PASSIVE SYSTEMS FOR LIGHT WATER REACTORS

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Abstract

The paper reviews the most original concepts that have been considered in Italy for the back-fitting of the nuclear power plants in order to reduce the probability and the importance of the release to the environment in case of a core melt. With reference either to BWR or PWR, passive concepts have been considered for back-fitting in the following areas:

- pump seals damage prevention and ECCS passive operation
- reactor passive depressurisation
- molten reactor core passive cooling
- metal containment passive water cooling throught a water tank located at high level
- containment isolation improvement through a sealing system
- containment leaks control and limitation of environmental release.

In addition some considerations will be made on the protection against external events introduced from the beginning on the PUN design either on building and equipment lay-out either on structure design.

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1. Introduction

Since a few years, there has been a growing attention in the italian society about the quality of the environment and, more generally, of the life, that leads on one side to a generalized request for an increased health protection and, on the other side, to a more direct involvement of the population in the decisions about land usage.

The strongest expression of this attitude has been the national referendum on some aspects of the nuclear energy utilization, that led in the last months to the political decision of cancelling the plants under construction, i.e. Montalto di Castro (2 BWR units) and Po 1 (2 PWR units) and abandoning the Unified Nuclear Project (PUN) based on the current PWR technology.

This situation enhanced the already existing attention of both the utility and the plant vendor towards those design improvements susceptible of reducing both the probability and the importance of the release of a severe accident, that is considered the major concern of the public opinion in Italy. A certain number of studies have been performed particularly to investigate the feasibility of passive systems, that appear to have a significant potential in dealing with degraded scenarios, as they do not rely on supporting systems to accomplish their function and then should be less prone to common failures.

In particular, passive systems both for the residual heat removal function and the containment function are presented in the following.

The other critical safety function, the reactor shutdown, is already achieved in the present reactors by making large use of inherent characteristics (negative reactivity coefficients) and passive features (e.g. gravity driven control rods) and then it appears as less critical to be improved in the context of backfitting.

In addition, some considerations are presented on a specific design area where passive features can give a significant contribution, i.e. the protection against man-induced special external events.

Finally, it must be noted that these studies are currently continued in the frame of the national program that has been established to investigate and develop, in an international contest, reactor designs with increased inherent and passive safety, that could become in a future of interest for Italy.

2. Residual heat removal

Residual heat removal after an accident is accomplished by the Emergency Core Cooling Systems, that in the current LWR designs are designed with a high and a low pressure injection stage. Low pressure stage can be replaced, when looking for passivization, by gravity driven flooding, provided that sufficient amount of water is available at high elevation, as was the case for Montalto Mark 3 BWR, that encompasses fuel transfer pools well above the core level (of course, it is not sufficient to inject water but it is also necessary to remove heat: but this is strictly linked to the containment design and so we will deal with it later on).

To substitute high pressure injection with passive system is a much more complex task, because of the wide variety of small breaks that must be considered and the phisical constraints that exist. In the advanced passive new designs this task is faced by providing high pressure make up tanks (PWR) or isolation condensers (BWR) in conjunction with very effective depressurization systems, that allow for a timely injection from the low pressure subsystems.

A similar but simplified approach has been studied for the PUN plant upgrading. In this case, instead of a passivization of the ECCS, we investigated the possibility of a passive "back-up" to the ECCS, aimed to provide a last defence against core meltdown should the original ECCS fail. The system, shown in fig. 1, basically consists of borated water accumulators at intermediate pressure and a borated water pool at containment pressure, that deliver to the Reactor Coolant System through existing connections, in conjunction with the actuation of a two stages depressurization System.

The first depressurization stage is actuated on a signal of inadequate core cooling; the discharge capacity requested to match the accumulator intervenction is comparable with the existing discharge capacity of the Pressurizez Relief System (4" equivalent diameter). The second stage, located on the RHR suction pipe, is actuated on both inadequate core cooling and low pressure signals and has a discharge capacity sufficient to depressurize the RCS to the containment pressure (12" equivalent diameter), thus allowing the pool water to enter the core.

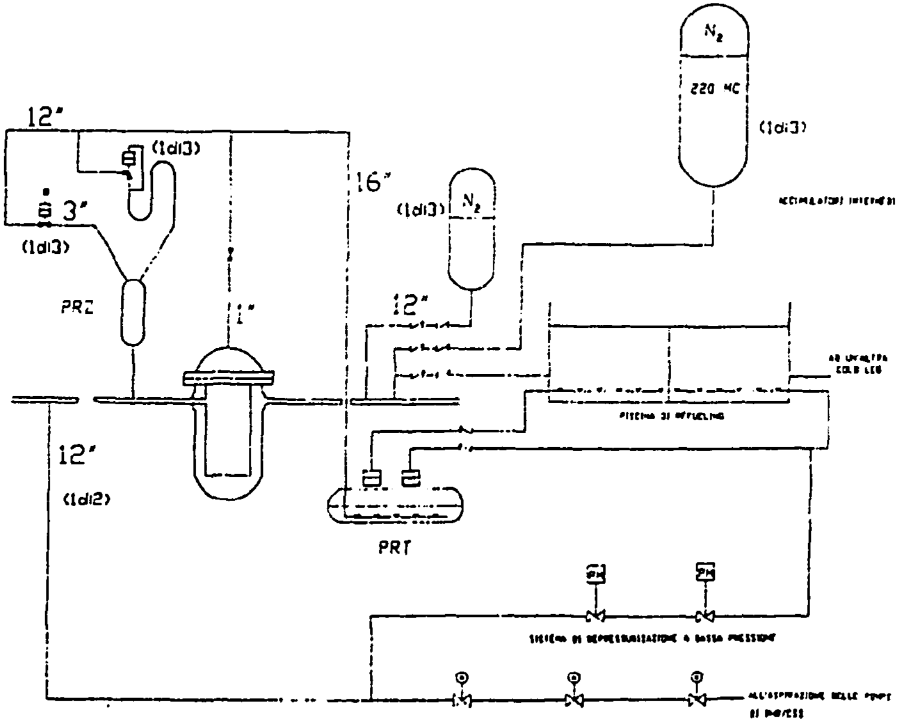


FIG. 1 – PUN PLANT : ECCS UPGRADING

The accumulator is sized to deliver just the flow rate needed to remove the decay power from the time of the intervention for a period of ten hours.

The above allowed for reducing to the minimum the accumulator volume.

3. Reactor Cavity Design

A special problem of decay heat removal is the cooling of molten reactor core material, once expelled from the vessel to the containment.

An event of core meetdown has a very low probability (about 10^{-6} ev/yr) in the current updated LWR designs (and some further benefits can likely derive from the adoption of passive safety features).

Nevertheless, the threat that such an event might constitute for the environment is so high that, in our opinion, it is necessary to provide, even for this scenario, a sound demontration that the associated releases will be limited.

To achieve this goal, both decay heat removal and containment functions must be accomplished satisfactorily.

The reactor cavity design is, in this respect, the critical point.

For the Montalto di Castro Nuclear Power Plant (2 x 1000 Mw_e BWR units) modifications of the *Reactor Cavity were proposed*, to be backfitted on the plant with the minimum possible impact on construction schedule.

Due to the small geometrical dimensions of the cavity the proposed design was based on:

- preventing the contact between the molten material ejected from the vessel and the structural concrete in the cavity; the above could be obtained by providing a heat resistant container (crucible) capable to collect the molten material
- allowing circulation of cooling water, externally to the crucible, through suitable flow paths between crucible bottom and lateral walls and the concrete
- providing additional heat transfer surfaces for heat rejection (also to externally flowing cooling water), by designing "chimney type" flow paths suitably distributed in the crucible volume
- providing connections from existing water reserves to the cavity region.

A tentative definition of the geometry of the crucible as well as preliminary estimates of the cooling flow requirements and of the effectiveness of heat transfer mechanisms to control the melt temperature have been done. A schematic of the proposed cavity for Alto Lazio is shown in figure 2.

For plants not yet in the construction stage, for which therefore no major constraints come from existing civil structures, the reactor cavity design can be furtherly improved to prevent phenomena which can pose a threat to containment integrity, or to the component support structures, like:

(i) molten fuel-coolant interactions

(ii) core debris concrete interaction

(high pressure melt ejection and hydrogen control are attained with provisions other than cavity design).

There is still no evidence that molten fuel-coolant interactions have the potential to pose a real threat to the containment, and perhaps they don't. However, interaction of large quantities of molten material with large quantities of water can be prevented by designing suitable structures capable to avoid water, discharged from any postulated break in the reactor coolant system piping, from reaching the cavity via paths external to the vessel itself. Moreover, water flows to the cavity via paths internal to the vessel immediately after vessel failure, should be limited.

Interaction of core debris with concrete can be avoided if the molten material is trapped, quenched and held in a long-term coolable geometry. Trapping and quenching of the molten material can be attained by use of a suitable dry gravel bed in the cavity, sized to provide a large surface area with high heat capacity. Long term cooling can then be attained by means of a controlled water flow to the cavity.

The above mitigation concepts have been already envisaged for the PUN plant (see figure 3) and are currently further investigated for simplified advanced passive LWR.

Present activities include feasibility of structures capable to guarantee a dry cavity at the time the melt falls, preliminary sizing of the gravel bed and of the vent paths to limit structural loods in the cavity region as well as sizing of the lines needed to provide water flows to the cavity sufficient for stable post-quenching and long term cooling.

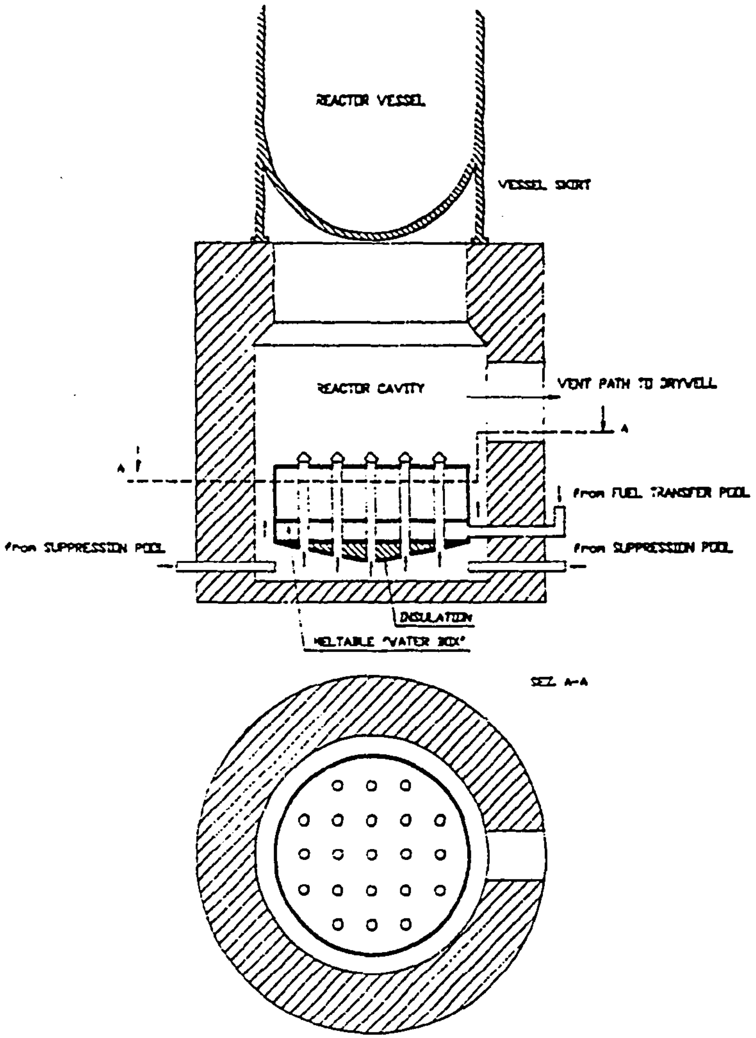


FIG. 2 - MONTALTO PLANT : REACTOR CAVITY

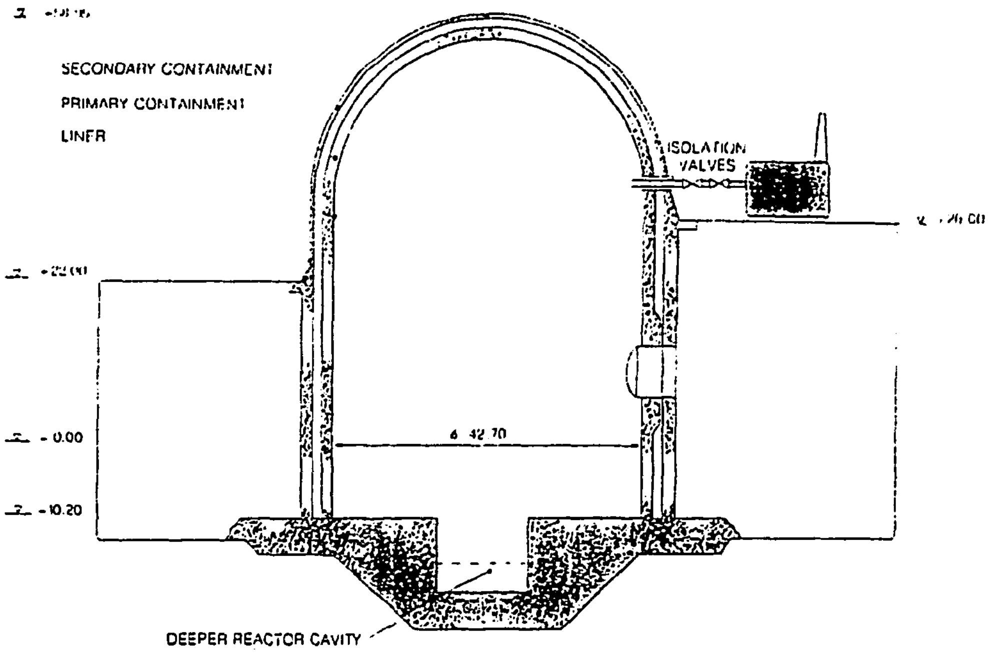


FIG. 3 - PUN PLANT : CONCEPTUAL SOLUTION FOR PASSIVE MITIGATION

4. Containment

It is easy to recognize in a containment system, as designed in current LWR, some passive features, e.g. the containment structure itself.
However, to reach the goal of assuring the function of radioactive release limitation in a passive way it is necessary to coherently design also those systems that support the containment structure.
The most relevant support function, in this respect, is the containment cooling, since a failure to remove heat generated inside the containment leads to the structural collapse and then to unlimited releases.
A very interesting possibility in this respect is the utilization of metallic containment walls as heat transfer surfaces.
Such a possibility (envisaged in many new passive plant designs) was studied in Italy for the Montalto di Castro plant, that was equipped with a metallic primary containment and a concrete secondary containment.
The design modification envisages a separation in two parts of the annulus between the two containments: a lower part, where all the penetrations are located, that is maintained sealed to recover primary containment leaks, and an upper part, open to the atmosphere through a "chimmey" on top of the secondary containment.
Water is sprayed on the metallic containment head to enhance heat transfer: a flow rate of 400 m^3/hr was adequate to remove the decay heat ten hours after the reactor shut down.
A water inventory was provided at high elevation to allow for a limited autonomy before the intervention of external water sources (e.g. firemen).
Such a design change was adequate to ensure a 24 hr grace period under any circumstance, including core melt down sequences, without significant releases from the containment.

Another relevant containment support function is containment isolation.
The actuation logics are in general quite simple and can be made highly reliable: the required power (limited by the "fail safe" approach) can be easily supplied by batteries.
However, to meet stringent requirements on radioactive releases, leaks through containment penetrations, even with an operating containment system, can be a serious problem, when managing severe accident source terms. Such leaks can be effectively limited through a sealing system, like the one proposed for the PUN Plant.
Such a system injects proper fluid (water or air) at pressure higher than containment pressure between the seats of parallel slide gate valves acting as containment isolation valves (see fig. 4). The fluid is provided by pressurized tanks located both inside and outside the containment (the tank inside serves the inner isolation valves).
The tank volume is adquate to make up the leaks for a few days.
In the case of the PUN plant, addition of such a sealing system only on lines of 6" and greater, as well as on presonnel airlocks, gives a benefit of about 67% in primary containment leakage reduction.

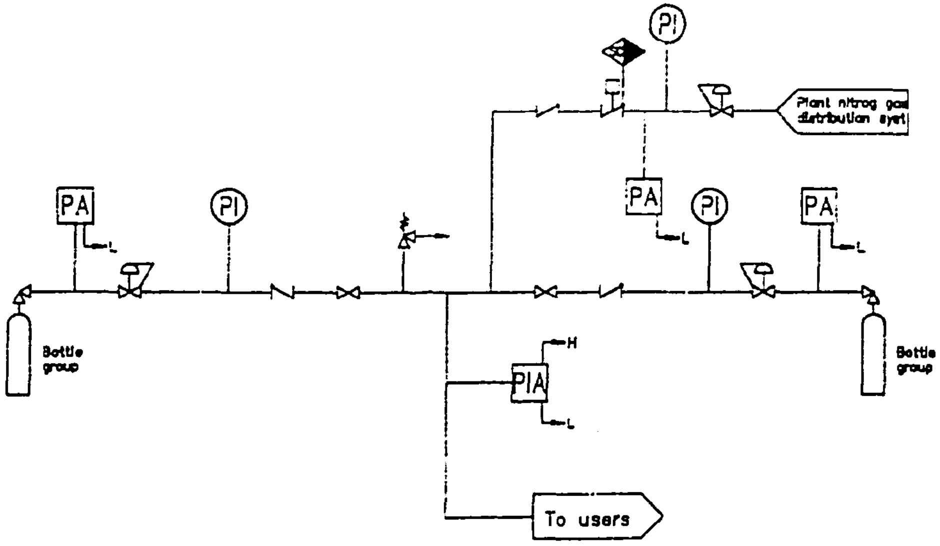


FIG. 4 - PUNT PLANT : CONTAINMENT SEALING SYSTEM (GASEOUS)

Furthermore, a study is presently conducted on a system operated only by D-C power, able to collect and filter any primary containment leak.

The system acts to maintain a slight negative pressure in those areas where leaks from the primary containment can be collected.

Such areas include the penetration rooms as well as rooms where essential systems needed for post-accident plant recovery are located.

The system consists of fans, HEPA filters and charcoal beds and discharges through a stocks : this guarantees for a further benefit in terms of doses.

5. Special External Events

Protection against man-induced special external events, and specifically against aircraft impact, is a field where a "passive approach" is particularly beneficial.

In the design of the italian plants, the following criteria were adopted in defining the plant layout and the building structure geometry, in order to provide adequate protection against direct impacts and to neutralize or limit the dynamic effects on safety relevant components :

A) These components are located in an area that is protected against the missile penetration by a barrier composed of a series of walls and floors adequate in number and thickness.

As a practical rule, according to the analysis of Schmidt and Heckhausen (rif. SMIRT 82 Sect. J), two ductile floors, 50 mm thick, are able to absorb the kinetic energy associated to a Phantom jet with an impact velocity of about 200 m/sec. For the italian plants, a concrete structure of 1.20 m thickness has been considered adequate to stop the missile penetration.

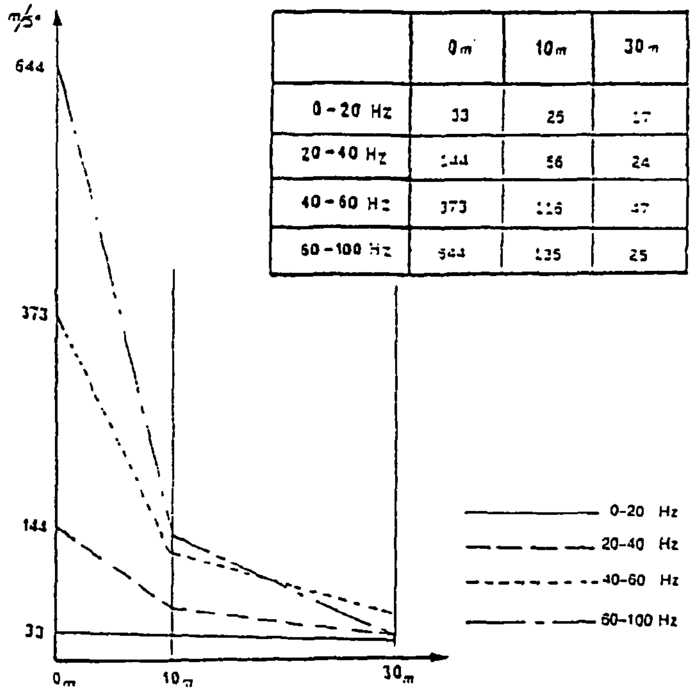
B) The structure geometries are defined in such a way to maximize the attenuation of the dynamic structural response.

As an example, for Montalto di Castro the original thorispherical shape of the containment dome has been modified to hemispherical in order to limit the vertical impact loads transferred along the containment wall to the mat and then to the component support structures.

C) The safety relevant components are preferably located in areas far enough from the assumed impact points, where the response attenuation (expecially the medium-high frequency acceleration components) is such that impact loads are comparable with seismic loads.

In no case a direct attachment of safety relevant component supports is allowed to the inside surface of peripherical walls or roofs where a direct impact can be assumed.

Fig. 5 show the results for a given horizontal impact of a sensitivity study performed by ISMES : the peak values of the acceleration response spectra at 2% structural damping in the frequency range 0-100 Hz are given.



	0 m	10 m	30 m
0 - 20 Hz	33	25	17
20 - 40 Hz	144	56	24
40 - 60 Hz	373	116	47
60 - 100 Hz	644	135	25

FIG. 5 - PUN PLANT : IMPACT ATTENUATION

As a general criteria, it can be assumed that for current structures at a distance of about 20 m, the impact dynamic effects can be suitably covered by the component seismic verification.

When such attenuation with distance cannot be applied (e.g. for layout constraints) dynamic isolation features are adopted to support relevant components.

6. Conclusions

The social situation in Italy requires a new approach to the design of nuclear reactors, based on a set of objectives and general requirements constituting a "step forward" in quality, which must be real and understandable.

It must be real in the sense that it allows for a limitation in radiological consequences in any possible accident scenario.

It must be understandable in the sense that it increases the confidence with the evaluation of residual risk associated with the plant, both in the engineers and in the population.

To reach this last objective, it is worthy to try to reduce or to remove the main reasons for this limited confidence, such as :

- the operator errors, including those external factors that can influence the operators (e.g. the need for operator action in a short term);
- the mistakes in the detailed design, the construction and the maintenance of very complex safety systems;
- the difficult experimental investigation of some phenomena.

From these points of view, the adoption of systems relying on inherent safety characteristics or on passive features should help in increasing the overall confidence in the high safety level reached by the nuclear power plants.

PASSIVE DECAY HEAT REMOVAL BY NATURAL CIRCULATION

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Abstract

The standardised 235 MWe PHWRs being built in India are the pressure tube type, heavy water moderated, heavy water cooled and natural uranium *fuelled reactors. Several Passive safety features are incorporated in these* reactors. These include: (1) Containment pressure reduction and fission product trapping with the help of suppression pool following LOCA, (2) Emergency coolant injection by means of accumulators, (3) Large heat sink provided by the low temperature moderator under accident conditions, (4) Low excess reactivity, through the use of natural uranium fuel and on power fuelling, (5) Residual heat removal by means of natural circulation, etc. of which the last item is the subject matter of this report.

1. INTRODUCTION

Pressurised Heavy Water Reactors (PHWRs) form the main stay of the first stage of the Indian nuclear Power programme. All the PHWRs in India, with the exception of those at Rajasthan Atomic Power Station (RAPS), are equipped with passive vapour suppression pool containment. During LOCA transients the suppression pool helps in removing the heat by condensing *the steam passing through and also reduce the concentration of fission* products by absorbing water soluble fission products. Condensation of steam helps in limiting the over-pressure inside the containment. The activity is also reduced by way of plateout, i.e. by surface deposition of the fission products on the structures. Experiments carried out on a model have confirmed the design functions of the containment for removal of heat and of pressure reduction. Further details of this work are available in [1]. Although, the earlier PHWRs at Rajasthan and Madras have only the low pressure emergency core cooling injection by pumps, the standardised design of PHWRs is provided with high pressure accumulators.

The primary heat transport system of a PHWR has a figure- of-eight configuration having horizontal fuel channels and vertical inverted U-tube type steam generators. The primary pumps are provided with flywheels which ensure that there is sufficient flow in the reactor core till power runs down to about 3 to 4% of the total power. At this power level, the natural circulation flow is sufficient to remove the decay heat. Previous investigations on natural circulation in Indian PHWRs were concerned with the prediction of transient behaviour of the plant during loss of off-site power [2,3]. Preliminary analysis [4] for station blackout condition indicates that adequate core cooling can be maintained by natural circulation in the primary circuit provided appropriate operator action is taken to maintain the required cooling water inventory in the secondary side of the steam generators.