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INNOVATIONS IN PHWR DESIGN, INTEGRATION OF NUCLEAR POWER STATIONS INTO POWER SYSTEMS AND ROLE OF SMALL SIZE NUCLEAR POWER PLANTS IN A DEVELOPING COUNTRY

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1. INTRODUCTION

India has chosen the Pressurised Heavy Water type reactors (PHWR) for its first stage of nuclear power programme. Because of its excellent neutron economy this type of reactor produces maximum amount of plutonium which is so vital for sustaining a sizable breeder programme during the subsequent stages, with the ultimate aim of thorium utilisation. Apart from fuel cycle aspects, the adaptability of this system for indigenous manufacture and use of indigenously available nuclear materials have been other considerations for choice of this system. The rapid increase in the quantum of indigenous supply in the nuclear power reactors taken up so far has proven this point. However, good understanding of the industrial capabilities that can be developed and a sound knowledge of the system design requirements are necessary for maximisation of indigenous supply. Experience gained during the past years has been valuable in this regard.

Consistent with the policy of self reliance, full responsibility for design, development, procurement, installation and commissioning was taken by the Department of Atomic Energy starting from two reactors (MAPS 1 & 2) under construction at Kalpakkam near Madras. Although these reactors are basically similar to the two reactors in Rajasthan

(RAPS 1 & 2) for which construction was started earlier, substantial changes have been introduced in MAPS reactors. The experience thus gained has been used in the design of reactors to be installed at Narora near Delhi (NAPS 1 & 2) which have seen considerable innovations. These units are expected to serve as prototype for larger PHWRs in the country. The operation of RAPS-1 and also the two BWR type reactors at Tarapur near Bombay has revealed the need to understand problems associated with small size grids with weak interlinks, load patterns and fluctuation in voltage and frequency. The economic penalties associated with these problems merit proper consideration in deciding the stage at which large size reactor units should be brought in.

2. REVIEW OF FIRST GENERATION PHWRs IN INDIA

RAPS-1 is the first operating PHWR in India. Basically this is a pressure tube type heavy water cooled and moderated, and natural uranium fuelled reactor. On power bi-directional fuelling is one of the very important features of this system. Fig. 1 and 2 show the general arrangement of the reactor components. Basic parameters of RAPS and the subsequent Indian PHWRs are given in Table I.

In the first unit at MAPS a major improvement was effected in the containment and the associated engineered safety feature. The RAPS containments are designed to limit leakage to less than 2.4% of the contained volume per day at the design pressure. This leakage limit complied with the standards that were prevailing in the sixties, but it is substantially higher than what we would like to permit from considerations of allowable ground release of Iodine 131. With the partial double containment provided for MAPS units the overall ground leak rate has been reduced to 0.36% of contained volume per day. For the future reactors, designs are being evolved to limit the leak rate to less than 0.1% of contained volume per day.

Though the dousing system was used at RAPS, in the subsequent designs it has been replaced by vapour supression system which does not depend on operation of any mechanical component. These design changes have been supported by considerable R & D work in areas such as permeability and elevated temperature behaviour of concrete, behaviour of prestressed concrete containment upto failure conditions, effect of stress concentration near openings, condensation and heat transfer in suppression pool and effect of non-uniform steam-air mixing in the drywell area.

RAPS-1 reactor employs cobalt adjuster rods for xenon over-ride and for reactivity regulation. The design of the adjuster rod assembly has been constrained by the fact that they had to be introduced in locations which were originally meant for U-235 booster rods. The need for frequent replacement of the absorber elements leads to substantial down time of the reactor and also man-rem exposure. While the Pu-239 boosters are being developed for subsequent PHWRs to achieve higher burnup, serious consideration is also being given to the use of stainless steel absorbers which do not require frequent replacement.

The second unit at MAPS uses stainless steel for the envelope of the end shield, while 3.5% Ni low alloy steel has been used in earlier designs. This has been done to avoid likely problems due to radiation embrittlement. The implications of running the earlier reactors with the $3\frac{1}{2}$% Ni low alloy steel envelope are being evaluated using fracture mechanics approach. Simultaneously corrective measures like 'in-situ' annealing of the end shields are also being considered.

3. INNOVATIONS IN DESIGN

Feed back from the engineering and operating experience of reactors in India and considerations such as reduction in capital cost, ease of transportation of heavy and over dimensioned components, seismicity of a site, current safety criteria, separation of heavy water and light water areas to improve recovery of heavy water, reduction of heavy water leakage, simplification and ease of scale up are some of the factors that led to innovations in the design of PHWRs for NAPS.

Fig. 3 shows the general arrangement of reactor components for NAPS. The earlier arrangement of seperate calandria and end shields suspended by support rods has been replaced by an integral arrangement supported directly by the reactor vault walls. This design considerably simplifies the alignment requirements between calandria tubes and end shield lattice tubes, and is more suited to conditions at a seismic site.

The shielding slabs of end shields in the earlier design have been replaced by steel balls which would be filled at the reactor site, thus keeping the component weight within manageable limits for transportation and also enabling substantial savings in cost.

In the NAPS design calandria is housed in a water filled concrete vault. The heavy water is not required to be dumped for reactivity control and hence the reactor always operates with the calandria full of heavy water. Furthermore, annulus seal bellows are provided between end fittings and corresponding lattice tubes. These changes have effected considerable simplifications by eliminating the dump ports in the calandria, dump tank, thermal shields, concrete cooling coils and have also resulted in the elimination of A-41 activity produced in the calandria vault.

The integral calandria-end shield design concept has been realised after considerable development work in critical areas such as tube-to-tube sheet welding for the particular joint configuration, method of filling steel balls and their density distribution, analysis for diaphragm supports under normal and abnormal conditions including seismic conditions, and collection of data in heat transfer, and light water distribution in packed beds and calandria.

The coolant channels are being studied for dynamic behaviour under excitation due to flow and seismic disturbances. To improve the life of the channel, from considerations of creep, to atleast the design life of the reactor, cold worked Zr-Nb alloy is being developed instead of zircaloy-2. Initial development work has been started for the development of rolled joints.

In line with the current design trends, two separate and independent fast shut down systems are provided. 14 mechanical shut off rods would serve as the primary fast shut off device and 12 liquid poison tubes would provide the back up for primary system. For purpose of fine and coarse power regulation four shim rods are provided. Four boosters/absorbers would be available for xenon over-ride. Development work is being done to check the adequacy and reliability of these systems.

Experience with the existing wire-wrap fuel bundles has been quite satisfactory. However, as 'split-wart' type fuel bundles offer certain advantages, these are also being developed. The fuelling machines for NAPS have also seen some changes based on earlier manufacturing and operating experience. Computer control of the fuelling machines is in an advanced stage of development.

As far as process systems are concerned emphasis has been laid on increasing the unit component sizes. In the primary heat transport (PHT) system, NAPS would have only four pumps and four steam generators as against eight pumps and eight steam generators at RAPS. The unit size has been chosen with a view to using identical components for bigger (say 500 MWe) units simply by increasing the number of such components.

The heavy water system layouts are being closely examined for simplification and whenever possible elimination of components like valves and seals to limit leakage rate. As pressure control by feed and bleed in PHT system is found inadequate for transient load fluctuations that have been experienced, a surge tank is being considerd to ease this problem.

The NAPS site is in a seismic zone about 50 KM away from a known geological fault. Consequently the structures at NAPS have to be designed for a ground seismic acceleration of 0.3 g, whereas those at RAPS were designed for a seismic acceleration of 0.05 g, and those at MAPS for 0.1 g. Extensive seismic analysis is in progress to prove the design under such conditions. Studies on RAPS and MAPS have shown that the suspended calandria and end shield units may require additional anchorage to avoid undesirable misalignments. Under such conditions the integral calandria/end shield assembly concept for NAPS has been designed to be comparatively insensitive to earth quakes of this magnitude.

The containment in case of NAPS is a full double wall containment. The inner cylindrical wall with a flat roof forms the primary containment, surrounded by an outer cylinder with a dome as the secondary containment. With this design, leak rate is expected to be less than 0.1% of the building volume per day.

The lay out of the equipment and process systems in the reactor building has been spread out to ease the maintenance work and thus reduce maintenance man-rems. The light water auxiliary systems have been shifted to locations outside the reactor building thereby reducing the frequency of entry into the reactor building for attending to equipment of this system. Based on the experience gained so far, the heavy water loss is expected to be considerably reduced.

Safety studies for conditions of loss of coolant, rupture of coolant channels, emergency cooling etc. have been carried out in the past. More rigorous theoretical analysis backed up with experimental work is in progress.

4. INTEGRATION OF NUCLEAR POWER STATIONS INTO POWER SYSTEMS

RAPS-I has been frequently subjected to disturbances from the connected power grid. Due to the small size and softness of the grid and due to the absence of effective power system control schemes, severe frequency and voltage disturbances have occurred quite often, leading to considerable number of outages of the station.

RAPS-I is designed to be a base load station with the turbine following the reactor. Frequency disturbance affects the governor valve opening and in turn the boiler pressure, and the reactor sees either a load rejection or a load assumption. The Primary Heat Transport (PHT) system being a buffer between the boiler and the reactor, is subjected to the mismatch between the reactor power and steam demand and consequently undergoes pressure transients. If the frequency disturbance results in a load rejection, the Boiler Pressure Controller (BPC) along with the bypass steam discharge valves (SDV) relieve the excess pressure in the boiler and a reactor set back at the rate of 1%/sec. occurs, the initiation and duration of the set back being dependent upon the magnitude of the load rejection. Although high pressure in PHT system to the extent of trip is avoided through the feed and bleed and PHT pressure control systems, the set back rate at 1%/sec. cannot be met by movement of adjuster rods. Hence moderator level is lowered. The dip in moderator level causes oscillations in moderator level, coolant flow to adjusters and other auxiliaries. The level cannot be regained for almost 2 minutes, resulting in undershoot of power, often resulting in low pressure trip and undesirable thermal cycling of fuel.

Since there is no provision in the control system to make the reactor follow the steam demand except through the operator intervention, in case of grid frequency going low or regaining after a high frequency the reactor is prone to trip due to low PHT pressure.

Frequency disturbance also affects the performance of the PHT pumps, boiler feed pumps, and in turn affects the reactor regulating system which is very much dependent upon temperature rise across the core which depends upon the PHT flow.

Voltage transients also affect the measuring and process control instruments significantly. The station regulated power supplies do not recover at the desired rate after a grid transient. Besides, it has been found that a dip of 15% in the grid voltage results in unwanted trips due to malfunction of relays connected to the indicating alarm meters. In the Tarapur Atomic Power Station time delays incorporated in some of the relay circuits have reduced spurious trips.

The control system of RAPS-I can be modified to make the r eactor load following to a limited extent. Simulation studies indicate that the reactor can sustain a step load increase of 5%, the limitation being the loading rate permissible for the turbine and the reactor which are 0.2% per sec. and 0.6%/sec. respectively. However, it is felt at the moment that the load following behaviour of the reactor will introduce undesirable thermal cycling on the fuel. Another alternative is to remove the setback initiated through the boiler pressure controller and bypass the steam to a dump condenser. Main condensers with capacity equivalent to 110% full thermal power, are being employed in MAPS and NAPS. The reactor power can be reduced manually by the operator depending upon the grid demand. Simulation studies indicate that the reactor power as well as PHT pressure are held within very close range of the initial values and the feed and bleed capacity for the PHT can be reduced.

5. ROLE OF SMALL SIZE NUCLEAR POWER PLANTS IN A DEVELOPING COUNTRY

The unit rating of power reactors available in international market has been progressively increasing. While these higher ratings may be appropriate for developed countries, the stage has not yet reached in a developing country like India for installating such large units. As has been highlighted in earlier section of this paper, certain pre-requisites from the connected power system should be satisfied if a particular size and type of unit is to operate satisfactorily.

In situations where the unit size of a nuclear station is a large fraction of the grid capacity, the impact of outages of such unit is most severe. This situation could be eased to some extent by choosing larger number of smaller size units.

Depending on the availability factor and the load factor of the station and on the difference in capital costs of the single unit and the double unit power stations and the interest rate, there could be certain sets of conditions under which the cost of power produced in a double unit power station may turn out to be lower than that from a larger single unit power station. Analysis has shown that with a unit availability factor of 60% and load factor less than 60%, and with a unit availability factor of 70% and load factor less than 50% the cost of energy generation would be less for a double unit power station than for a single unit power station, both being of 500 MWe. Under conditions where the unit size installed is much larger than what is really required to meet the power demand in the system, this would be particularly true.

Smaller units are attractive from considerations of optimal utilization of capital, which is often one of the scarcest resources in a developing country. Installing large nuclear power reactor units and operating them at reduced capacity during the first few years also results in blocking capital resources. Phased installation of smaller units will enable the diversion of the capital to other industries which would make contribution to the national economy.

Perhaps the standardisation of the power reactors in the higher size range by power reactor suppliers coupled with available credit facilities is the main reason why some developing countries with limited installed power capacity opt for large single units. This should be viewed together with the penalties that could be associated with such units under certain conditions.

6. CONCLUSION

With the innovations introduced in the Indian PHWRs, apart from realisations of other advantages, it would be possible to scale up the unit size as soon as it becomes necessary. The connected power system should however be ready to accept such larger sizes. With conditions prevailing in developing countries the optimum unit size that should be installed appears to be much smaller than the popular sizes being installed in developed countries. Phased installation of smaller size units would be beneficial from the view point of optimal utilization of capital resources for the maximum possible growth of the national economy.

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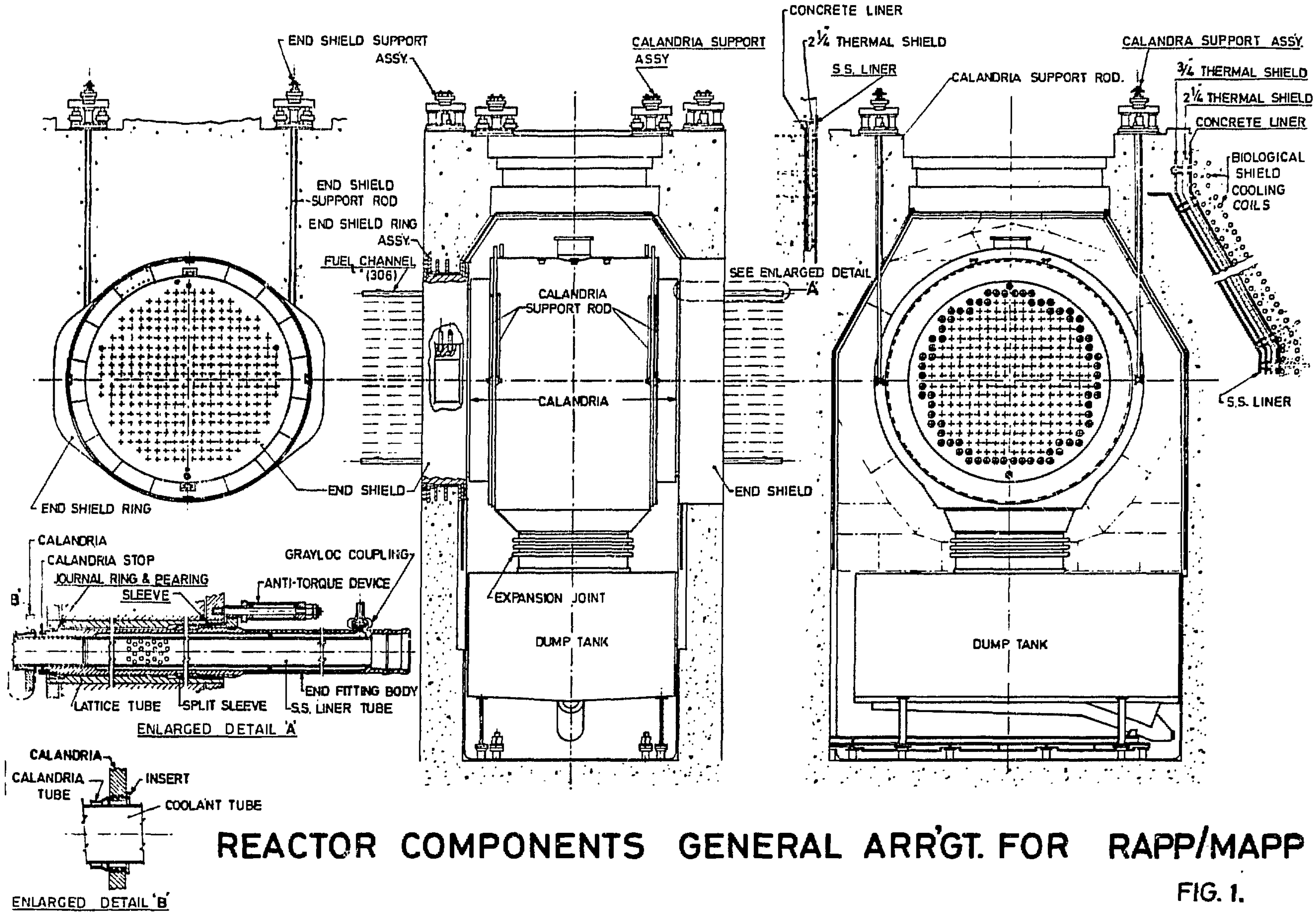
TABLE-1

BASIC PARAMETERS OF INDIAN PHW REACTORS

Parameter	RAPS 1 & 2	MAPS 1 & 2	NAPS 1 & 2	Proposed 500 MWe	Remarks
Power MWe Net	2 x 203	2 x 220	2 x 220	500	About 10% increase in power is obtainable in MAPS & NAPS by slight increase in PHT Flow.
No. of Channels in reactor	306	306	306	390	
Pressure Tube					
i) Dia	82.55 mm	82.55 mm	82.55 mm	103.4 mm	
ii) Thickness	3.94 mm	4.01 mm	3.33 mm	4.1 mm	
iii) Material	Zr - 2	Zr - 2	Zr-Nb cold worked	Zr-Nb Cold worked	
Coolant					
i) Inlet Temp	249°C	249°C	249°C	249°C	
ii) Outlet Temp	293°C	293°C	293°C	293°C	
iii) Inlet Pr.	102.5 kg/cm^2	102.5 kg/cm^2	102.5 kg/cm^2	102.5 kg/cm^2	
Max. Channel Power MW	2.75	3	3	5.125	
Type of Fuel Bundle	Wire Wrap	Wire Wrap	Split Wart	Split Wart	

TABLE-1 (contd.)

Parameter	RAPS 1 & 2	MAPS 1 & 2	NAPS 1 & 2	Proposed 500 MWe	Remarks
Steam Conditions at Turbine Inlet	41 kg/cm^2	41 kg/cm^2	41 kg/cm^2	41 kg/cm^2	
	0.26% wet	0.26% wet	0.26% wet	0.26% wet	
Containment Features					
i) Types of containment	Single Wall	Double Wall for cylindrial portion only	Total double wall	Total double wall	
ii) Accident pressure-kg/cm^2	0.422	1.16	1.2	0.9	Dousing Tank for RAPS 1 & 2; Vapour suppression for others
iii) Accident Temperature	71°C	32.2°C	120°C	112°C	
iv) Test Pressure kg/cm^2	0.527	1.45	1.45	1.035	
v) Allowed Leakage Rate	0.1% of contained volume per hour	0.015% of contained volume per hour	.002% contained volume per day	...	



REACTOR COMPONENTS GENERAL ARR'GT. FOR RAPP/MAPP

FIG. 1.

MAPP
REACTOR BUILDING SECTION LOOKING NORTH

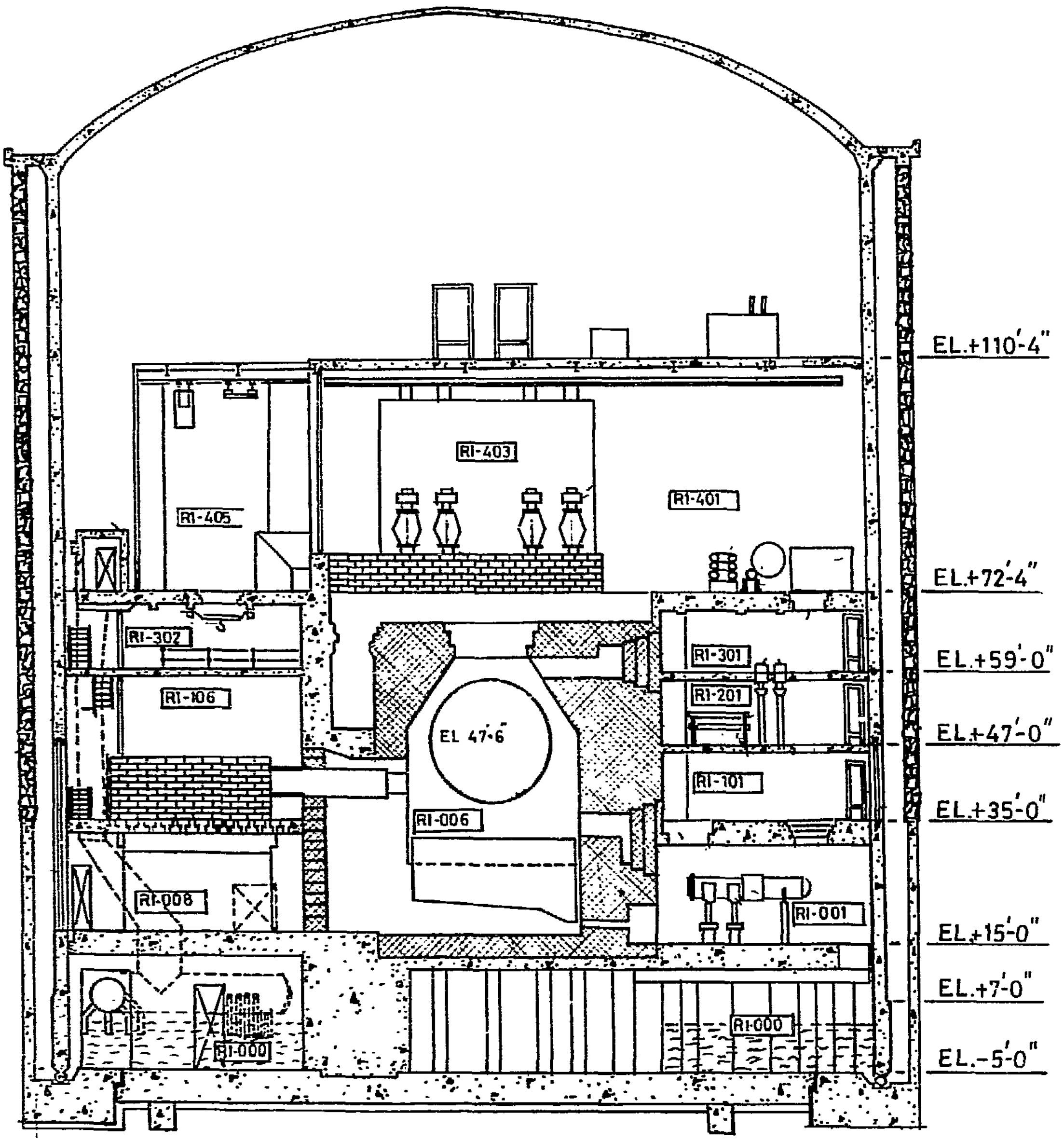


FIG -2

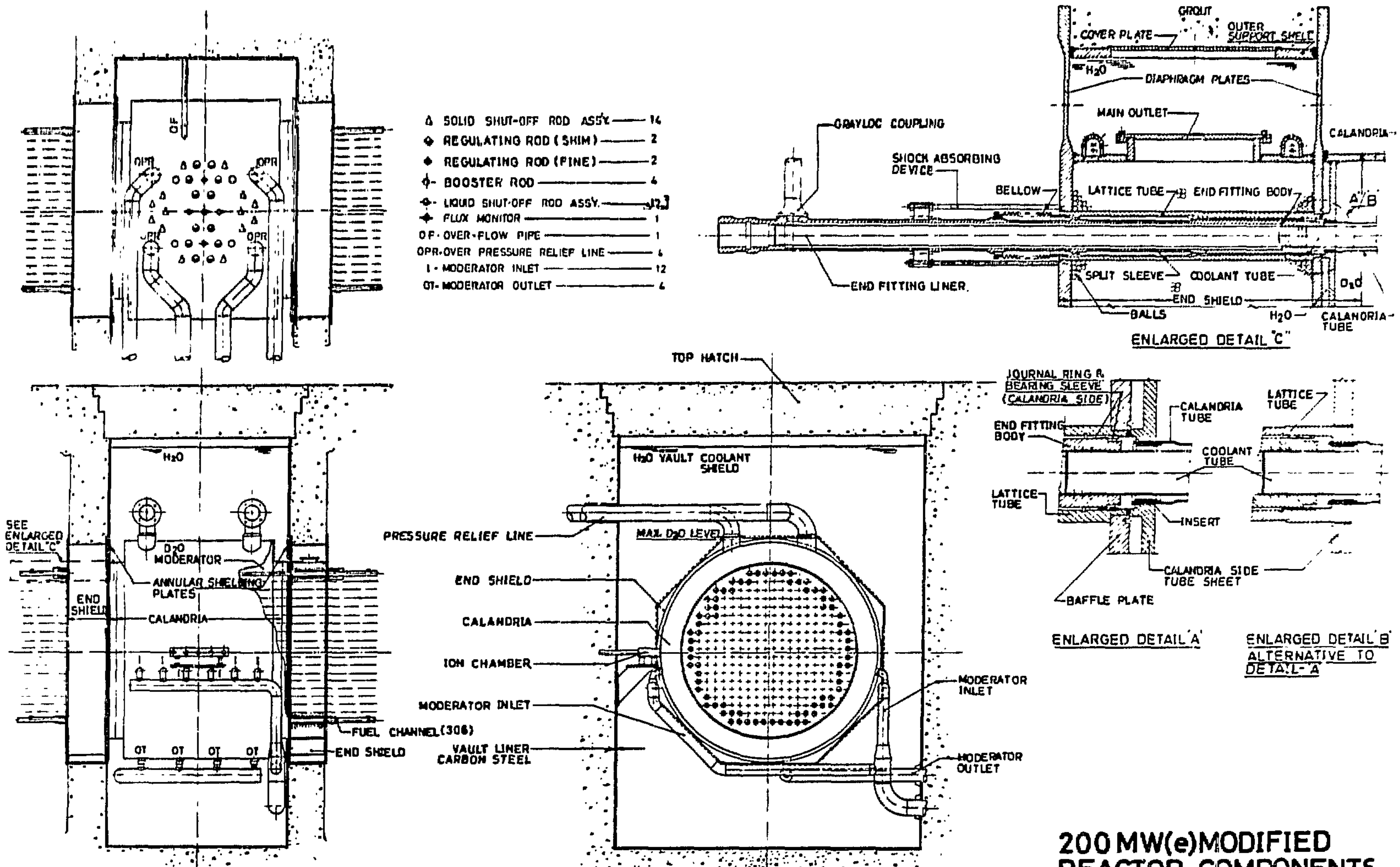


FIG. 3 NARORA ATOMIC POWER PROJECT
REACTOR COMPONENTS GENERAL ARR'GT.

200 MW(e) MODIFIED REACTOR COMPONENTS GENERAL ARR'GT.

SKETCH NO-