essential requirement of PFBR Fuel cycle. The growth of FBR initially will depend on availability of technology, availability of finance, public acceptance and then on Plutonium. PFBR will be a breeder reactor but without emphasis on high breeding. Economics of fuel cycle is an important factor at this stage of FBR development.
- Experience in design, construction and operation of all the FBRs, particularly all the incidents and accidents, shall be considered systematically in PFBR design.
- The reactor shall meet the PFBR safety criteria issued by Atomic Energy Regulatory Board (AERB).
- Design simplification i.e. reduction in number of systems and components without compromise on safety and reliability is to be carried out. Experience of thermal reactors indicates that complex plants take longer times to construct and are difficult to operate.

In this paper the main options selected for PFBR are discussed. Options of core, main heat transport systems, core component handling systems and safety are presented in the companion papers of this meeting.

3.0 MAIN OPTIONS

3.1 Sodium Coolant

Sodium has been the unanimous choice of all fast reactors due to the following.

- Nonmoderating properties essential for FBR

- High boiling point permits high temperature without pressurisation. This results in high thermodynamic efficiency and thin walled components.
- High thermal conductivity of sodium results in high heat transfer coefficients, even at low velocities. Heat transfer areas are low. Passive decay heat removal is possible due to high heat transfer, large ΔT and low viscosity.
- No corrosion of structural materials at high temperature over long periods of operation.
- Large margin between operating temperature (~ 823 K) and high boiling point (~1155 K) gives sufficient safety margins for heat removal in emergency conditions.
- Owing to extensive R&D and reactor operating experience over 4 decades, high level of technological maturity has been reached.

The disadvantages of sodium are the following:

- High radioactivity of primary sodium, deposition of sodium vapour in cold region of covergas, cleaning of sodium from components can be taken care of by proper design.
- Opacity of sodium, its chemical reaction with air and relatively high melting point (371 K) make inservice inspection and repair difficult. Very careful considerations have to be given in the conceptual design and development of special devices needed for this purpose.
- Large leaks of sodium can result in fires and Na-concrete reactions. Provision for diverse sodium leak detection systems, sodium collection trays, selection of suitable concrete, steel lining, etc. can mitigate the problem.
- Large sodium water reaction in SG: High quality of manufacture of SG, sensitive leak detection system, isolation of SG on detection of small leaks can avoid this problem. Also by proper design of secondary sodium circuit, this can be taken care of.

3.2 Pool type Concept

The loop and pool concepts have been discussed qualitatively in several forums. Both types are in practice. We have decided pool concept for PFBR.

The main advantages of pool type are:

- Simple shape of reactor vessel without any nozzles and low neutron radiation dose, results in high reliability and its easy inservice inspection and repair.
- Large thermal inertia of the pool attenuates thermal shocks, results in slow temperature rise during decay heat removal and load throw conditions, and gives long times for operator actions.
- capability to withstand higher work potential under core disruptive accident.
- containment of radioactive components and fluids is easy.

- Compact primary sodium circuit layout.

The disadvantages of pool type are:

- Thermal hydraulics of hot and cool pools is complex. Specially developed computer codes and several scaled down water models can solve these problems successfully. Operation of EBRII, PHENIX, PFR, BN600 and SUPER PHENIX have demonstrated satisfactory performance.
- Large size of vessel needs site assembly. The vessels are assembled in site workshop by welding only. Hence same quality as in shops can be achieved without any additional time for manufacture.
- There is concern about seismic design of thin shell vessels with large mass of sodium. Preliminary analysis indicates that the structural integrity can be assured for moderate seismicity.
- There is more interdependence in component designs . The designs of primary sodium pump, IHX, inner vessel, roof slab get interconnected very much. 2-3 iterations can give good judgement for design decisions.
- Difficulty of maintenance on top of pile: Due to closeness of many components on reactor assembly resulting in space constraints can prolong maintenance works, thus affecting capacity factors. This can be taken care of by reducing the number of components and making them compact. Thorough check on drawing boards for lack of interference and adequate space for component handling and full scale sector mock up can eliminate such problems.
- Measurement of flux in startup range and primary sodium flow require special instrumentations.

3.3 Reactor Power

Reactor power is the most important decision in the design of India's prototype fast reactor. 200-300 MWe capacity, as has been the case for all the FBR countries would appear an obvious choice to avoid large extrapolation from FBTR (15 MWe). However, the following considerations lead to select 500 MWe capacity .

- Large size pool type reactors have operated in other countries upto 1250 MWe and basically there are no technological problems. Such a confidence was not there in the late 60's.
- Specific capital cost is lower for 500 MWe than lower power, say 250 MWe (~30 %).

- Medium size power is very much desirable for constructing more number of follow on plants, before a large commercial size plant is built.
- Coal fired power plants and PHWR of 500 MWe capacity have been designed. The coal fired plants are in operation and PHWR are under construction. The conventional power equipment of this size, particularly TG set, are readily available.
- Design and development efforts for 250 MWe and 500 MWe plants are comparable.
- Constructability of 500 MWe size components was assessed based on the experience of 220 and 500 MWe PHWR and FBTR. The Indian industries are equipped with necessary machines. High quality SS welding can be done if attention is paid to training of welders and taking care of weld shrinkages. Transportation of components except reactor vessels and roof slab is possible. The vessels and roof slab will be assembled in site workshop. Development of manufacturing technology is in progress to gain industrial experience. Delivery schedules need considerable improvements.
- Financial risk is of course more for a 500 MWe plant than a smaller plant. This would be reduced by systematic design and development.

3.4 Fuel

PuC-UC has been used as fuel for FBTR due to nonavailability of enriched uranium for mixed oxide option. For PFBR enriched uranium is not required. Though carbide gives high breeding ratio, it raises safety problems in fabrication because of its pyrophoricity. Fabrication cost is also high. Fuel burnup is lower compared to oxide because of its high swelling rate. Reprocessing on prototypic scale has not yet been done anywhere and this cost is also expected to be more. Being a large power plant, proven fuel cycle is essential. High breeding is not the objective for PFBR. As the entire plant must be designed around the fuel, a firm and early decision is essential. Most of the large size FBR use MOX fuel. This choice was natural since the technology of mixed oxide fuels is very similar to that of UO_2, which is used in thermal reactors. MOX fuel has shown excellent performance in all FBR with respect to high burnup (up to 2,00,000 MWd/t on full size subassemblies) and has proven reprocessing technology. A large amount of safety experimental results is available. Extensive experience is also available in India from thermal reactors. After thorough debating on choice of fuel, MOX has been decided.

3.5 Main Structural Materials

20% CW D9 material is selected for cladding and hexcan because of its improved resistance against swelling due to neutron irradiation, high strength at operating temperature and good corrosion resistance against Na and fuel. AISI 316M has been used in FBTR for sodium components except SG. It has given very satisfactory results. We like to continue its use with some improvements. SS 316 LN gives improved corrosion resistance while maintaining high temperature strength. Hence it is selected for out of core sodium components . Use of SS 304 LN for cold leg sodium components is being discussed. Modified 9Cr-1Mo steel has been selected for SG because of its adequate high mechanical strength, freedom from the risk of stress corrosion cracking (problem with stainless steels) and also decarburization (problem with 2.25Cr-1Mo).

3.6 Operating Temperatures

High reactor outlet temperature is always preferred for achieving high thermodynamic efficiency. However, this is limited by the fuel burnup and component structural integrity considerations. In order to satisfy the allowable clad hotspot temperature of 973 K, the reactor outlet temperature is to be limited to 833 K for core ΔT of 150 K. As regards structural integrity of high temperature components, with the recent advancements in high temperature design codes and structural analyses methodology, it is possible to select as high as 825 K for the reactor outlet. Detailed inelastic and viscoplastic analyses have been performed for the control plug, inner vessel and IHX using ORNL and Chaboche viscoplastic models. While the permissible reactor outlet temperature is about 770 K in order to satisfy the design rules of RCC-MR through 'elastic' route, the viscoplastic analysis indicates that the temperature can be 825 K. Modified. 9Cr-1Mo can permit upto 775 K steam temperature. The turbines used in the conventional thermal power stations allow steam temperature of 811 K. The reactor inlet temperature and hot & cold temperatures of the sodium in the secondary sodium circuit are arrived at from overall cost optimisation studies.

Based on all the above considerations and discussions with the supplier of turbine for steam reheat cycle, the following plant temperatures have been selected.

- Core inlet/outlet : 670/820 K
- Primary sodium inlet/outlet to IHX : 817/667 K
- Secondary sodium inlet/outlet to IHX : 628/798 K
- Feed water inlet/steam outlet : 508/766 K
- Steam conditions : 763 K at 16.6 MPa

3.7 Number of TG Set

Turbine is the most important component, on the conventional side of a NPP. It is also the most costly equipment. It operates at high pressure and high temperature and rotates at high speed. It has large number of parts and auxiliaries. Reliable TG is essential for a high capacity factor. In India, the TG sets are manufactured by M/s Bharat Heavy Electricals Ltd. As in most of the countries, the present day large size turbines are modular in design and can give the desired power output with the specified steam conditions by combination of proven modules having high reliability. Reliable turbines are available for sodium to steam reheat as well as steam to steam reheat cycles. Presently, there are 15 TG sets of 500 MWe capacity operating in India, for the coal fired power plants. Their reliability is very high (~ 99% availability excluding planned maintenance times).

Use of a single TG set in place of two saves about 30% of total TG cost and reduces plant maintenance. Therefore, single turbine of 500 MWe gross output is selected for PFBR after detailed discussions with the supplier.

3.8 Plant Life

Longer life with higher plant capacity factor is desirable for economic production of electricity. Plant life is mainly limited due to radiation and creep-fatigue damage. Considering the selected materials, analyses capability and maturity of design codes, a 30 y life and 75 % capacity factor is used for the design.. Some of the components, such as SG, control rod drive mechanism, cold traps, may have to be replaced. However, for the calculation of UEC, 25 y plant life with 62.8 % capacity factor is used based on the costing procedure .

4.0 Site Selection

PFBR will be located at Kalpakkam site on the coast of Bay of Bengal for the following reasons:

- Closeness to the design office, R&D laboratories and FBTR
- Site of low seismicity
- Infrastructure availability
- Kalpakkam is away from coal fields
- Electricity demand of this region.

Kalpakkam will be a part of the Southern Region Grid, the current capacity of which is about 15 GWe and expected to reach 35-40 GWe by the year 2005.

5.0 SUMMARY

Demand for energy will continue to grow for decades. Large energy resources available in India are coal and nuclear energy through FBR. Apart from reducing the capital cost, it is essential to plan to minimise the the construction time even at the conceptual design stage for commercialisation of FBR. Sodium coolant, pool type, 500 MWe, oxide fuel, 20 % CW D9, SS 316 LN & Modified 9Cr-1Mo materials have been selected for PFBR. Steam temperature of 763 K at 16.6 MPa and a single TG of 500 MWe gross output have been decided.