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Research Article

Effect of Coolant Inventories and Parall
Interconnections on the Natural Circula
Various Heat Transport Systems of a Nu
Plant during Station Blackout

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Abstract

Provision of passive means to reactor core decay heat removal e
availability. In the earlier Indian pressurised heavy water reactors
crash cooldown from the steam generators (SGs) is resorted to m
the 700 MWe PHWR currently being designed an additional pa
incorporated to condense the steam generated in the boilers durin
the various heat transport systems (i.e., primary heat transpor
depends on the corresponding system's coolant inventories and t
and interconnections). On the primary side, the interconnection
role to sustain the natural circulation heat removal. On the secon
initial inventory in the SGs prior to cooldown, that is, hooking
attempts to open up discussions on the concept and the core i

provide continued heat sink during such accident scenarios. The di
performance of such concepts already implemented and proposes
MWe IPHWR. The designer feedbacks generated, and critical ex
added passive system to the existing generation II & III re
systems/inventories in fact perform in sustaining decay heat remo

1. Introduction to 700 MWe Pressurised Heavy Wa

In the 700 MWe PHWR, the primary coolant heavy water under
exit) the fission heat generated in the reactor core and transfers it
generators (SGs). The primary heat transport (PHT) system consi
into two identical loops. Each loop consists of two primary circula
loop configuration as shown in Figure 1. There are two passes thr
flows over the fuel bundles placed inside the channels, it picks up
core. In each pass, 98 channels are connected to a common head
from the reactor core, the coolant flows through the reactor outle
transferring heat in the SGs, the primary coolant is pumped (by
reactor core through reactor inlet header (RIH).

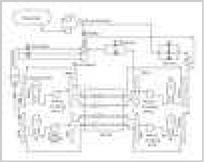


Figure 1: 700 MWe PHWR primary heat tran

The SG provides the thermal linkage between the PHT system an
in the 700 MWe reactors are of the inverted U-tube type with in
side, and the hot primary coolant from the reactor core (ROH) flo
at the top of the downcomer. The recirculation flow from the ste
down the annulus (downcomer). Then, it rises up through the
extracting the heat, the secondary fluid (steam-water mixture) ri
steam separator and dryers. Here, the two-phase mixture gets se
is led downwards, after mixing with the feed water, to the annula
steam outlet and then to the turbine.

The average of the two ROH pressures is controlled around a set
and over-pressurisation in the PHT system. In the 700 MWe P
pressuriser (surge tank) is also provided along with the Feed/Blee
feed/bleed system is provided for controlling the water level in
provided on top of the pressuriser vapor volume to control the in
heavy water steam into the bleed condenser (BC) through the PH
provided to take care of the low-pressure transient, by switchin
pressure. The hot bleed from the RIH, and the relief from the sou
BC. The BC pressure is controlled at 34 Kg/cm^2. In the event of
also start relieving heavy water steam into the BC. At 100%
temperature is 266 C, the core outlet temperature at the ROH is
3% only.

2. Experience during 220 MWe PHWR NAPS Fire I

An incident of fire in the generator at one of the units of Narora A

IV and class-III power supplies for all the plant loads such as prin
cooling pumps and main and auxiliary boiler feed pumps on se
scenario. Fire water had to be manually hooked up by going to b
secondary systems did work, and there were no fuel failures, wi
safety systems which are designed to be highly reliable. In spit
reliability, requirement of analysis and suitable provisions for bey
blackout, LOCA without ECCS actuation, and so forth, are necessar

A debate on the concepts to be adopted for nuclear power plants
several different approaches being in vogue. One approach being
that the plant design is similar to well proven design with some e
passive design. The “evolutionary” approach considers greater
features such as lower-core power density, greater RB volumes, ar
from Chernobyl, NAPS fire incident, and even recent Tsunami incid
availability of heat sink is the major issue to be addressed even
manner.

3. Passive Decay Heat Removal System (PDHRS) fo

Long term removal of decay heat is essential to avoid fuel heat up
sinks are available for various states of reactor shutdown such
accident conditions such as LOCA. During normal shutdown, initia
with steam being dumped to condenser and/or through atmosph
make up to steam generators is by main or auxiliary boiler feed pu
to room temperature is by shutdown cooling system with the heat
(APW) and subsequently to service water loop and then to atmospl

In case of station blackout, the envisaged heat sink is the p
recirculating the steam generator secondary side inventory throug

For removing the heat generated by the PHT, PDHRS is provide
steam generator inventory during station blackout scenario (see Fi
condenser inside a tank having inventory of 125 m^3 of water. Th
line taken off from the main steam line, this steam gets condensec
the condensate returns back to steam generator. During this proce
the tank inventory which would initially heat up, later starts boili
Four sets of such PDHR tanks, gets, and piping are provided one s
The stored inventory in the tank is adequate to provide decay h
inventory make up to the tank can be initiated. During the normal
envisaged by DM water connection. During the station black out sc
the firewater.

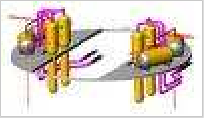


Figure 2: Layout for the four SGs and the 4

As a design practice, it is always followed that the tested PHT syst
of the earlier generation and operating power reactors are augmer
and other passive systems. It is conveniently assumed that additi
continued removal of decay heat under adverse conditions. The pe
another aspect which is very important, and it points out at the de

more than adequate coolant inventories in the primary, secondary and analysis of all the anticipated scenarios, this problem can be safety systems and coolant inventories can be achieved for the SB

It has been reported in recent literature that RELAP5/MOD3.2 is c [1 - 4]. The SG boil-off and SBO response for a PWR are des incorporation of PDHRS, its design, and modeling. Reference [7] d The present study deals with boil-off in PDHRS connected to the connection leading to depletion of heat removal in the presenc PDHRS. Such study aims at analysing all the worst possible SB accident conditions [8]. The thermal hydraulics modeling method for the present study are based on [9 - 16], though RELAP5/MO were carried out to finalize the present nodalisation, which are not

4. Modeling & Nodalisation

Primary heat transport (PHT) system model has been developed w passes through the core (see Figures 3 and 4). In each pass, 98 heat slabs are connected to the fuel in each pass of core. The fee on one side of the reactor, and on the other side the pressurise surge line. Surge line is modeled using two pipe volumes and a br pressuriser is modeled using 12 control volumes with 1.5 MW logic for pressuriser heaters has been developed based on the (SBVs) open following an increase in the PHT system pressure. T simulation of the steam generator with pressure controller, level region is simulated with 10 control volumes; the unheated riser connecting the primary and secondary systems thermally. The st downcomer model also includes 10 control volumes. The PDHR sy with all the 4 steam generators. All the steam lines up to governor and single volumes. Steady state conditions were achieved on integrated together for a plant simulation model.

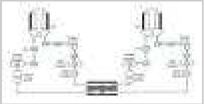


Figure 3: 700 MWe PHWR loop-1 nodalisatio

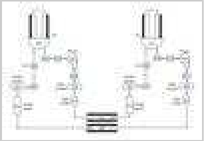


Figure 4: 700 MWe PHWR loop-2 nodalisatio

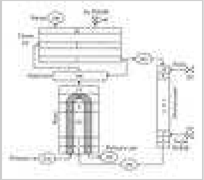
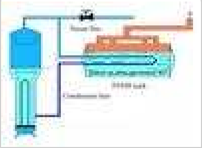


Figure 5: Steam generator nodalisation.

Figure 6: Schematic of a PDHR.



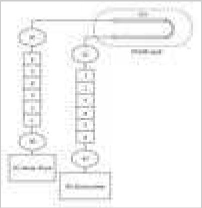


Figure 7: PDHR nodalisation.

5. Results and Discussion

SBO scenario includes the loss of all the operating pumps, that
pressurising pumps (PPPs), and all the boiler feed pumps (BFPs).
PCPs; is generated within one second. To study the effect of the
interconnections, three case studies carried out, are is, (i) effe
cooldown, (ii) effect of the steam line interconnection, and (iii) effe

5.1. Effect of Initial SG Inventory

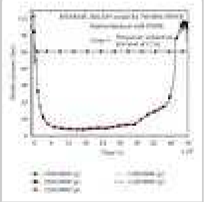
Two cases are presented in this category, that is, (a) SBO analy
analysis with no delay in valving of the PDHR. Because of the de
system), certain amount of SG inventory is lost through the ASD
inventory of the SG coolant is higher prior to the initiation of coold

5.1.1. Station Blackout Analysis with PDHR Valving in after

Station blackout was initiated by tripping all the PCPs, PPPs, and
reactor trip on no PCP available signal was delayed by one secor
delayed by one second considering the delays for rod insertions
maintained for initial six minutes with the help of atmospheric ste
steam lines, after this all the four PDHRs valves were opened to
seconds. Once the PCPs are tripped, the differential pressure acr
pressures start falling together.

Following the reactor trip and the valving in of the PDHR, the PHT
bar at $t = 508$ seconds), and the pressuriser level falls below 1.7
this, the PHT system pressure falls rapidly to 8 bar at $t = 7$
approximately up to 27000 seconds. Later on the PHT system pr
following depletion of shell side inventory in the PDHRs. It comes
seconds, it falls to 11 ton, and thereafter it remains almost const
tube bundle.

Figure 8: PHT system pressure case-6 minute



The SG pressure (see Figure 9) shows a peak of 49.3 bar at $t = 4$
due to reactor trip, it falls to 41.8 bar, at $t = 7000$ seconds, then i

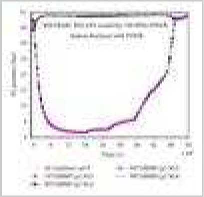


Figure 9: SG Pressure variation case-6 minute

All the four SGs are connected through the steam lines. Any PHDF
all the four SGs, but it sends back condensate only to the SG to w
the four SG pressures is very small, the SG with maximum SG
addition to the PDHRs to which it is directly connected. The retu
which was going to the corresponding PDHR (directly connect
condensate to the other SGs. This initiates an inventory transfer,
encountered during natural circulation at low pressure in the PHT
(see Figure 10) in two SGs goes down and the other two SGs,
through steam lines is observed but the total SGs inventory remai
in the four SG pressures) is the difference in the PHT flow through

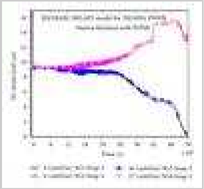


Figure 10: SG level variation case-6 minutes

The total primary core flow (see Figure 11) remains around 7
decreasing trend. The PHT system core exit quality remains low u
(also observed in the core flow), it even reaches values up to 50
back to lower values (<2%). It can be concluded that the PDHRs
during this period additional water inventories can be lined up.

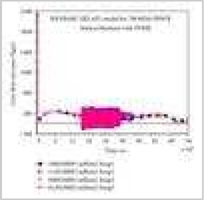


Figure 11: Core flow variation case-6 minutes

5.1.2. SBO with No Delay in Valving in of the PDHRs

In the previous station blackout case, it was assumed that the PDH present case, it is assumed that the PDHRs valves are opened with blackout at $t = 1$ second. The results obtained are similar to the e 16) but the oscillation/fluctuation in the PHT and the SG flows conditions are observed due to higher SG inventories. In the 6 mi go down from 32 ton to almost 27 ton, a loss of 5 ton throug the initial 6 minutes. For the no delay case, the ASDVs open only around 32 ton with negligible loss. As the steam lines were not i (see Figure 13). It can be concluded that valving in of the PDHR sh

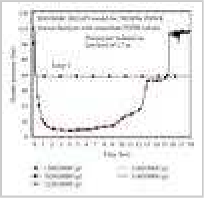


Figure 12: PHT pressure variation case-no del

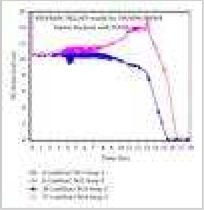


Figure 13: SG level variation case-no delay in

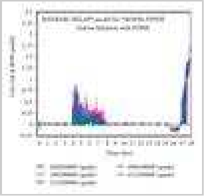


Figure 14: Core exit quality variation case-no

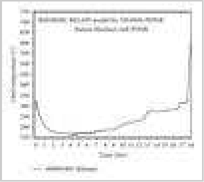


Figure 15: Clad temperature variation case-n

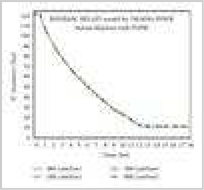


Figure 16: PDHR shell inventory variation cas

5.2. SBO with Steam Line Isolation

All the steam lines interconnections were isolated to avoid any inte available in the steam lines. Each of the SGs is connected only to are snapped.

Station Blackout Analysis with Isolation of Steam Lines

In the previous station blackout transient analysis, it was obs significantly after 30000 seconds, and in the other two SGs, it w inventory of all the four SGs constant. This was attributed to low-c at low pressure in the PHTs, SGs, and PDHR, resulting in an inven explanations, another hypothetical station blackout with complete was observed that the SG levels (see Figure 17) do not diverge ar SGs, though the levels are not exactly same, but they follow a sim other parameters, the trend is almost similar as compared to the steam lines. It can be concluded that the alternative parallel pa transfer. This leads to drying out of one SG in each loop, but the c the loop with its own inventory and the transferred coolant invent for the complete loop.

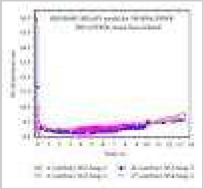


Figure 17: SG level case-steam line isolation.

5.3. 3 PDHRs with/without Primay Loop Isolation

In these cases, one PDHR connected to one of the SG in loop-1 wa heat removal from one of the bank, the primary coolant at higher pass. After some time as the two phases appear in the return pass a stagnation phase at $t > 4200$ seconds (see Figure 18). Since compared to healthy loop (cooling unaffected), there is a continuou 2 through the ROH connection though the pressuriser is isolated, b

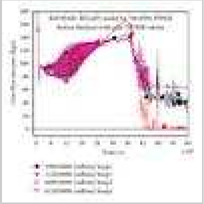


Figure 18: Core flow case-3PDHRs with no loc

To avoid this inter-loop PHT inventory transfer, a case study with carried out. With the arrest of primary inventory removal from t nonworking PDHR), the core flow (see Figure 20) through the two remains at a higher-positive value for a considerable period of t maintained. The PDHR isolation valve failure leads to the failure o cannot be neglected. Based on this study, it is highly recommen when there is an unsymmetrical mode of PDHR operation.

5.3.1. Station Blackout (SBO) Analysis with Only 3 PDHRs

In this SBO transient analysis, it is assumed that, one passive dec result only 3 PDHRs are available to cool the steam from all the and the 2 PHT loops are isolated from each other on pressuriser

PDHRs available case for the initial period, but the decay heat rem
with all PDHRs available case, the decay heat removal is not affect

For the PHT loop isolation case, the nonfunctional PDHR inventory
working PDHR, in the affected PHT loop-1, the PDHR inventory fall
PHT loop-2, with both PDHRs working, the PDHR inventory falls
hours, the affected loop clad temperature (see Figure 21) shoo
reduction and exposure of the PDHR heat exchanger tubes in the
a working PDHR, the SG-inventory falls to almost one ton within 1
does not fall to zero. For the SG in the affected PHT loop-1 with
below one ton after 5.8 hours, that is, both the SGs in the affected
SGs in healthy PHT loop-2.

This unfavorable situation is caused by inventory transfer from the
both PDHRs are operational. Steam flow from all the four SGs
pressure between these components. More steam flow goes from
PHT flow) to the PDHRs, based on the pressure, all the SGs send
steam/condensate will accumulate more inventory. This phenome
(except for the SBO without steam lines). It leads to total SG inve
the SGs of the loop with 2 PDHRs working, as a result both the
5.8 hours for the PHT loop isolation case, and the clad temperature

5.3.2. SBO Analysis with Only 3 PDHRs Available and withou

Here, only 3 PDHRs are available following SBO, and it was also
2 PHT loops, and the 2 PHT loops remain hydraulically connect
falls below 1.7 m. For this case, the primary flow reduces almos
loop, leading to an increase in clad surface temperature (see Figu
primary coolant flow (see Figure 18) in this core path is hamp
affected loop which is at higher pressure and temperature tries to
path. As the flow reduces and stagnates (see Figure 18), the core
of coolant inventory is available in the SGs and also in the PDHR
shoots up due to core flow stagnation. For the SG without PDHR w
in one hour. For the other SG in the healthy loop-2 with working
m level at about 1.5 hours. Here, also the phenomenon of SGs
healthy loop is observed, but the clad temperature shoots up far a
PHT inventory transfer from affected loop to healthy loop.

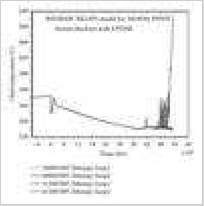


Figure 19: Clad temperature case-3PDHRs wit

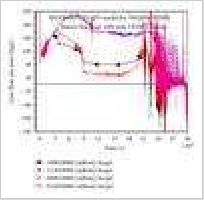


Figure 20: Core flow case-3PDHRs with loop is

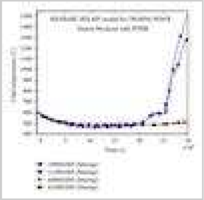


Figure 21: Clad temperature case-3PDHRs wi

The results obtained with RELAP5 model show a similar behavior [1–4]. It can be concluded that the 2 PHT loops should be isola transfer through the surge lines, which leads to stagnation of c pressure distribution. This undesirable situation is further aggrava affected loops to another loop with both PDHRs operational.

Concluding Remarks

(1) It can be concluded that the 4 PDHRs, with an initial in core decay heat without any increase in the clad temperature system, if all the 4 PDHRs are available.
(2) No delay in valving in of the PDHRs is recommended aft higher inventory in the SG leads to more stable natural ci transport system. The rate of change of primary and secondar
(3) The secondary inventory transfer from SGs in one loo interconnected steam lines. Following the SBO and cooldown driving forces in the PHT, SGs, and PDHRS, this phenomenon c
(4) For the SBO with three PDHRs available case, the PH affected loop (cooling affected due to inventory transfer to oth to pressure imbalance and parallel paths inter-connected surg two PHT system loops is helpful in mitigating the consequence loop interconnection the decay heat removal is not hampered f
(5) The designer feedbacks generated from the analysis, results for the added passive system to existing generation these safety systems/inventories in fact perform in sustaining c

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