Bulletin of Radiation Protection, Vol. 9, No. 4, Oct.-Dec. 1986

PRESSURISED HEAVY WATER REACTOR — A REVIEW IN THE LIGHT OF CHERNOBYL ACCIDENT

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ABSTRACT: The inherent safety features of pressurised heavy water reactors are reviewed in the light of Chernobyl incident.

Nuclear power is perhaps the only long term answer for meeting the bulk electricity generation needs for overall industrial and economic growth in the energy hungry developing world. In the Indian context this is even more important. The development plans that are being implemented require electrical power as an essential input. The experience over past many years has been one of power shortages and as such there is need to tap all available power sources which can cater to the bulk electricity production. In the long run nuclear power would have to play even more dominant role as fossil fuel are expected to run down. If we keep in mind the role of nuclear energy as major source in future, we must start developing nuclear power with a view to be able to reach a level of production commensurate with the expected capacity of the primary source of energy in good time.

As is well known, we have chosen pressurised heavy water reactors of pressure tube type construction as the main reactor system for the first stage of our nuclear power programme. While four reactors of this type are already operational, a number of them are under construction and work is also in progress for construction of the larger 500 MWe units. This reactor system has been chosen from the point of view of our ability to achieve self-reliance not only in the manufacture and construction of reactor system but also in all aspect of fuel cycle and special materials required for the reactor system. That this decision was a right one, has been aptly demonstrated by the fact that almost entire reactor plant and its fuel cycle is indigenised.

Track record of nuclear power, both from the point of view of performance as well as safety has been generally excellent. Incidents like the ones at Chernobyl-4 and TMI-2 have however lead to considerable psychological impact which has to be taken into account in addition to the required review of individual reactor system from safety view point and also from the point of view of risk benefit analysis for this important source of power. We must keep in mind that nuclear power is perhaps the only source of bulk power with minimum environmental impact.

This article is an attempt to review our pHWR system and its safety characteristics in this context.

The Pressurised Heavy Water Reactor consists of a reactor calandria which contains heavy water moderator at low pressure and low temperature (Fig. 1). A large number of tubes penetrate the calandria horizontally. These tubes contain natural uranium oxide fuel bundles. The heat generated in these fuel bundles due to nuclear fission is removed by heavy water coolant which flows over

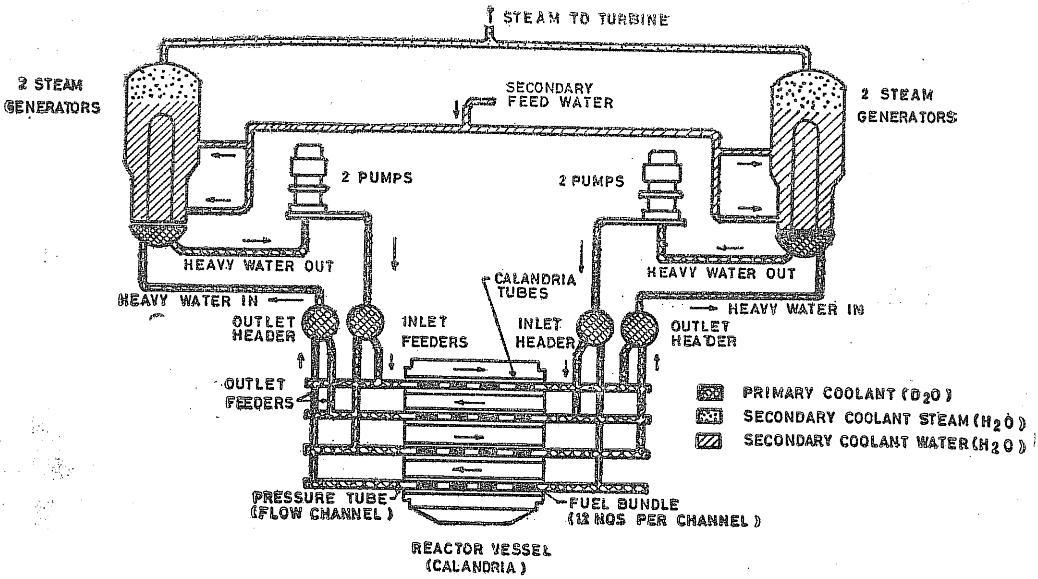

FIG. 1. NAPP REACTOR PRIMARY HEAT TRANSPORT SYSTEM

these bundles in the pressure tube. This heat is carried to steam generators where it is transferred to water for raising steam which drives the turbo-generator for generation of electricity. The control of the reactor is done by movement of neutron absorbing elements which are located vertically in the calandria. For reactors at Rajasthan and Madras — shutdown of the reactor is accomplished by dumping moderator from calandria into a dump tank placed below the calandria. For reactors from Narora onwards shut-down is achieved by two independent fast acting shut-down systems in the form of mechanical shut-off rods and liquid poison tubes located vertically in the calandria.

The reactor is housed in a thick shielded vault. A structurally strong containment building houses the reactor vault as well as the entire primary heat transport system which circulates pressurised heavy water through the reactor for the purpose of transport of heat from the reactor to steam generator. Number of barriers in the form of sheathing of nuclear fuel element, pressure tight boundary of primary heat transport system and the containment provide successive barriers against the release of radioactivity to outside the reactor plant.

In addition to the cooling of the reactor provided by the primary heat transport system, redundant cooling systems in the form of natural circulation in the primary heat transport loop, shut down cooling system through independent shut down cooling pumps and heat exchangers are available to cool the reactor core during the shut down. Additional provisions to bring in external cooling water in case of an accident involving loss of coolant from the primary circuit are also provided in these reactor systems. One major advantage of low temperature moderator within the reactor core is its capability as an alternate heat sink in emergency conditions.

It can thus be seen that the reactor system, has built in defence in depth mechanisms in mitigating various possible abnormal situations which could take it outside its normal operating domain. It is these set of possible redundant safety provisions which make the reactor system much safer than other systems.

ACCIDENTS AT CHERNOBYL AND TMI.

Accidents at Chernobyl and TMI represent two major events with power reactors which have led to review of safety of nuclear reactors all over the world.

The TMI accident was caused by partial loss of coolant conditions caused by stuck open relief valve while the heat removal got obstructed due to failure of feed water supply. The blocks installed on the emergency feed water supply during an earlier maintenance were left in place inadvertently and operator had difficulty in correctly diagnosing the system behaviour particularly the response of pressuriser. The result was a growth of hydrogen gas bubble in the reactor pressure vessel on account of metal water reaction caused by over heating of fuel which in turn bared a good portion of core and made core cooling difficult. The gas bubble had to be slowly dissolved out in absence of any other means. Although some active water was released through over flow of liquid waste sumps, some noble gases were released in a controlled manner, and there has been considerable damage to the reactor plant, the exposure of members of public as well as plant personnel has been well within normally per missible levels. There was however considerable psychological impact and a number of additional safety measures have been incorporated in reactor plants world over based on the reviews carried out in light of TMI accident.

The Chernobyl accident was caused by a series of human failures. A reactivity excursion took place on account of positive coefficient of the reactor core configuration at the time of the accident, while the newly fitted emergency power supply system to derive power from mechanical inertia of coasting down turbine rotor, was being tested out. The excessive energy deposited on the fuel led to steam explosion exposing the hot graphite to steam and water. The damage to the reactor and release of very large quantities of explosive gas led to global explosion leading to extensive damage of the reactor building, graphite fire and release of hot plume rising from the reactor core straight up into the atmosphere.

Significant amount of radioactivity was released into environment which could be detected in many countries even at far away distances.

A number of plant personnel were over exposed and there were some deaths (most of them being fire fighters). There were large scale evacuations. The accident was brought under control by dropping large quantities of materials on the reactor core from helicopters. The choice of materials included substances which would shut down the chain reaction, provide a CO_2 cover to quench the fire and provide shielding as well as some heat removal through use of lead. Additional measures to cool the core using liquid nitrogen were also taken.

Chernobyl is the first nuclear accident with a power reactor involving fatalities, large scale emergency actions and very serious impact on public domain. An international debate on various safety issues connected with nuclear accidents has been sparked off. It appears that the safety philosophy in design and operation of nuclear reactors would get thoroughly reviewed and new trends towards greater inherent safety would set in.

PERSPECTIVE ON RISK BENEFIT OF NUCLEAR POWER

It must be appreciated that any new technology while it brings sustantial benefits for development of society is also associated with risk of a kind different than what one is used to with regard to technology being practised in the past. In general the consequence of a single rare event associated with a new complex technology could be higher as compared to maximum possible consequence of a single event with earlier simpler technology. At the same time we must also keep in mind that through the use of reliable and redundant components, equipment and systems, possibility of such events is extremely rare. As a part of technology development, the system safety can be progressively improved particularly through the use of inherent safety features which can be brought into play. The benefits that the society gets through the use of such technology are so large that the risk per unit of benefit is orders of magnitude smaller with newer technology. It is of course necessary that implementation is done taking into account the relevant standards of safety. To illustrate this point let us take the example of transport sector. In olden times with primitive methods of transport, the maximum consequence associated with a single risk event was at a very small level although the number of such events could be very large. With the advent of better means of transport such as automobile, railway, aviation etc. although the number of fatilities in a single worst case event could be much larger, the overall risk through such events is much smaller particularly when we consider the probability of fatal risks in the context of large passenger traffic handled. The point therefore is that we must keep in mind the risk that a nuclear power plant poses to us in comparison with the benefits that the plant would bring to the society. A number of studies done in the past have clearly demonstrated that nuclear power plants are far safer than most of the other sectors of developmental activity.

The arguments made above may appear difficult to digest as far as common man is concerned in the light of major events like those at TMI-2 and Chernobyl-4. If one examines the attitudes in some depth, it would be apparent that the problem of acceptance of nuclear power is more psychological in nature. The risk posed by most other industrial developments have at least some fraction in a form which human beings can sense or see it happening in the environment. However, when one hears that the release of radioactivity has been to a certain level, it is extremely difficult for common man to perceive the impact on him as well as on the environment and an inevitable comparison with effects of exposure to extremely high levels of radiation of a large number of people which happened in events like Hiroshima and Nagasaki takes place. It is this fear of unknown that perhaps is an important contributor working against acceptance of nuclear power.

SAFETY CHARACTERISTICS OF PHWR SYSTEM

We should, therefore, examine PHWR not only from the point of view of its behaviour under operating and accident conditions envisaged while carrying out the design but also under conditions which are beyond design basis although the probability or occurance of such event may be so low that such events are considered incredible. If we are able to demonstrate that in a worst case situation the maximum danger to the surroundings will not exceed a level far smaller than what one saw say at Chernobyl — may be it would help in the meeting public acceptance of nuclear power. The purpose of following paragraphs is to bring out these aspects in a qualitative manner by comparing the inherent system details and characteristics of PHWR with respect to those of reactors at Chernobyl.

It is to be noted that there are considerable differences in terms of both design philosophy as well as in system details between different reactor systems. A comparison of two reactor systems in detail could therefore be unrealistic. However, a review of overall safety features as well as likely consequences in case of some extreme upper bound conditions is considered worth while.

The three most important safety requirements that need to be satisfied by any reactor system are :

(a) Capability should exist at all times to shut down the reactor safely and to maintain it in safe shut down state.

(b) Cooling of reactor core should be assured at all times to maintain fuel temperatures within safe limits to prevent or minimise damage to nuclear fuel.

(c) Escape of radioactivity and exposure of plant personnel as well as members of public should be kept at lowest possible acceptable levels.

Some of the basic safety characteristics in case of PHWR are as follows :

(1) Existence of two diverse fast acting shut-down systems to overcome any undesirable transients independently.

(2) Existence of large quantities of noninflammable and cool moderator right within the reactor core which can provide significant heat sink to limit the maximum possible fuel temperature in an accident, even if there is failure of emergency core cooling system.

(3) Location of shut-down devices in low pressure environment precluding possibilities of accidents that can be caused on account of ejection of absorber material due to high pressure.

(4) Absence of positive void co-efficient during normal operation of the reactor.

(5) Availability of double containment around the reactor and its primary heat transport systems which would protect environment and surrounding population from any accident that might be caused in the reactor.

(6) Limit on excess reactivity in the core. This is feasible on account of on-load refuelling feature of PHWR system.

All these above features are distinct advantages of PHWR system over other reactor types in making PHWR system safer. The safety review of this system has been an on-going process. Criteria for release of radioactivity in case of an accident were established at very early stage in our programme. These criteria, which have been more stringent than many other countries necessitated a very close look at the containment system. The reliability as well as leak tight ness of the containment system has been improved through the adoption of double containment system with a vapour suppression pool for management of energy released into the containment and thus limitation of maximum pressure seen by the containment building. The vapour suppression pool system is a totally passive system and does not depend on operation of any active components like valves in case of dousing spray system. The scheme can therefore be expected to be far more reliable. With this system, visibility in the accessible areas within the containment during an accident is not impaired and escape of personnel out of containment is easier. Further there are no problems likely to be caused by submergence of safety related items consequent to dousing. Siting criterion adopted by us ensure an exclusion radius of 1.6 km. There are also further stipulations for sterilised zone and also on the population within a specified distance around the plant.

Another important safety characteristics of pHWR of the type being constructed by us is the existence of non-flammable heat sink right inside the reactor core in the form of low temperature heavy water moderator. This provides significant capacity to absorb heat quite diverse from the other dedicated heat removal systems. Thus even under conditions of a total failure of dedicated heat removal system like the emergency core cooling system, the temperature in the core can be prevented from rising beyond a threshold as long as alternate capability to cool the moderator is available. A limitation on the maximum temperature inside the core also means a correspondingly less maximum metal water reaction and hence the rate of hydrogen gas generation. This also means a limitation on the maximum damage caused on the fuel cladding and also the release of fission products from the feul.

Release of hydrogen as a result of metal water reaction poses risk in two ways. In case the proportion of hydrogen and air exceeds a threshold, there is a possibility of hydrogen burning or exploding depending on the gas concentration. Further trappping of hydrogen (which is non-condensible) in the primary heat transport circuit may pose obstruction to flow of coolant and thus inhibit core cooling.

A tube type pHWR also has the inherent advantage of limitation of maximum size of hydrogen gas bubble within the primary heat transport system to the maximum diameter of the piping which is small. Any further growth in the accumulated gas bubble can only take place along the length of the piping. A configuration like this is relatively easily displaced by pressure application at suitable points and hence the size of undissolved gas bubble that cannot be physically displaced within the primary heat transport system and can be displaced only by gradual disolution is negligibly small.

Provision of two diverse shut down systems each having full shut down capability is yet another advantage of pHWR system. Further these systems are located in low pressure moderator and hence have inherent safety against accidents involving fast ejection of absorber material consequent to some structural failure. One of the shut down systems is based on injection of liquid poison for shutting down the reactor. The concept is relatively insensitive to deformations that can be caused due to events like internal rupture inside the calandria or external loads like earthquake and would have the capability to insert negative reactivity inspite of damage inside the calandria.

Two very important characteristics observed during Chernobyl accident have been

(i) Fast release of very large amounts of energy through a reactivity excursion: It has been estimated that the energy release took reactor power spike to a value as high as 100 times full power.

(ii) Release of very large amounts of explosive gas in a very short time and large scale damage to super structure consequent to a global explosion.

Review of pHWR in terms both these characteristics reveals the following:

(i) Various possible scenarios which can cause reactivity excursion have been examined and it appears that under equillibrium conditions the maximum possible power spike is restricted to only around 6-7 times the full power using conservative assumption and postulating an incredible, simultaneous failure of emergency core cooling system and shut down system following a worst case LOCA. In case of a fresh core the corresponding power spike could be higher (about 30 times) but this does not have significant relevance to impact in public domain as the inventory of radioactivity within the core is missing.

(ii) The only mechanism which can release explosive gas in pHWR is metal water reaction between zircalloy and steam. In Chernobyl, an additional contributor was graphite steam reaction. Even if one were to assume a 100% reaction between the available inventory of zircalloy fuel cladding and steam, the emerging hydrogen gas can not take the proportion of hydrogen-air/mixture in the containment to a threshold where a global explosion can occur. This is on account of the much larger containment volume in our case as compared to most other reactor systems. As indicated earlier, the inherent heat sink provided by moderator system ensures that maximum temperatures even in a worst case incredible accident would be restricted and thus providing an inherent limitation to the maximum possible metal water reaction.

It is thus clear that pHWR can neither sustain energy release of the kind that took place at Chernobyl nor can lead to a global damage of the containment on account of a global explosion. Thus both the driving force to drive the inventory of radioactivity out of the core is smaller and the barriers to prevent escape of large scale activity to the surroundings are more dependable.

The question of potential for fire hazard and its consequences, possibilities of problems due to human errors are under constant review and would have to be reviewed in detail again in the light of recent accident. The Chernobyl event is reportedly caused by multiple human errors. These kind of possibilities and the whole question of man-machine inter-action needs to be reviewed and all associated aspects such as operator training, positive prevention of operator intervention in automatic reactor protection systems, balanced information to operator regarding the reactor status, proper design and layout of control room and other operator areas, etc. have to be thoroughly re-examined for possible improvements. Issues connected in the station black out as well as multiple ground fault conditions have also to be examined in detail. Further a more exhaustive probabilistic safety analysis of our reactor systems needs to be carried out to identify weak links with a view to strengthen them.

Finally the question of emergency preparedness at power station sites would also have to be reviewed again. Emergency plans for handling emergencies already exist. These will be reviewed in light of the Chernobyl accident. For this purpose all possible accident situations beyond design basis accident are being reviewed against to evaluate their possible impact in public domain and the existing emergency preparedness plans would have to be checked for their adequacy.

There is also a need for enhanced safety research to better understand all phenomena that are involved in various accident situations in more quantitative terms. We should also be searching for additional inherent safety features which could be brought into play to assure even greater safety.

In conclusion, it appears that consistent with the tradition of continuing safety review of our nuclear programme, while detailed review would be made of our power reactors. there are a number of inherent safety features in Pressurised Heavy Water Reactors which are the main stay of our power programme and hence the worst case accident would be less severe than the Chernobyl accident. Further the design configuration of our reactors make such situations far less probable. This however, is no justification for any complacent attitude. The lessons arising out of the Chernobyl accident must be learnt and improvements effected as necessary.