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.

The above analyses helped to examine the safety of the plant during these transients. However, there are certain other natural circulation transients relevant to PHWRs which need further study. Some of the transients identified are power failure at hot shutdown condition and the effect of a continuous feed and bleed from the system. Preliminary experimental and theoretical investigations on the above aspects were carried out in a low pressure test facility and the results of these are presented in this report.

2. POWER FAILURE AT HOT SHUTDOWN CONDITION

Normally transient analyses are carried out with initial condition of 100% power and 100% flow. However, loss of off-site power can happen at any power level of the reactor. Of particular interest is power failure at hot shutdown conditions in a PHWR. During a hot shutdown, the primary pumps continue to operate leading to almost uniform temperatures throughout the loop. Pumping power failure at this time results in flow coastdown, at the end of which the temperature differential between the hot and cold legs of the loop may not be large enough to initiate sufficient natural circulation flow. Depending on the magnitude of this temperature differential, the flow can even stagnate temporarily and restart after some time. Experimental and theoretical investigations of this situation have been carried out in a small size figure-of-eight loop.

2.1 Experimental Investigations

The experimental loop (see Fig. 1) consisted of two horizontal heaters of annular geometry, with the inner tube directly heated by electric current. The heaters were connected to headers and the latter were connected to vertical inverted U- tube coolers by small diameter pipes. The system pressure was maintained at near atmospheric by a small expansion tank provided at the highest elevation. The loop was insulated using precast asbestos magnesia.

There were 24 thermocouples installed at various points in the loop (see Fig. 1) to measure the heater surface and water temperatures. All the thermocouples were connected to a datalogger which could scan all the channels in less than 2 seconds. The natural circulation flow rate through the loop was estimated from the measured heater power and temperature rise across the heater. This method of flow measurement was compared against that measured by a magnetic flowmeter under forced flow conditions and the agreement was found to be within 5%. The secondary side flow rates to the individual coolers were measured with the help of two rotameters. The water temperatures at the inlet and outlet of both the coolers were measured. Additional details of the experimental loop are given in [5].

2.1.1 Pumping Power Failure at Hot Shutdown Condition

Under hot shutdown conditions, the prevailing initial conditions are those of high mass flow rate with very low power and almost negligible ΔT across the core. The situation may be characterised by a flow ratio, F_R, where F_R is defined as

$$F_R = \frac{W_{in}}{W_{ss}}$$

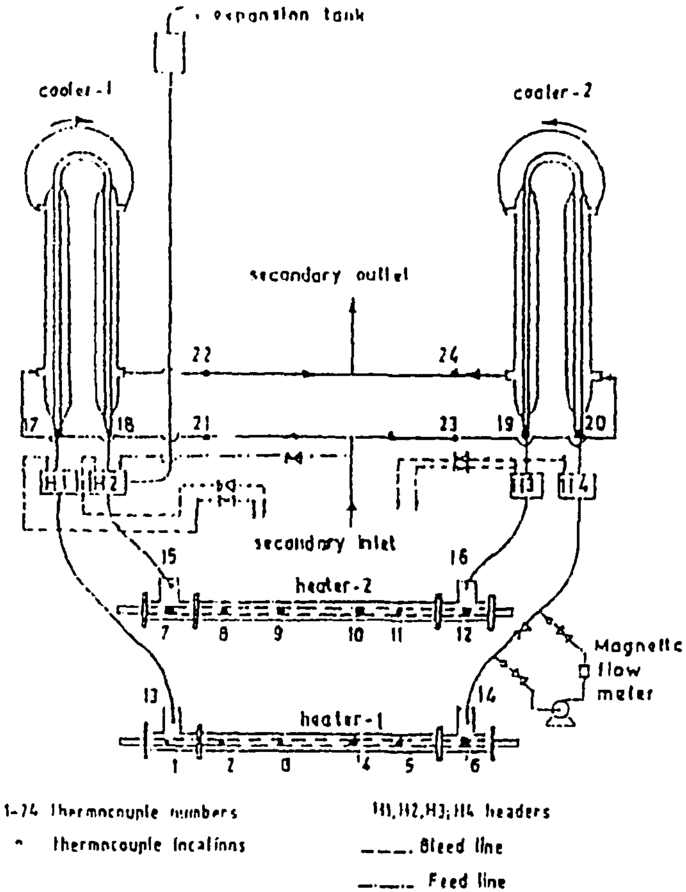

FIG. 1. Experimental loop.

where W_{in} is the initial forced flow and W_{ss} is the steady state natural circulation flow rate. For hot shutdown condition $F_R >> 1$ (typically 15 to 40) and the reactor power is of the order of 0.5 to 1%. Experiments were conducted with F_R in the range of 16 to 20 in the loop described in section 2.1. These experiments show flow stagnation immediately after the pump trip (see figure 2). The flow stagnation is followed by a steady increase of heater temperature which causes boiling in the heaters. Boiling in the horizontal heaters helps to diffuse a temperature difference across the vertical legs of the heater which eventually develops a flow through the loop (see Fig. 2). However, the

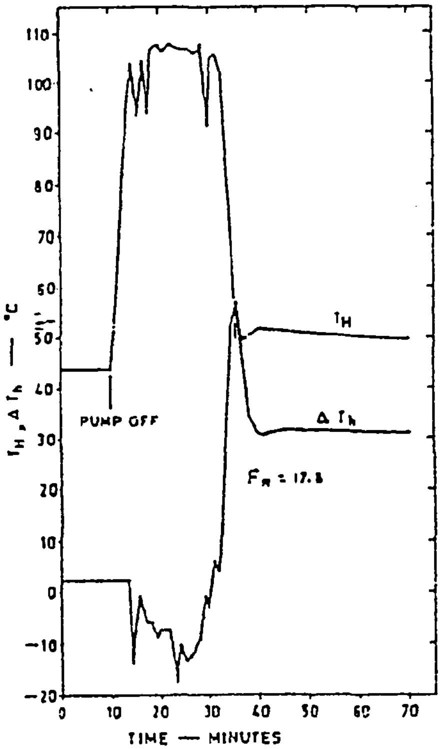

FIG. 2. Transition from forced to natural circulation at large initial forced flow (Grm = 3.14 × 10[10]).

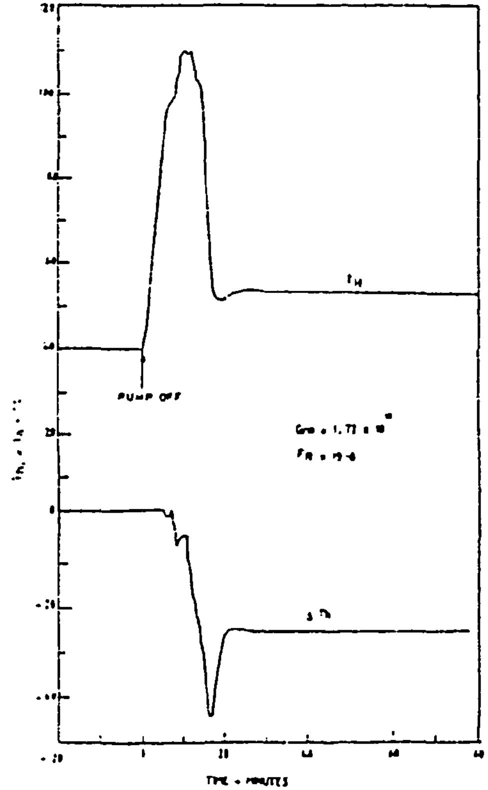

FIG. 3. Transition from forced to natural circulation at large initial forced flow.

direction of this flow can be the same or opposite to that of the initial pumped flow as shown in Fig. 3. Once the flow restarts the heater temperatures drop and single-phase conditions prevail in the loop.

It may be mentioned that if the heater power is very small, then boiling does not occur. Here, the natural convection currents generated in the horizontal heaters, which are stable to start with, become unstable with continued heating and this helps in diffusing a temperature differential across the heaters which eventually develops a flow through the loop. However, in this case, the time taken for flow development can be very large (one to two hours). In this case also, the developed natural circulation flow can be in the same direction or opposite to that of the initial forced flow. Further, for extremely low powers, experiments show that loop natural circulation may not initiate at all.

It may be noted that the present experimental loop has only one heated channel in each pass whereas in a PHWR, several parallel channels exist. The behaviour in a parallel channel system can be much more complicated as brought out in [6].

2.1.2 Theoretical Prediction

The transient behaviour of the loop is predicted numerically by solving the one-dimensional energy and momentum equations applicable to natural circulation flow. The predicted transient behaviour corresponding to the experimental condition for the data of Fig. 2 is given in Fig. 4. Although, the predicted and measured steady state behaviour matches reasonably, neither boiling nor flow stagnation is predicted contrary to the experimental observations. This is because, the one-dimensional analysis employed here does not take into account the effect of local convection currents in the heater. The effect of the local convection currents becomes significant when the loop flow is small.

Fig. 5 shows the predicted transient behaviour for a PHWR following power failure at different initial operating powers. As shown in figure 5 a minimum flow rate is predicted towards the end of flow coastdown. With decrease i.. initial operating power, the predicted minimum flow rate also decreases. This suggests that if the operating power is sufficiently low,

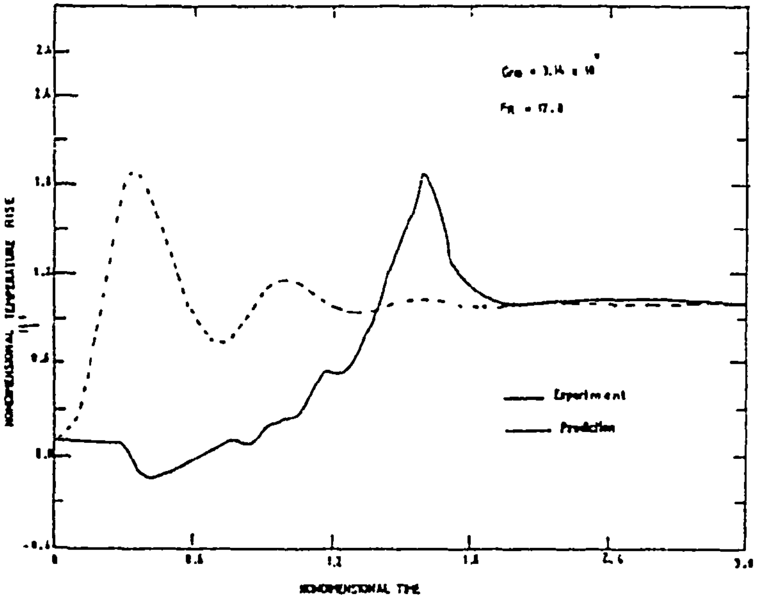

FIG. 4. Transient behaviour at $F_R > 1$.

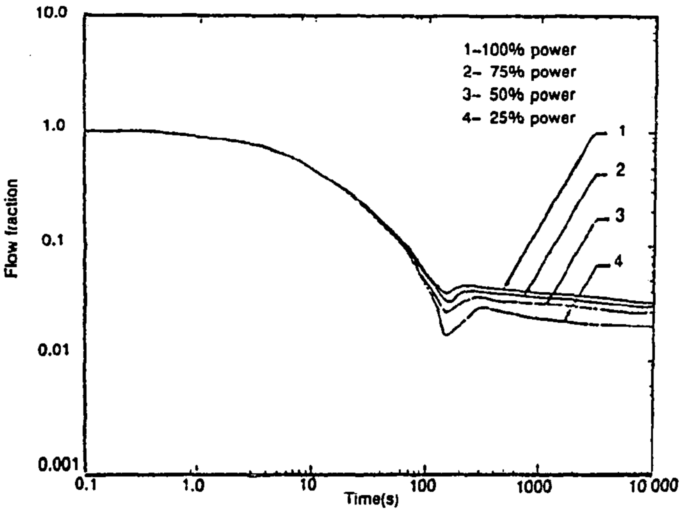

FIG. 5. Variation of flow fraction.

flow stagnation can be expected. However, the exact value of this power can only be arrived at by performing experiments in the actual system as theoretical methods based on the one dimensional approach are seen to be inadequate.

3. EFFECT OF THROUGHFLOW

During natural circulation conditions, it is often necessary to have a continuous feed and bleed flow. For example, in a PHWR, coolant is injected *continuously into the system* through the *primary* pump glands. Additional injection can be introduced from the fuelling machines if these were operating at the time of power failure. Further, in order to maintain the system 'water-solid' any shrinkage due to cooldown and leakages past the primary system pressure boundary must be compensated by injection. In this context, natural *circulation* with throughflow (in natural circulation literature, the continuous feed and bleed is also termed as throughflow) assumes significance in reactor safety. Natural circulation studies with throughflow have not been carried out experimentally, so far, even for simple loops. In the present report results are presented for a figure-of-eight loop with throughflow *for different feed and bleed points*. The paper also compares the natural circulation flow rates obtained with hot leg and cold leg injections.

3.1 Experimental Investigation

During these experiments, the injection of water at room temperature was started after the system reached steady state natural circulation conditions without throughflow. A few seconds later, the bleed flow was started and then the system was allowed to attain the new steady state with throughflow. During the transient, the loop temperatures were recorded at intervals of one minute. The bleed flow rate was also measured.

3.2 Results of Theoretical Investigations - Steady state Case

The one-dimensional energy and momentum conservation *equations* applicable to natural circulation with throughflow are solved with suitable assumptions and analytical solutions obtained for the steady state case for different throughflow inlet and outlet points. Steady state solutions are also obtained in this way for the case with hot leg and cold leg injections. Additional details of the theoretical *method* are given in [7].

3.2.1 Effect of Bleed Point Location

In the present loop all feed and bleed points are associated with the headers H1, H2, H3 and H4 as shown in *Figure 1*. The *injection is possible* only in header 2, whereas the bleed flow could be taken out through any one *of the four headers*. The inlet temperature of throughflow is same as the inlet temperature of cooling water as the feed flow is branched off from the inlet side of secondary cooling water line (see Fig. 1).

From Fig. 6 it is seen that for a fixed injection point the natural circulation flow rate depends on the location of the bleed point. For *injection in header-2, the* best natural circulation flow rate is obtained for bleeding from header-2. The next best flow rate is obtained for bleeding from header-1, followed by header-4 and header-3. In other words

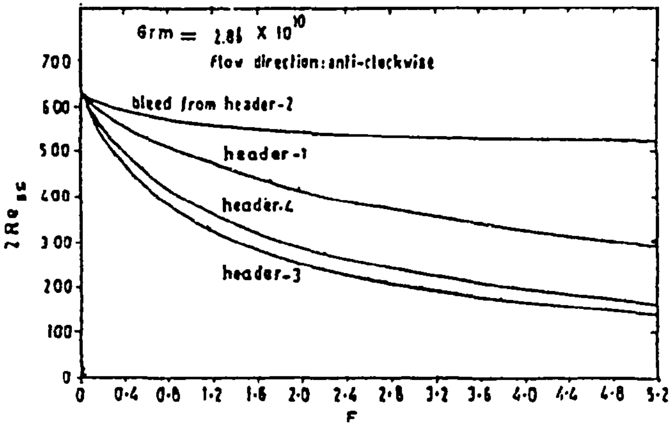

FIG. 6. Effect of bleed point location on natural circulation flow (injection in header-2).

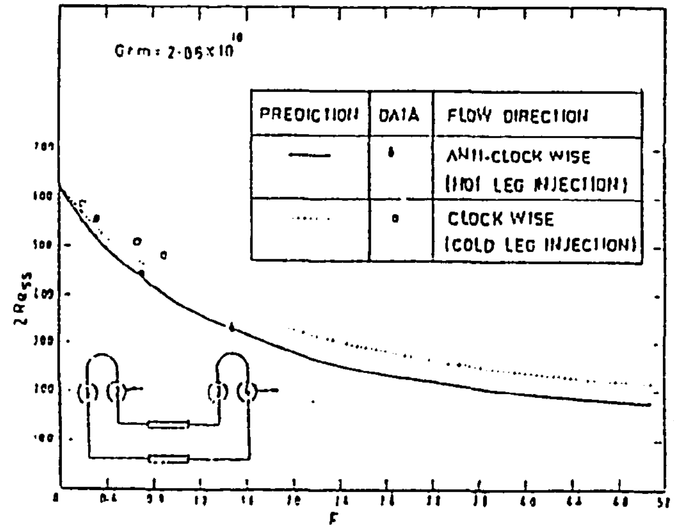

FIG. 7. Effect of flow direction (steady state).

the best natural circulation flow rate is obtained for minimum distance in the direction of flow between the points of injection and bleed. This is to be expected as the effect of throughflow is to reduce the buoyancy force and to increase the frictional resistance.

3.2.2 Hot Leg Injection Versus Cold Leg Injection

For fixed injection and bleed points, hot or cold leg injection can be obtained with different initial flow directions (i.e. clockwise or anticlockwise) in the loop. From the results in section 3.2.1 it has been established that the natural circulation flow rate depends on the distance between the points of injection and bleed. Hence to study whether hot leg or cold leg injection is preferred, one has to locate the feed and bleed points in such a way that both the branches of the loop (the low flow branch and the high flow branch) are of equal lengths irrespective of flow direction. This condition is satisfied for injection in header-2 and bleeding from header-4. The results of this study are given in Fig. 7. From this figure it is seen that with hot leg injection the flow rate is only marginally lower than that obtained with cold leg injection. This is because in a figure-of-eight configuration each half of the loop contributes to the buoyancy driving force and the reduction in buoyancy force due to hot leg injection in one half of the loop is partially compensated by the accompanying increase in the contribution to buoyancy force in the other half of the loop. The increase in buoyancy force, however, is obtained only by a corresponding increase in the heater surface temperature in the low flow branch. The available experimental data are also plotted in Fig. 7 which show good agreement with the predictions (within 15%).

4.0 STABILITY OF NATURAL CIRCULATION

Stability behaviour of natural circulation with and without throughflow in a figure-of-eight loop has been investigated the results of which are presented in this section.

4.1 Stability Without Throughflow

These tests were performed by deliberately disturbing the steady state natural circulation flow at a given power. The disturbance was in the form of a power increase or decrease for a period of 30 seconds. Sufficient time was allowed to attain the steady state condition before and after the disturbance was introduced. Stability was checked by measuring the rise in the fluid temperature across the heaters, i.e. $\Delta T_h = T_{hl} - T_{cl}$, where T_{hl} and T_{cl} are the hot leg and cold leg temperatures respectively.

Fig. 8 shows the typical variation of ΔT_h with three heat fluxes which correspond to modified Grashof number (Grm) equal to 5.6×10^{10}, 1.5×10^{10} and 2.6×10^{9} respectively; the definition of Grm is given by

$$Grm = D_e^3 \rho^2 \beta \; g \; Q_h \Delta Z \; / (A_e \mu^3 Cp)$$

where D_e and A_e are the equivalent diameter and flow area of the loop, ρ is the density, β is the coefficient of thermal expansion, g is the

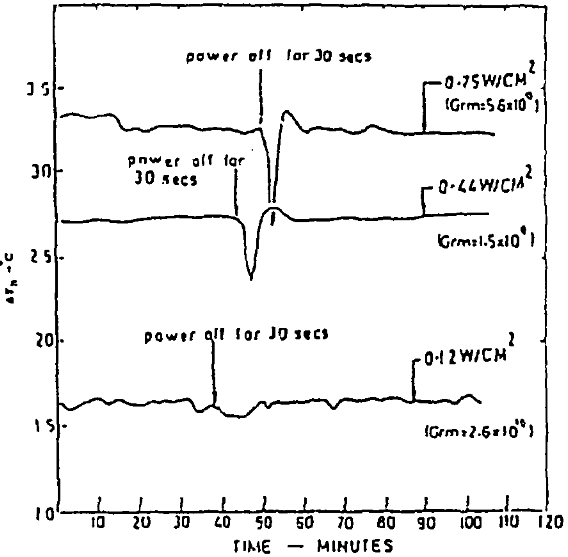

FIG. 8. Stability test at different heat fluxes (without throughflow).

acceleration due to gravity, Q_h is the heater power, ΔZ is the elevation difference between the cooler and the heater, μ is the viscosity and Cp is the specific heat. It is observed that the pre- and post-disturbance behaviour of ΔT_h at the moderate Grm of 1.5×10^{10} shows no oscillations; at high Grm (eg., 5.6×10^{10}) and low Grm (eg., 2.6×10^{10}), small amplitude oscillations occur which, however, do not amplify with time. Within this range of Grashof numbers, the loop is thus unconditionally stable. In fact, such behaviour was observed for the entire single-phase region (i.e., 10^9 < Grm < 2×10^{11}).

4.2 Stability With Throughflow

These experiments were performed with continuous injection of cold water (at room temperature) in header-2 and bleeding from header-4. Thus for clockwise circulation, the flow rates in the branch having cooler 2 and heater 1 were lower than those in the branch having heater 2 and cooler 1. The injection was started after the system reached steady state natural circulation condition without throughflow and then allowed to attain the new steady state with throughflow.

Fig. 9 shows the actual temperature records obtained from three thermocouples (TC) numbered 20, 9 and 3. These records are obtained for four values of nondimensional throughflow rates, F, which is defined as the ratio of the magnitude of the throughflow rate to steady state natural circulation flow rate.

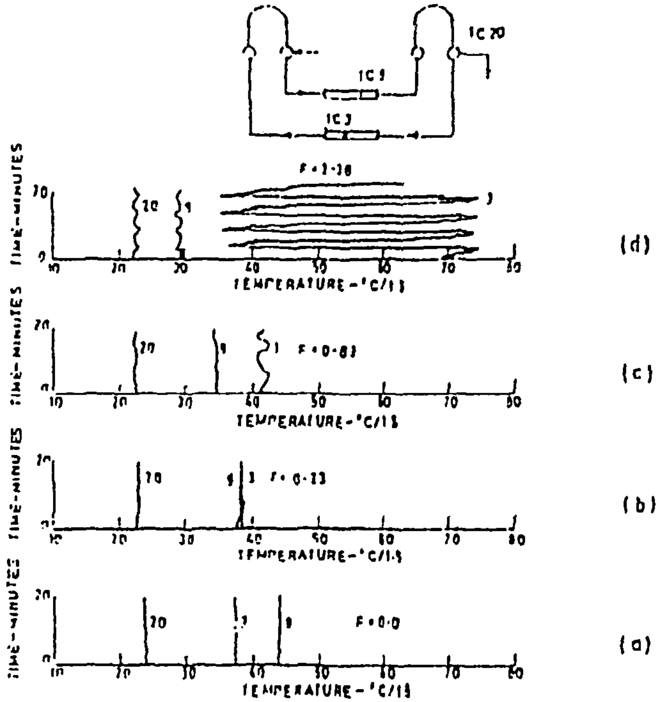

FIG. 9. Results of stability studies at 0.58 W/cm^2 (Grm = 2.86×10^{10}) with throughflow.

At small throughflow rates, the steady state reached is qualitatively similar to that reached without throughflow (compare figures 9a and b). As the throughflow rate is increased, certain steady state temperatures in the low flow branch (especially in heater-1, e.g.,TC3) become oscillatory (see Fig. 9c). With continued increase in throughflow, a stage is reached where all steady state temperatures are oscillatory (see Fig. 9d). A characteristic of these oscillations is that their amplitude is larger in the low flow branch than in the high flow branch (compare measurements of TC3 with TC9). Further increase in throughflow rate (i.e. F > 2.38) resulted in flow reversal in the low flow branch.

Similar tests were conducted for both initial flow directions and different bleed point locations keeping the feed point location same in the header-2. In all cases, similar stability behaviour with throughflow was observed.

4.3. Stability Analysis

The stability behaviour has been analysed using the linear stability method. In this method, the steady state flow rate and temperatures are perturbed by a small amount and if the perturbations grow with time, instability is indicated. The Nyquist criterion is made use of in identifying the stable and unstable zones. Further details of the analysis are given in [8].

4.3.1 Stability Without Throughflow (F = 0)

With the linear stability analysis, natural circulation without throughflow has been found to be stable for values of Grm in the range of

$$1.25\times10^{8} < Grm < 1.04\times10^{12}$$

It may be recalled that the experiments with F = 0 were conducted in the range of $10^{9} < Grm < 2\times10^{11}$, and hence no instability was observed. The results of the linear stability analysis thus accord with the experiment.

4.3.2 Stability With Throughflow (F > 0)

Applying the Nyquist criterion, the stable range of Grm was obtained for a specified value of F. For example, at F=2, natural circulation with throughflow is found to be stable in the range

$$2.78\times10^{9} < Grm < 2.415\times10^{10} \qquad (F = 2)$$

The stability range for various values of F were identified in this way, and the upper and lower bounds of Grm were plotted to obtain the marginal stability curve 'a' shown in Fig. 10. The region enclosed by the curve is stable and the region outside the curve is unstable. The experimental data for both F=0 , and F>0 are plotted for comparison. It is observed that the linear stability analysis successfully predicts the stable range.

In the reactor, the expected throughflow rates are small and therefore instability may not be encountered, though, no analysis has been carried out as yet. However, in case of significant leakages past the primary system pressure boundary, instability may be encountered.

5. CONCLUSIONS

Experiments suggest that in the event of a power failure during hot shutdown condition, the flow in a figure-of-eight loop can stagnate initially and restart after some time. When the flow restarts, the direction of the flow can be the same or opposite to that of the initial forced flow.

Studies with throughflow indicates that for a fixed injection point, the natural circulation flow rate depends on the location of the bleed point. Best flow rates are obtained for minimum distance in the direction of flow between the points of injection and bleed. With hot leg injection,

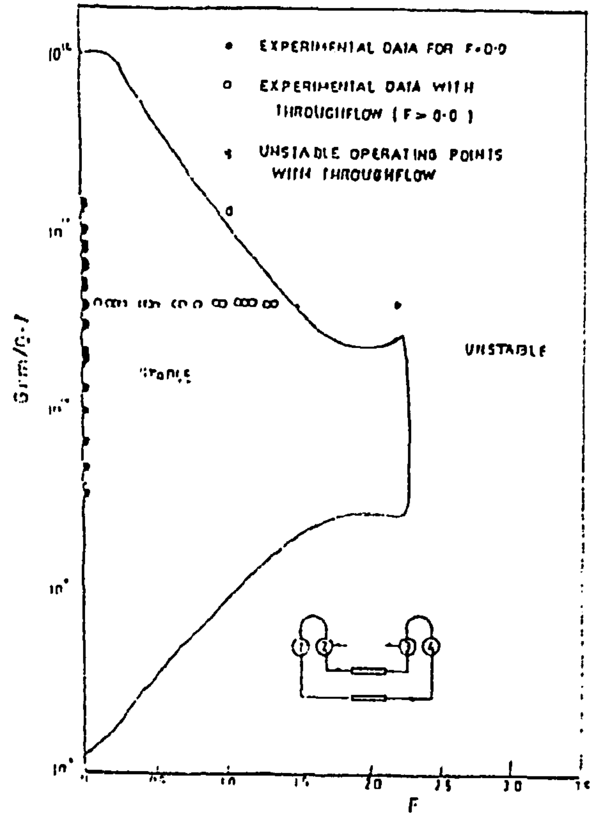

FIG. 10. Marginal stability curve obtained by the linearized stability analysis.

the steady natural circulation flow rate is only marginally lower than that obtained with cold leg injection. The experimental data from the present figure-of-eight loop are well predicted by the linear stability analysis both for the case of with and without throughflow.

ACKNOWLEDGEMENT

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