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ANALYSIS OF DECAY HEAT REMOVAL BY NATURAL CONVECTION IN PFBR

N. KASINATHAN, G. VAIDYANATHAN,
S.C. CHETAL AND S.B. BHOJE

NUCLEAR SYSTEMS DIVISION
INDIRA GANDHI CENTRE FOR ATOMIC RESEARCH
KALPAKKAM, PIN 603 102, INDIA

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ABSTRACT

PFBR is a 500 MWe, 1200 MWt pool type LMFBR. In order to assure reliable decay heat removal, four totally independent Safety Grade Decay Heat Removal Systems (SGDHRS) which removes heat directly from the hot pool, is provided. Each of the SGDHRS comprises of a hot pool dipped decay heat exchanger (DHX), a sodium - air heat exchanger (AHX) at a suitable elevation and associated piping and circuits. This paper brings out the step by step approach that have been taken to decide on the preliminary sizing of the SGDHRS components, and static and transient analysis to assess the adequacy of the Decay Heat Removal capacity of the SGDHRS during the worst of the foreseen design basis conditions.

The maximum values the important safety related temperatures viz., clad hotspot, hot pool top surface, reactor inlet, fuel subassembly outlets etc., would reach, can be obtained only through a comprehensive transient analysis. In order to get quick and reasonably meaningful results, one dimensional thermal-hydraulics models for the core, hot and cold pools, IHX, DHX, AHX and various pipings were developed and a code DHDYN formulated. With this a total power failure situation followed by initiations of DHR half an hour later was studied and the results revealed the following: (i) clad hotspot temperature in the in-vessel stored spent fuel subassemblies could be held below 800 deg C only if primary sodium flow through these subassemblies are increased upto three times the originally allocated flow in the design, (ii) hotpool top zone temperature reaches 572 deg C, (iii) reactor inlet tempeature reaches 482 deg C, (iv) the hot pool top zone temperature cools down to 450 deg C in about 25 h. Thus these results satisfactorily established the adequacy of the sizing and the capability of the SGDHRS.

DHDYN code is also used to study the RAMONA water experiments conducted in Germany. Initial results available has brought out the conservative nature of the DHDYN predictions as compared to the experimental results.

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1. INTRODUCTION

Prototype Fast Breeder Reactor (PFBR) is a 500 MWe, 1200 MWt pool type LMFBR with four primary pumps. It has four secondary loops each being serviced by two Intermediate Heat Exchangers (IHX), a pump and three modules of straight vertical shell and tube type Steam Generators (SG) each comprising an evaporator, superheater and a reheater. The schematic of PFBR is shown in Fig 1. In order to assure reliable Decay Heat Removal (DHR) four totally independent direct reactor (hot pool) cooling loops known as Safety Grade Decay Heat Removal System (SGDHRS) is provided. The concept, design criteria, preliminary estimation of the SGDHRS capacity and some results of worst case transient analysis are brought out in the overview paper at this meeting.(1) The various details of the hot pool immersed Decay Heat Exchanger (DHX), Sodium-Air Heat Exchanger (AHX) and associated circuit pipes and air stack, damper etc., which constitute the SGDHRS were brought out in detail in one of the earlier specialists meeting held in Oarai in 1991.(2) In this paper the major features of the one dimensional thermal hydraulic models, the formulation of the DHDYN code and studies made are reported.

2. THE NEED AND OBJECTIVES OF TRANSIENT ANALYSIS

Static analysis with AHX and DHX modelled through LMTD (Log Mean Temperature Difference) and core through a point heat source brought out the detailed values of the possible temperatures and natural circulation flows in all the circuits, for a given reactor power and air inlet temperature to the AHX. This analysis however did not bring out (i) peak values of safety related temperatures like clad hotspot, hot pool top surface, reactor inlet etc. (ii) thermal gradients over main vessel and inner vessel and core support structure (iii) the lowest value of the sodium outlet from the AHX as and when the air-side dampers are opened for initiating DHR and (iv) the duration of the structural materials being subjected to high temperature where creep is important. These temperatures depend upon the evolution of the reactor power after reactor scram, primary and secondary flow coastdowns, various thermal capacities, the thermal stratification phenomena in the hot and cold pools and the time of initiation of DHR. These can be found only through a transient analysis for which suitable thermal-hydraulic models have to be developed. For this purpose one dimensional thermal models for core, IHX, pipelines, hot and cold pools, DHX, AHX, and hydraulic models for primary, secondary and SGDHRS sodium circuit were developed and interfaced with each other to form the DHDYN code. In the following paragraph a brief outline of the features of these models are brought out.

3. FEATURES OF THE TRANSIENT MODELLING OF THE SGDHRS

One dimensional thermal models to describe the heat transfer process in DHX, AHX, air stack and pipelines are developed by interfacing sufficient number of control volumes for which governing equation is obtained from mass and energy balance. The hydraulic models for the primary sodium circuit, secondary sodium circuit, flow path in the DHX primary side, SGDHR sodium circuit and the air flow path in the AHX - Air stack are developed from the governing equations obtained from a momentum balance. For the hot and cold pool thermal models, three zone mixing models taking care of thermal stratifications and plume efect of the flow out of core and IHX primary outlet are developed. The features of the transient models developed for SGDHRS were presented earlier.(2) For the sake of continuity and to bring out additional details, a brief outline of the features are given here.

The schematic of the SGDHRS and reactor primary circuit modelling details are shown in Fig 2.

3.1 Decay Heat Removal circuit

Thermal calculations for SGDHRS are made in a sequential modular approach starting from the DHX. Depending on the latest calculated buoyancy conditions, the air flow, circuit sodium flow, DHX primary side flow and reactor primary circuit flows are calculated. The model incorporates provisions to take care of flow reversals in the circuit sodium flow and DHX primary sodium flow. The DHX model is interfaced to the hot pool thermal model.

In the AHX thermal model, the thermal capacity of the tube and fin material is all added to the thermal capacity of sodium flowing inside the tubes. The airside thermal capacity being small compared to sodium, the same is neglected in the transient calculations. These air temperatures are used as boundary conditions for transient sodium temperatures.

3.2 Hot and Cold Pool Thermal Models

Modelling the hot pool and cold pool as single mixing volumes does not bring out the effects of thermal stratification and the plume effect of a relatively hot flow into a cold plenum or vice versa. These effects can be better modelled by subdividing the hot or cold pool into two or more discrete volumes and specifying the plenum inlet flows to take appropriate path depending upon the inlet and the plenum temperatures. For PFBR, the hot pool volume in the inner vessel is divided into three zones as shown in Fig 2.

The occurence of thermal stratification in the hot and cold pools is a function of the prevailing pool temperatures and core outlet and IHX primary sodium outlet temperatures. In the hot pool if the temperature of the core outlet flow is higher than that of the bottom zone but less than that of the top zone then the core outlet flow would mix with the middle zone capacity.

In the transient energy balance equations of the discrete volumes in the hot pool, the convective heat transport effect by the DHX primary side flow is also included. The DHX thermal model is interfaced with the hot pool as mentioned earlier.

3.3 IHX And Secondary Sodium Circuit

To describe the primary inlet temperature to the cold pool, an IHX model with twenty nodes along the heat transfer length has been integrated along with the SGDHRS model. The transient variation of secondary sodium flow and secondary inlet temperature are obtained from the detailed thermal models of the secondary sodium circuit hydraulics model and pipeline thermal models. Since all the incidents to be studied with this model should incorporate a complete loss of normal heat sink, the SG units are modelled as simple pipes.

Other features of the transient modelling are: during initial steady state conditions hot and cold pool are characterised by their mixed mean temperatures. This is based on the 2-D studies of the hot pool which indicate that under normal operating conditions, there is a fall of only 3 deg C between the core top and hot pool top due to heat transfer across inner vessel.(3) Main vessel is considered as an adiabatic surface. For conservative estimate of sodium temperatures, the effect of thermal capacity of shielding assemblies are neglected. Effects of main vessel cooling flow and the subsequent effects due to its stoppage are not expected to alter the conclusions of the different studies. During normal reactor operation the air dampers of IHX are kept crack open to maintan some sodium flow in the SGDHRS so that stratification does not occur. This is modelled by introducing suitable hydraulic resistance in the air path of AHX.

4. RESULTS AND DISCUSSIONS

A computer program DHDYN has been coded according to the modelling details given above and it is used in the transient studies of SGDHRS. The results of analysis of the total power failure situation with and without the heat load sharing by the thermal capacity of the secondary sodium circuit were brought out in another paper.(1) This paper brings out the other parametric studies carried out for the total power failure situation with all the four main secondary loops available. The major parametric studies carried out are:

i) emergency battery power supply available for primary pumps alone,

(ii) reduction of SGDHR circuit pipeline size i.e decrease of sodium thermal capacity and increase of circuit hydraulic resistance,

(iii) effect of 20% uncertainty in the decay power levels and

(iv) the effect of in-vessel stored spent fuel subassemblies.

4.1 SGDHR With Emergency Power Supply For Primary Pumps

The total loss of power supply is the most severe and is expected to occur only five times in the life time of the plant. During 120 occassions of offsite power supply failure, on site emergency power supply system through diesel generator sets and/or storage batteries is available. The SGDHR with battery back up for running the primary pumps at 15% of nominal speed has been studied.

Primary pumps coastdown on flywheel inertia (with 10s speed halving time) upto 15% when emergency power supply through batteries take over. DHR is initiated by opening air dampers at 0.5 h. After 1 h the primary pumps again coastdown on flywheel inertia (66.7 s speed halving time). In other words the emergency battery capacity considered is for 1 h.

The salient features of the results for the case of battery take over in comparison with the total power supply failure are given in Table I. The clad hotspot temperature is seen to be appreciably decreased - by 41 deg C. The peak hot pool temperature decreases by 17.5 deg C. The coldest AHX sodium outlet decreases by 20 deg C. The peak hot pool temperature occurs at around 2 h in the case with battery take over as compared to the total power supply failur case where it occurs around 1 h. Cold pool temperatures are higher in the case with battery takeover as compared to the total power failure case as forced circulation is maintained in the primary circuit.

In the case where battery back up is available only for 0.5 h instead of 1 h, the situation is not much different except that the peak hot pool top zone temperature reaches 556 deg C.

In the case where emergency diesel generator power supply is available without interruption, the hot pool top zone temperature reaches 516 deg C.

4.2 Effect of SGDHRS Pipeline Size

A parametric study was carried out for SGDHRS, with lower pipe diameter (125 mm N.B instead of 250 mm N.B) and the results are shown in table II. The values of peak hot pool surface temperature, DHX cold end ΔT at t=1h, SGDHR circuit sodium flow and power removed by DHX at t=1 h are also included along with the lowest AHX outlet temperatures. It can be concluded that the lowest AHX outlet temperature is very sensitive to changes in pipe size. It is also clear that there is scope for reducing the SGDHRS sodium circuit pipe diameter. However the minimum sodium temperature comes down to 173 deg C from 306 deg C in the reference case. With provision for controlled opening of the dampers, the temperature of sodium at AHX outlet can be kept higher so that freezing of sodium does not occur. Such a provision may not be necessary with higher pipe size of 250 mm NB.

4.3 Effect of 20% Uncertainty in Decay Power Levels

Estimation of decay power levels is subject to some uncertainties. Therefore a 20% excess decay heat is assumed and the total power supply failure situation is analysed. In this, the clad hotspot reaches a peak value of 729 deg C at 1.2 h and the hot pool top zone temperature reaches a peak value of 567 deg C as compared to 711 deg c and 550 deg C for the same temperatures in the nominal case. Reactor inlet temperature reached a peak of 477 deg C as compared to 462 deg C in the nominal case.

4.4 Effect of In-Vessel Stored Spent Fuel Subassemblies

In PFBR, one hundred and eight locations are available for in-vessel storage of spent fuel subassemblies on the main grid plate after the boron carbide shielding assemblies. Provisions are available for admitting 0.8 kg/s/subassembly by forced cooling at full power condition. The incident studied is again that of total power failure, where the decay power in the spent fuel subassemblies is taken at a level 10 d after a normal shutdown.

The analysis are carried out for different values of nominal storage subassembly flows. In the case of 0.8 kg/s/SA, the clad hot-spot temperature of stored subassembly crosses 800 deg C at 500 s and goes even beyond 1200 deg C after 15 minutes. Therefore, it is necessary to increase the nominal flow rate through these storage subassemblies for limiting this temperature to levels below 800 deg C. The studies showed that only with 2.3

Kg/s/SA of flow the temperatures are within acceptable levels. The clad hotspot temperature for storage subassemblies reaches a peak value of 796 deg C at around 1.32 h and gradually reduces to 755 deg C by the end of 8 h. The clad hotspot temperature peak reached in the central subassembly is 721 deg C around the same time. These results show that atleast 2.3 kg/s/SA of flow through the storage subassemblies is essential.

The main disadvantage envasaged in having this larger flow through the storage location during normal operation is that the mean core outlet temperature decreases. For 0.8 kg/s/SA flow there is a fall of 4.5 deg C, for 2.3 kg/s/SA fall by 8.5 deg C, compared to the case without consideration of storage positions.

The peak value of the hot pool top zone (or Main Vessel top) and Reactor inlet (or core support structure) temperatures are 572 deg C (at 1.6 h) and 482 deg C (at 3.5 h) as compared to that of 568 deg C (at 1.4 h) and 477 deg C (at 3.3 h) obtained in the studies without the effect of spent fuel in-vessel storage.

Another important factor to be considered in the design of the SGDHRS is to assess how long the important structures are subjected to high temperatures when creep damage is significant. Therefore, some of the important studies described above are analysed upto a time when the hottest pool temperature is reduced to less than or equal to 450 deg C. This value and the other important temperature peaks are summarised in the table III.

4.5 Results of DHDYN Analysis of RAMONA Experiments

A 1:20 scale, water model of SNR-2 (RAMONA) has been constructed at Karlsruhe and many experiments carried out and the details of the experimental set-up have been published as a benchmark.(4) Results for two experiments simulating reactor and pumps trip with DHR initiated at 240 s (case 1) and 3000 s (case 2) have also been compiled.(5) In order to provide some validation to the DHDYN code, the same was used for the analysis of RAMONA experiments.

The input conditions like core power, secondary flow through IHX, IHX secondary inlet temperature, DHX secondary flow, DHX secondary inlet temperature were specified as ramp inputs with respect to time. The secondary flow coastdown with a halving time of 3 s and flow stop at 15 s is approximated to a ramp to zero flow in 15 s. The primary flow coastdown is represented by specifying the head developed by pump in the hydraulic equation governing the flow through primary pump. The pump head in turn is taken to be proportional to the square of the pump speed. At the end of 130 s, the pump head is equated to zero to simulate the pump stop. This way, a pump speed halving time (PSHT) of 14 s is found to reasonably follow the measured flow rate. Tables IV and V gives the comparison between the various important temperatures. In this table the experimental values of hot pool top and hot pool bottom as recorded are the average values obtained from the four probes(5) at the maximum and minimum axial locations respectively. The calculated values are the top zone and bottom zone mixed mean temperatures obtained through the three zone hot pool model. The experimental values of the DHX inlet and outlet as recorded in these tables are the lowest temperatures measured through the probe closest to the DHX(7).

It can be seen that the calculated difference between the hot pool top and hot pool bottom zones, (a measure of the thermal stratification) is about 10 deg C whereas the measured difference is about 3.2 deg C. This shows that the inter-zonal mixing is not adequately modelled. Indeed the inter-zonal heat transfer coefficient value used in the calculation, when varied between 0.613 to 9.0 $W/m^2/K$, showed very little variation. Thus any better prediction of the experiments could be possible only by the use of 2-D or 3-D representation of the hot and cold pools.

5. SUMMARY

A 1-D computer code DHDYN has been developed for the transient analysis of the Safety Grade Decay Heat Removal System of PFBR wherein natural convection of sodium and air are involved. Scoping studies carried out with the code show that

1) with emergency battery supply available for primary sodium pumps for half an hour, the peak clad hot spot temperature can be limited to the normal values,
2) there exists the possibility to reduce the pipe sizes of the SGDHRS sodium system without getting into problems of sodium freezing,
3) a 20% increase in decay power level increases the temperature by about 20 deg C,
4) the SGDHR capacity appears to be more governed by the peak temperatures of clad in the in-vessel storage rather than in the fuel subassemblies in core, and
5) there is need to go in for 2-D and 3-D modelling of hot and cold pools to have more accurate evolution of the temperatures during DHR. Experiments in scale models are planned to verify the code predictions.

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Table I

Results for SGHDR with Battery Backup to Primary Pumps and its Comparison with Total Power Supply Failure Case.

		SGDHR with Battery backup to primary pumps	SGDHR after total power supply failure
Peak hot pool temperature, deg C		548	550
Peak clad hotspot* temperature, deg C		670	711
Coldest AHX outlet temperature, deg C		285	305
Hot pool temperatures, deg C	Top zone at 1 h	515	545
	Top zone at 2 h	543	544
	Middle zone at 1 h	506	508
	Middle zone at 2 h	502	499
	Bottom zone at 1 h	425	424
	Bottom zone at 2 h	427	423
Cold pool temperatures, deg C	Top zone at 1 h	503	471
	Top zone at 2 h	489	483
	Middle zone at 1 h	500	447
	Middle zone at 2 h	477	468
	Reactor inlet at 1 h	500	443
	Reactor inlet at 2 h	478	458
	Core flow at 1 h kg/s	894.1	84.0
	Core flow at 2 h kg/s	99.7	86.0

* Peak clad hotspot during SGDHR with battery backup to primary pumps does not exceed the nominal steady state (full power operation) value of 693 deg C.

Table II

Effect of SGDHR Circuit Piping

	DHR initiated at t=0.5 h	
	Nominal 250 mm	Nominal 125 mm
Peak hot pool (surface) temperature deg C	578	580
AHX Sodium outlet temperature, deg C (Minimum)	306	173
DHX cold end T at t=1 h, deg C	76	191
SGDHR circuit flow, at t=1 h kg/s	37.5	16.3
Power removed by DHX at t=1 h, MW	15.8	14.5

Table III

Important Results of SGDHR Studies

Summary Points Cases Studied	Reactor Inlet peak, deg C at (time,h)	Hot Pool Top zone peak, deg C at (time,h)	Clad Hotspot peak, deg C at (time,h)	Time for Hot Pool Top zone to Cool to 450 deg C h
1. Deployment of Two DHR Circuit with No Influence of Secondary Circuit	461 (0.97)	581 (0.53)	>1000 174<t<214s 780 (1.0)	6.5
2. Deployment of Two DHR Circuit with Realistic Influence of Secondary Circuit	462 (2.25)	550 (1.23)	711 (1.07)	11.38
3. Same as 2 above but with 20% Uncertainty in Decay Power Levels	477 (3.28)	568 (1.39)	730 (1.19)	16.0
4. Same as 3 above but with the effects of In-Vessel stored spent fuel sub-assemblies	482 (3.5)	572 (1.6)	796 (1.32) for spent fuel 722 (1.3) for central subassembly	25.0

Table IV

Comparison of Experimental and Calculated Values of Temperatures in deg C, for RAMONA Case 1

time h	Hot pool top		DHX inlet	DHX outlet		Hot pool bottom		Reactor inlet	
	Cal*	Exp**	Exp.	Cal	Exp	Cal*	Exp**	Cal	Exp
0.5	44.4	42.4	42.4	34.6	36.5	37.2	37.8	36.8	37.6
0.1	44.1	41.0	40.6	33.1	34.0	34.5	36.2	40.4	38.8
2.0	42.9	38.7	38.5	31.7	32.5	32.5	34.9	39.5	38.4
4.0	40.8	37.0	37.0	30.1	31.5	30.7	33.8	37.2	37.2

* hot pool bottom is the volume upto an elevation of 302.7 mm, hot pool top is the volume between 500 and 580 mm elevation.

** the experimental values reported here are the azimuthal average of the temperatures obtained from the thermocouple trees.

Table V

Comparison of Experimental and Calculated Values of Temperature in deg C, for RAMONA Case 2

time h	Hot pool top		DHX inlet	DHX outlet		Hot pool bottom		Reactor inlet	
	Cal*	Exp**	Exp.	Cal	Exp	Cal*	Exp**	Cal	Exp
0.5	45.0	42.7	42.7	40.7	40.5	42.2	41.2	37.1	38.0
0.1	45.9	42.7	42.5	36.2	38.0	39.7	39.8	41.0	39.8
2.0	45.0	40.9	40.8	33.4	34.5	34.4	36.6	41.9	40.0
3.0	43.5	39.3	39.2	31.8	33.4	32.9	35.4	40.2	39.0
4.0	41.8	38.2	38.2	30.7	32.5	31.4	34.7	38.4	38.4

*, **, – notes same as given below Table 7

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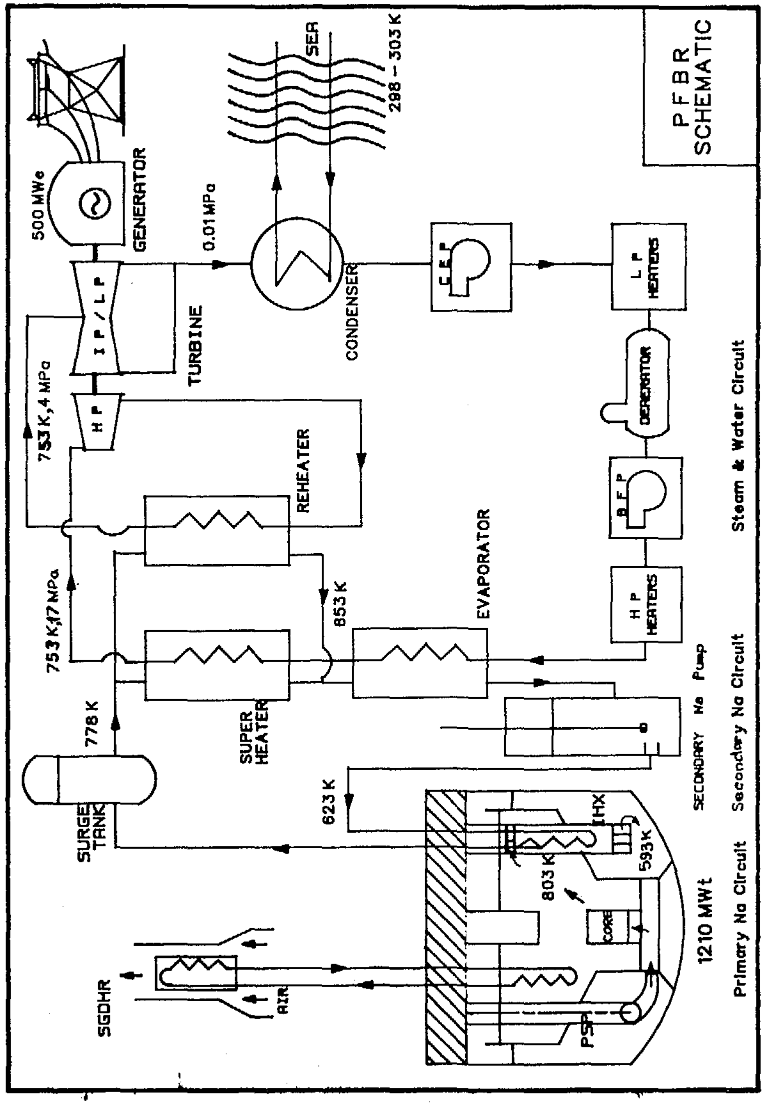

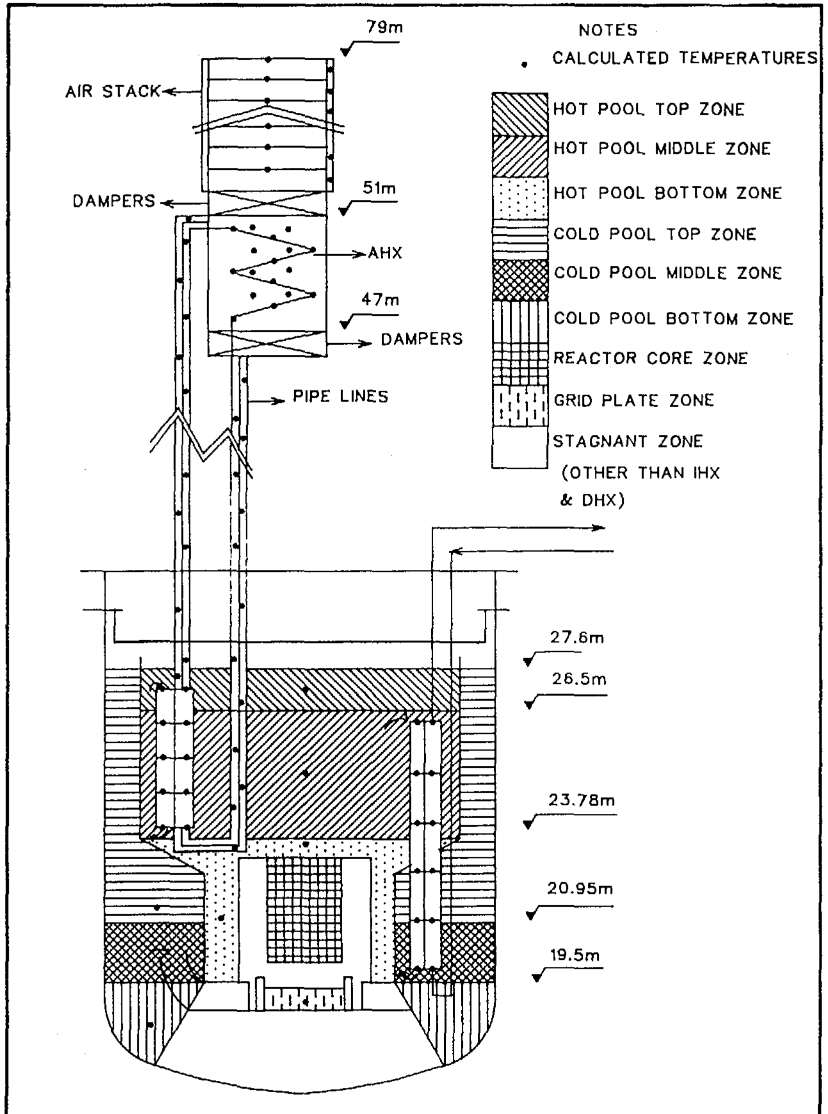

FIG SGDHRS AND REACTOR PRIMARY CIRCUIT MODELLING SCHEMATIC

sgdhr1

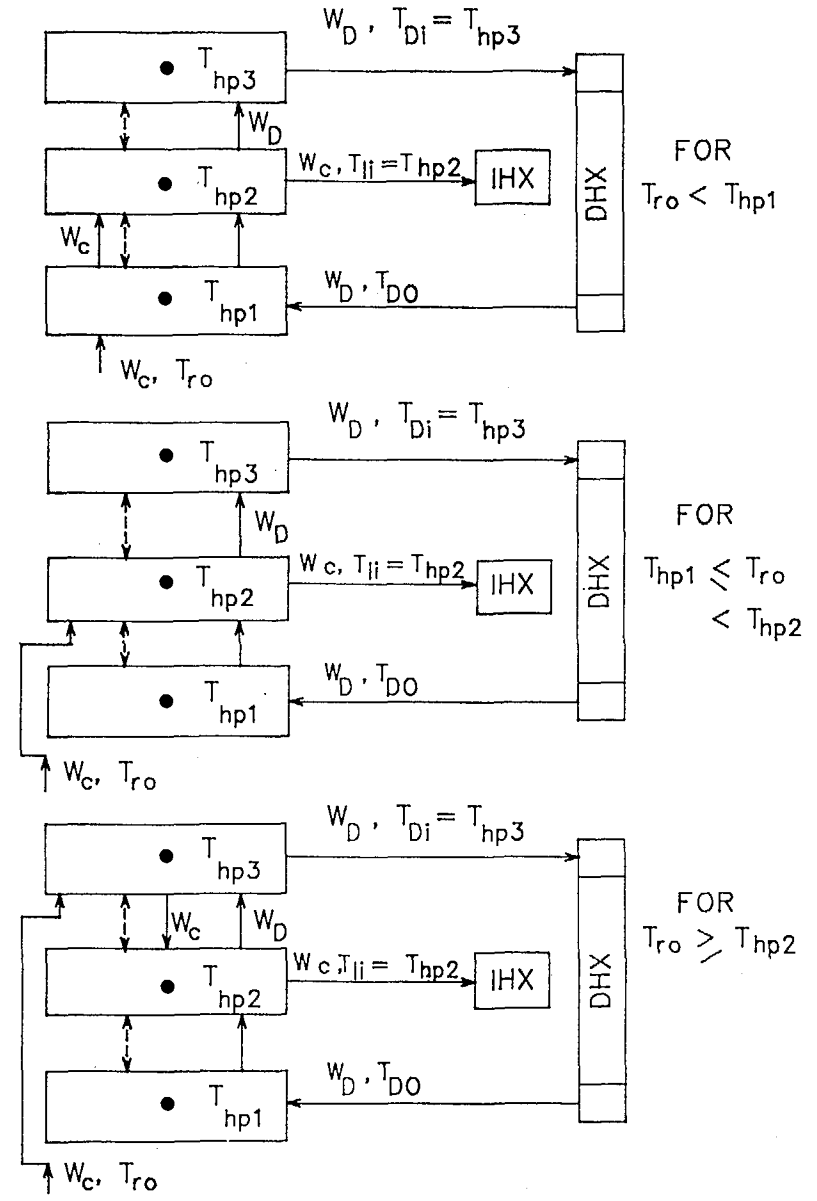

FIG THREE ZONE HOT POOL MODEL FOR THERMAL STRATIFICATION