EFFECTS OF PARALLEL CHANNEL INTERACTIONS, STEAM FLOW, LIQUID SUBCOOL AND CHANNEL HEAT ADDITION ON NUCLEAR REACTOR REFLOOD TRANSIENTS

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ABSTRACT

Tests were performed to examine the effects of parallel channel interactions, steam flow, liquid subcool and channel heat addition on the delivery of liquid from the upper plenum into the channels and lower plenum of Boiling Water Nuclear Power Reactors during reflood transients. Early liquid delivery into the channels, following a loss of Coolant Accident, will help prevent overheating and melt down of the reactor fuel bundles. The tests were performed at the General Electric Nuclear Energy Division Laboratory, California.

The channels consisted of two 5.22m long *25.4mm long*23.6mm i.d. stainless steel tubes, with unequal orificing at the bottom, and equal orificing at the top. Provisions were made for electrical resistance heating of 3.5m of each tube, and for visual observation of flows through the tubes. Test fluids were steam and saturated or subcooled water. Subcools ranged from 3.3 deg C to 37.2 deg C, and system pressures varied from near atmospheric to a little over 1.7 bar. Test section heat fluxes were between 2.58 and 13.95 KW/m^2. It was observed that channel heat additions tended to make each tube behave independently of the other. As a result of subcool and vapour condensation, vapour supply into the lower plenum increased liquid delivery into the channels, and decreased the system rewet and reflood times when the subcool was in excess of about 20 deg C. Parallel channel interactions were observed to produce co-current downflow in the less restricted tube, with counter-current flow existing in the more restricted tube. This is desirable. When conditions permitted, the interactions gave rise to the classical "steam bound" flow configuration - (i.e. water hold up in the upper plenum due to top orifice Counter Current Flow Limitation, partial filling of the more restricted channels, a partially full lower plenum, and pure vapour flow in the less restricted channel). This configuration is undesirable for thermal recovery of a reactor following a loss of coolant accident.

NOMENCLATURE

K - Orifice friction loss coefficient.
LRC - Higher power and less restricted tube.
MCR - Lower power and more restricted tube
CCFL - Counter-current Flow Limitation
QCV'S - Quick Closing Valves
ECCVS - Emergency Core Cooling System.
UP - Upper Plenum
LP - Lower Plenum
W - Flow rate kg/hr
Q - Power kw
P - Pressure Bar
ΔP - Pressure drop or difference bar
ρ - Density Kg/m^3
T - Temperature ^{o}c

BWR - Boiling Water Reactors
PWR - Pressurized Water Reactors
A - Area m^2
Subscripts
1 - Higher power and less restricted tube
2 - Lower power and more restricted tube
gt - Total vapour supply to system
ft - Total liquid supply to system
lp - Lower plenum
ch - Channel
t - Total

1. INTRODUCTION

The design basis loss of Coolant Accident (LOCA) of a Boiling Water Nuclear Reactor (BWR) assumes a guillotine rupture of one of the main coolant water recirculation pipes, and is described completely in reference [1]. The coolant loss is followed by rapid depressurization of the reactor, and then by flashing and rapid bulk vapourization of the liquid in the lower plenum. When the latter subsides, there is a severe depletion of liquid coolant in the fuel bundles. At this time various Emergency Core Cooling Systems (ECCS) are switched on, one of which sprays subcooled liquid into the Upper Plenum of the reactor. Various factors which exist during this reflood period may restrict or aid the delivery of liquid into the channels and, subsequently, into the lower plenum. These include Counter Current Flow Limitation (CCFL) at the upper, the fuel bundles, liquid subcool, steam flow from the lower plenum into the channels, steam generation due to heat addition in the channels, and interactions between the parallel channels of the reactor.
The objective of the tests was to examine the effects of the above factors in aiding or restricting the early delivery of liquid into, and rapid rewet of the hot channels. The test loop design was biased towards the BWR, but some **of** the phenomenological effects observed are applicable to Pressurized Water Nuclear Reactors (PWR). While certain important similarities to the BWR were maintained in the test loop, it was not designed to be a full geometrical and hydrothermal scale of the actual Reactor.

2. THE EXPERIMENT

2.1 The Test Loop

The test loop is illustrated in Fig. 1. The steam generator was an Electro-Magic (Model 3100) unit, and had a pressure regulator connected to it, downstream. Steam flowed through a distributor, shown in figure 2, into the lower plenum. An inverted cup at the top of the upper plenum removed some of the entrained liquid before the steam was exhausted into the atmosphere.
The water loop was a quasi-closed circuit, and included a make-up water tank, regenerative heat exchanger, and a $33\frac{1}{2}$ KW preheater. Water was introduced into the upper plenum in which a weir arrangement and an overflow drain line were provided.
The test channels consisted of two 5.22m long *25.4mm o.d. *23.6mm i.d. stainless steel tubes. One tube had an orifice plate with a 9.5mm hole, at its bottom entry, and was denoted the less Restricted Channel (LRC). The other, being the More Restricted Channel (MRC), had a 6.4mm hole orifice plate at its bottom entry. The (K/A^2) ratio of the orifices was 5. The orifice plates at the top of the tubes were identical, and had 4* 7.6mm holes. These two channels simulated the less restricted central fuel bundle group of a BWR and the more restricted peripheral bundle group. Each tube had a 1.22m long visual section, made of Pyrex tube of same internal diameter as the tubes, below the heated section and between the quick closing

valves. 3.5m of the steel tube above the visual section was rigged for electrical resistance heating. A visual port was also machined unto the lower plenum.
The mixing region above the distributor is a 51mm wide section, running diametrically across the cylindrical lower plenum. The channels were located symmetrically at 114.3mm radius from the axial centerline of the lower plenum. Figure 3 shows other dimensions of the test system.

2.2 Instrumentation

The test loop was instrumented as shown in figure 3. Brooks rotameters, and Orifice meters, were used for water and steam measurements, respectively. A 0-15KW table wattmeter was used for power measurements. Valedyne pressure and differential pressure transducers, BLH differential pressure transducers, and thermocouples were used for pressure and temperature measurements. Fluid level changes in the upper and lower plena were also tracked with BLH transducers. All the instruments were calibrated on site before use. The instrument outputs, in Volts, were connected through a signal conditioner to a Hewlett Packard Model 2017D Data Acquisition System (the'DYMEC). All the 62 Dymec data signals were also printed on paper tape within a cycle time of 11.594 seconds. Some transducer outputs, such as the plenum fluid level indicators and test section thermo- couples located at 0.154m, 1.981 and *5.22m* from the top of the heated sections, were connected to a Sanborn Recorder for visual display. Further details of the test loop and instrumentation are given in reference [2].

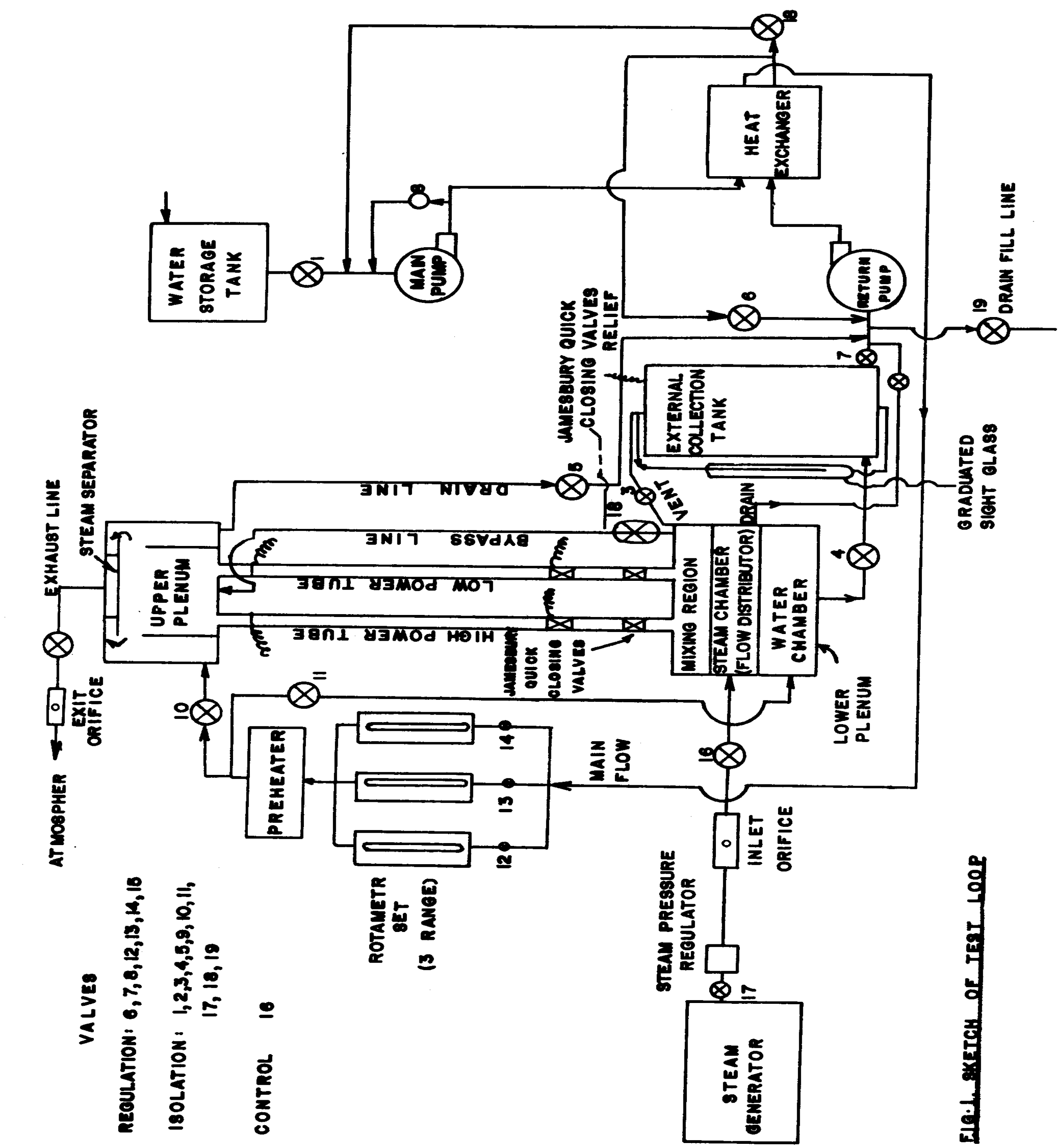


FIG.1 SKETCH OF TEST LOOP

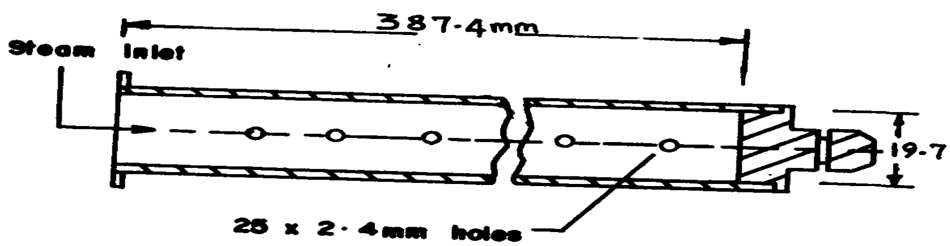


FIG.2 FLOW DISTRIBUTOR.

2.3 Experimental Procedure and Test Matrix

In general, the system was first filled with water, the pressure and differential pressure transducers bled of any air or vapour locks, and the Dymec/Recorder displays zeroed. The tubes and plena were then drained of water. The steam flow and channel powers were set to required values, and steady tube wall temperatures established before the introduction of saturated or subcooled water into the upper plenum. The required water temperature was achieved using the preheated and pressure transducer. The channel wall temperature transients and fluid level changes in the plena were continuously recorded. Continuous variations in flow behaviour inside the tubes were deduced from observations of flow through the transparent sections of the channels. Table 1 shows the test matrix for these runs. The power supply to the channels was in the approximate ratio of 2:1, with the less restricted channel having more power. In an actual BWR transient, the power ratio is not constant, but the above ratio is representative.

3. RESULTS AND ANALYSIS

Figures 4 to 7, showing tube temperature and plena fluid mass transients, have been selected to illustrate the observed phenomena. The complete results may be obtained from reference [2]. Relevant system variables are indicated. Thermocouple numbers 1, 2, and 3 were located at 0.15, 1.68 and *3.54m* from the top of the heated sections of both tubes.

The tests were broadly divided into two. The first involved tests with steam addition into the lower plenum, as would exist in a BWR during the earlier reflood period following the activation of the ECCS. During this period, some steam would still be evolved from the lower plenum. The second refered to tests without lower plenum steam addition, as would exist during the latter reflood stages. In both cases, power was supplied to each channel.

A: <u>Tests With Steam Supply to Lower Plenum</u>

<u>A-l. Saturated Liquid Supplied to Upper Plenum, eg. Run 1017, Fig. 4</u>.

When steam was introduced, most of it would flow through the LRC because of its lower restriction. As a result, on the introduction of liquid into the upper plenum, it was observed to flow down the MRC first, due to greater CCFL at the LRC upper orifice. Rewet of top regions of MRC occurred earlier. With the evaporation of saturated liquid entering the channels, liquid downflow through the top orifices was further

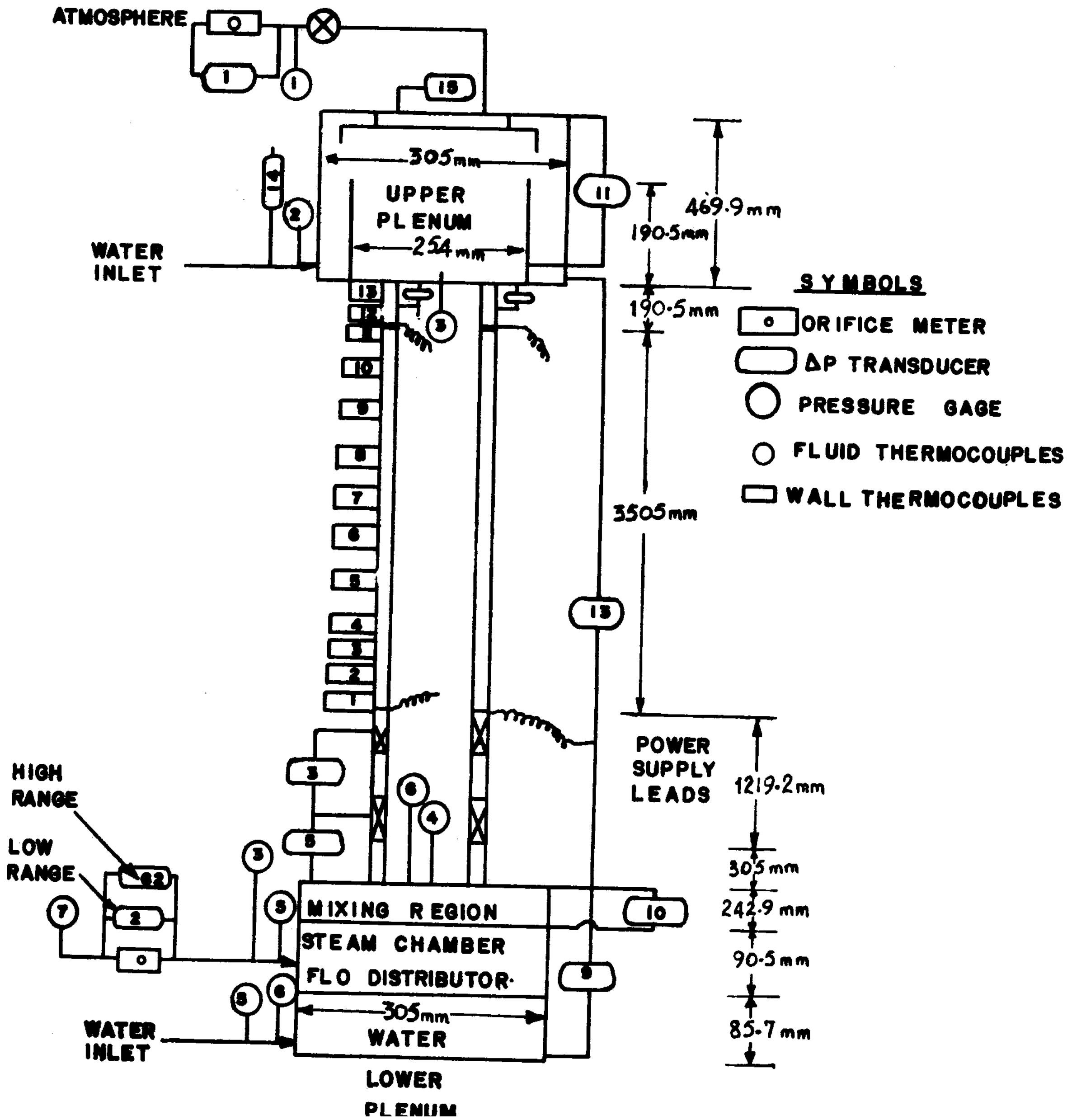


FIG:3. TEST SECTION INSTRUMENTATION

limited, due to increased CCFL effect. This resulted in decreased vapour evolution within the channels. The consequence was to diminish CCFL at the upper orifices and permit more liquid to re-enter the channels. With this interaction of CCFL and channel vapour generation, liquid delivery into the channels fluctuated. Subsequently, some channel wall temperatures fluctuated between film boiling, rewet, and back to film boiling values again, - until eventual complete rewet. Liquid accumulation of the upper plenum showed identical variations. Towards the end of the test, a stead liquid level was visible in the MRC, with steady liquid delivery into the Lower Plenum through this channel. All the steam supplied to the lower plenum was

TABLE 1. TEST MATRIX FOR UPPER PLENUM FLOODING TESTS

Run No.	Channel Power(kw) LRC	MRC	LP Steam flow (kg/hr)	UP Water flow (kg/hr)	UP Water subcool °c	Average subcool °C
1017	1.96	1.06	8.18	260.8	0.0	0.0
1018	3.6	2.2	8.63	236.8	0.0	0.0
1019	4.07	2.375	8.41	230.0	32.2	32.2
1020	4.06	2.25	8.18	270.3	37.2	37.2
1021	4.06	2.325	8.18	327.5	22.2	22.2
1022	3.73	2.125	8.86	312.5	12.2	12.2
1023	3.70	2.075	8.63	283.6	3.3	3.3
1030	3.72-3.77	2.05-2.17	4.54	27.5	0.0	0.0
1015R	1.95	1.0	0	257.6	0.0	0.0
1016	3.9	2.0	0	264.4	0.0	0.0
1024	3.9	2.0	0	270.5	27.8	27.8
1025	3.6-5.4	2.0-2.25	0	290.0	31.7-33.9	32.8
1026	3.6-4.5	2.05-2.4	0	296.3	22.8-27.2	25.0
1027	3.6-4.24	2.0-2.32	0	242.1	18.3-20.6	19.45
1028	3.4-3.81	2.0-2.25	0	270.5	5.6-22.8	14.2
1029	3.6-3.96	2.0-2.25	0	270.5	5.0-12.8	8.9

diverted into the LRC, with its upper orifice under complete CCFL. This is the classical "steam binding" situation, and does not lead to early rewet of the higher power less restricted channel, as can be seen from figure 4.

A-2. Subcooled Liguid Supplied to Upper Plenum, eg. Run 1021, Fig. 5.

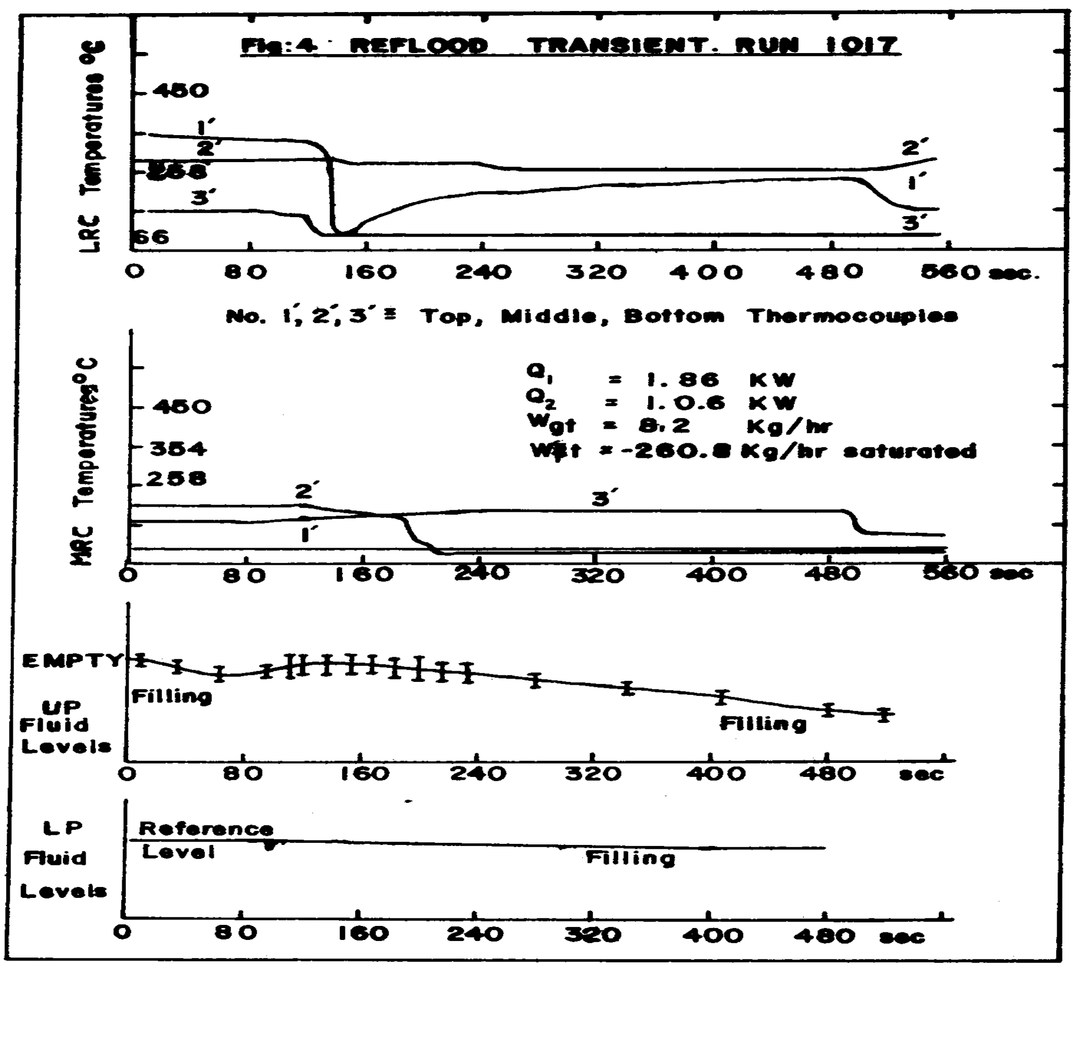
Again, with lower plenum steam supply; liquid was first observed in the MRC. It started as a fast moving streak of liquid. At about 120 seconds, very fast moving slugs of liquid flowed simultaneously down both channels, and made very loud noise as they hit the bottom orifices. The wall temperatures showed instantaneous drops, but except for the MRC, they recovered almost immediately. The fast liquid slugs were in fact travelling behind condensing fronts. As the highly subcooled liquid entered the channel side of the top orifices, the resulting condensation of the vapour created a severe depressurization which pulled liquid from the upper plenum into the channels with a strong force.

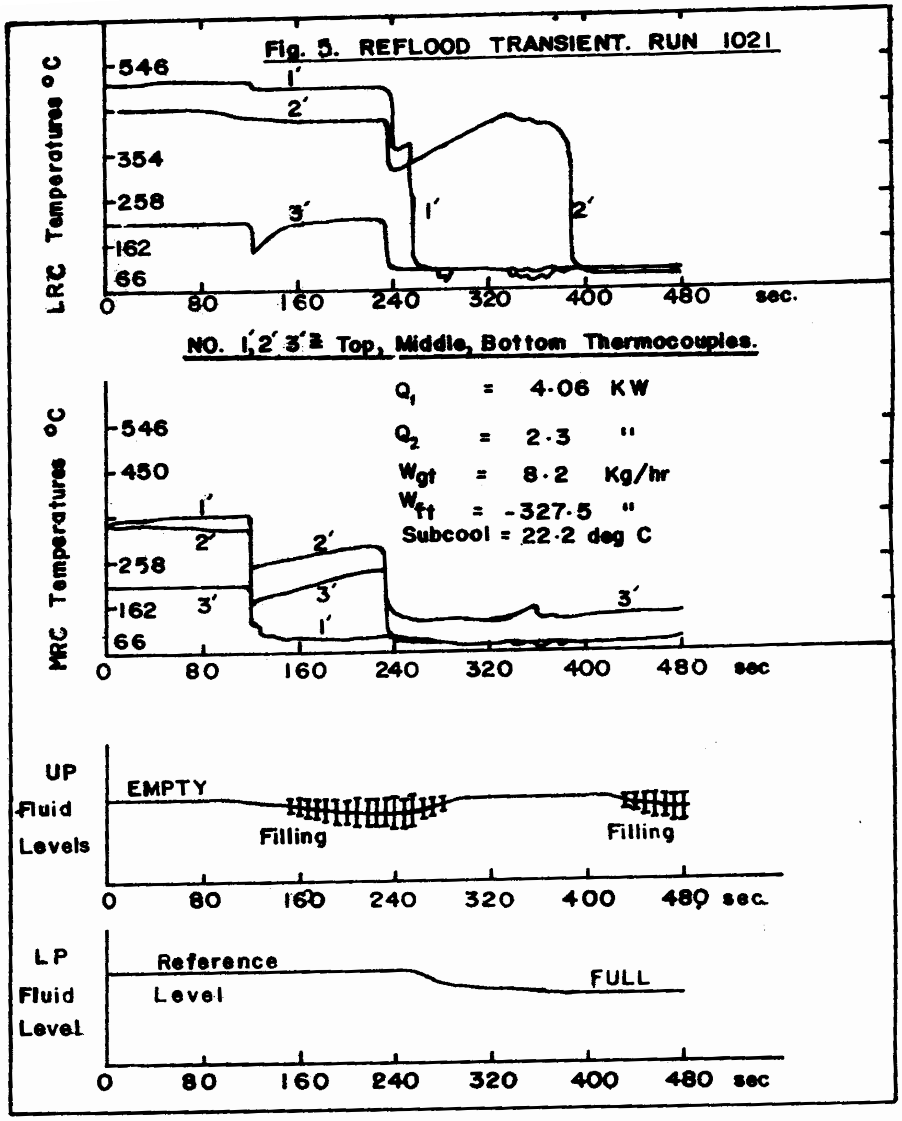
Following the entry of the above liquid slugs into the channels, liquid levels developed in both tubes, thus cutting off vapour flow from the lower plenum into the channels. The vapour in the lower plenum was partially condensing and partially raising the lower plenum pressure, while liquid gradually drained from the channels into the lower plenum. Inside the channels, evaporation was taking place sufficiently to maintain partial CCFL at the upper orifices. The liquid accumulated in the LRC drained off faster into the lower plenum, permitting vapour to re-enter that channel. The flow of a second fast condensing front and a liquid slug down that channel (at about 240 seconds) led to rewet of its top and bottom locations. The MRC showed full rewet at approximately the same time. Since the lower plenum was not yet full, it's likely that the pressurization of the lower plenum from the second condensing front led to a bold up of liquid in the MRC, and hence to a re-fill and bottom reflood of that channel.

After the second condensing front in the LRC, a Chugging counter-current flow in that channel, with single phase liquid downflow in the MRC, was· set up. As the lower plenum filled up, co-current upflow in the LRC and single phase liquid down-flow in the MRC was set up. Throughout the transient, the upper plenum filled and drained with fluid in sympathy with variations liquid delivery into the channels.

B: <u>Tests Without Steam Supply to Lower Plenum B-1. Saturated Liquid Supplied to Upper Plenum, eg. Run 1015R, Fig. 6.</u>

Upon introduction of liquid into the upper plenum, liquid flowed into both channels, but was first observed in the LRC. Shortly after this, liquid downflow into both channels ceased, and liquid began to accumulate in the upper plenum. The liquid which had entered the channels had evaporated. The outflow of the vapour





generated, through the upper orifices, caused complete CCFL at the orifices, and prevented further liquid downflow into the tubes. Since no further vapour could be generated, CCFL then broke down at the orifices and more liquid was admitted into the channels. Thus liquid delivery into the channels was intermittent due to the feedback effect of vapour generation on CCFL at the top orifices. It remained intermittent until the eventual rewet of the tubes. From the temperature profiles, the start of film boiling breakdown appeared to have occurred almost simultaneously in both tubes, with the LRC leading by about 4 seconds. Final rewet however occurred earlier and more rapidly in this channel. This was attributed to two factors, viz - an earlier breakdown of CCFL in the LRC, and secondly, better rewetting characteristics of this tube. This second factor arose from its higher temperatures. It had in fact been overheated at some point during the tests with black oxide layer appearing on its outside surface. The inside surface would have been similarly oxidized. It had been shown in reference [3] that oxide deposited improved the rewet characteristics of flow surfaces.

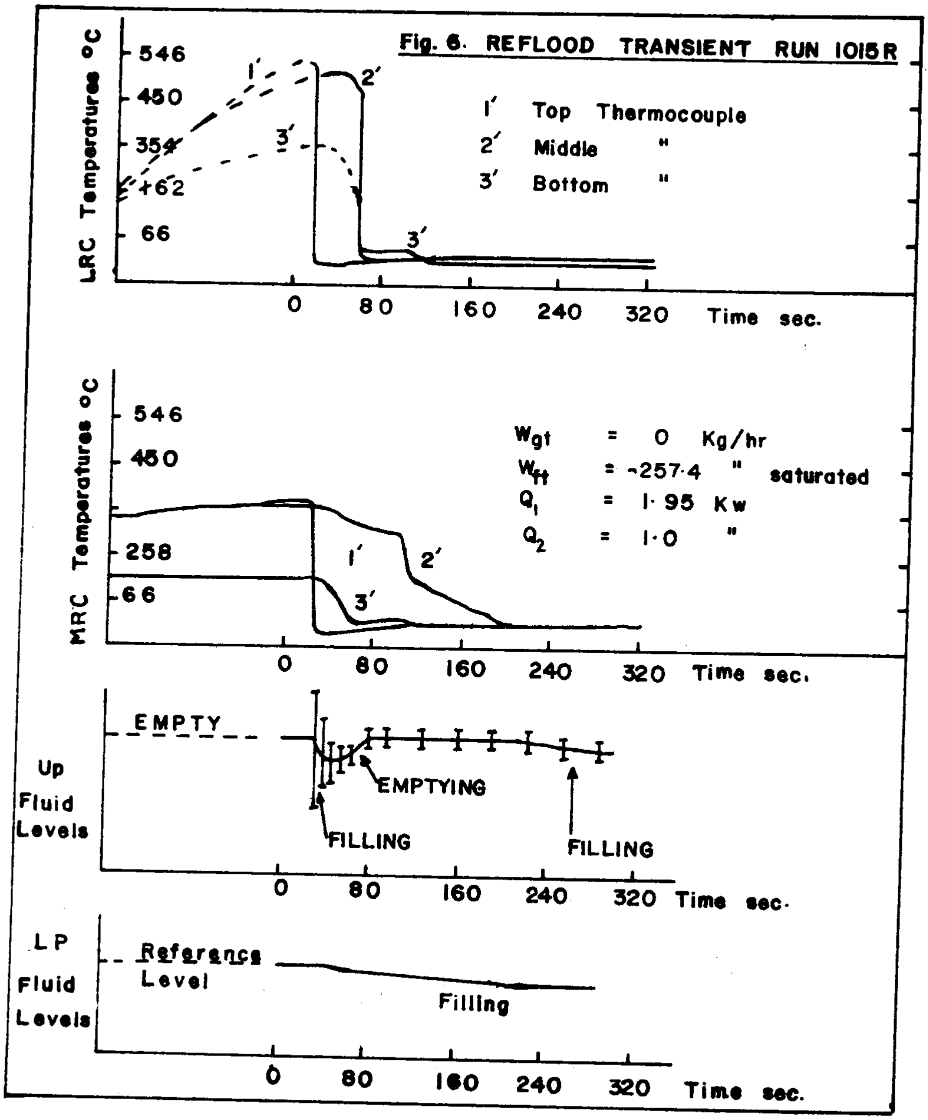
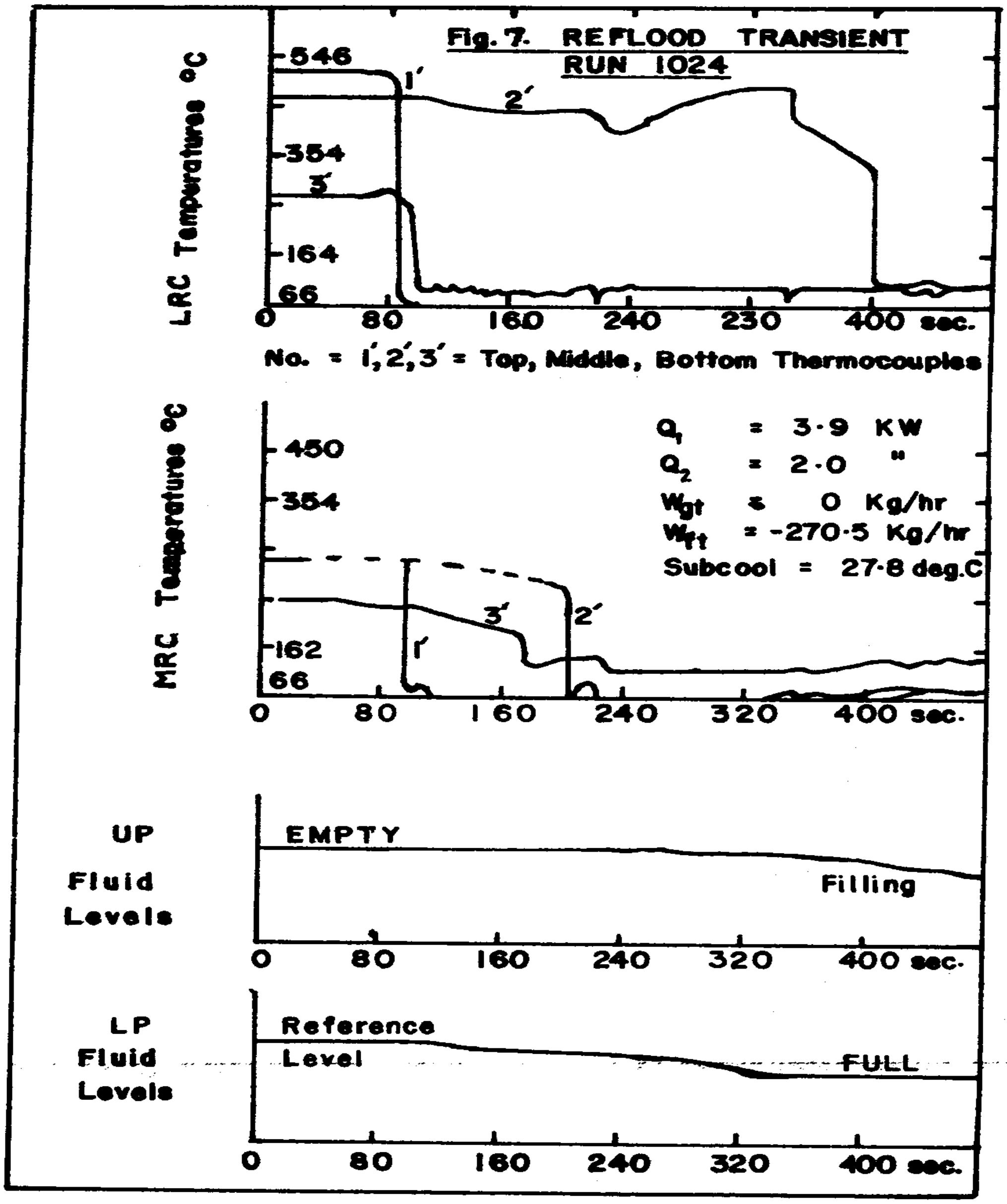


Fig. 6. REFLOOD TRANSIENT RUN 1015R

Before final breakdown of CCFL in the LRC, both channels tended to behave independently. When CCFL finally broke down in the LRC, the downflow of liquid was so rapid that it swept the vapour generated in that channel downwards into the lower plenum (ie. co-current downflow).Since the lower plenum was not yet full of liquid, vapour in the lower plenum together with that coming down the LRC were swept into the MRC, thus delaying liquid influx into, and eventual wetting of this tube - as seen in figure 6. When both channels had been wetted, equal liquid levels existed in the tubes (visible through the Pyrex tube), steady vapour generation inside the tubes maintained partial CCFL at the top orifices, and liquid accumulation in the upper plenum continued at a more rapid rate.

B-2. Subcooled Liquid Supplied to Upper Plenum, eg. Run 1024, Fig. 7

As for case BI above, liquid downflow was first observed in the LRC. Its top thermocouple showed full rewet 8 seconds ahead of the top thermocouple of the MRC and bottom thermocouple of the LRC. The high power levels for these tests kept the middle sections in film boiling for a much longer period. After an initial delay, all the liquid entering the upper plenum



Flowed into the channels, and except for the amount that evaporated, entered the lower plenum. The upper plenum was empty, equal liquid levels in both tubes were visible through the Pyrex tube, and the channels remained partially wetted. The complete draining of the upper plenum is to be contrasted with case Bl (saturated liquid inlet), in Which upper orifice CCFL commenced almost as soon as water was introduced into the upper plenum. As was to be expected, liquid subcool enhanced breakdown of CCFL at the upper orifices, (see reference [4]).

Unlike case Bl above, the MRC fully rewetted first. The resulting rapid downflow of liquid forced vapour through the lower plenum into the LRC, further delaying the latter's rewet. Eventually, the lower plenum filled up, vapour slugs entering the LRC ceased, and a fast stream of liquid flowed down the tube. Its middle temperature began to drop more rapidly, and eventually showed full rewet as the channels filled up with water. It was not clear, however, whether the final rewet was due to bottom or top flooding

Rewet. Times

Of primary importance in a Loss of Coolant Accident is that the Reactor should rewet fast enough before over- heating of the fuel rods can occur. Table 2 shows the rewet times for the two-tube test system. At low subcools, (< 20^0C), the introduction of steam delayed the eventual rewet. This is due to the effect of CCFL being greater than that of subcooling. At subcools greater than this, the rewet times were significantly reduced.

TABLE 2. REWET TIMES FOR REFLOOD TESTS

Run No.	Steam Flow kg/hr	Av. subcool deg C	POWER				Rewet Time(sec)
				HPT	LPT		
				KW/m^2	KW	KW/m^2	
1022	8.17	37.2	4.06	10.49	2.25	5.81	226
1023	8.17	22.2	4.06	10.49	2.33	6.02	268
1024	8.85	12.2	3.73	9.64	2.13	5.50	790
1025	8.62	3.3	3.7	9.56	2.08	5.38	1350
1026	0.0	27.8	3.9	10.08	2.0	5.12	312
	0.0	32.8	4.5	11.63	2.13	5.50	316
			4.05	10.47	2.23	5.76	316

4 CONCLUSIONS

1. Expectedly, the effect of steam efflux from the lower plenum with saturated or insufficiently subcooled upper plenum reflood liquid < 20^0C), was to delay rewet of the system, - particularly the rewet of the hotter less restricted channel.

2. With sufficient subcool of the re-flood liquid, (>20^oC), steam efflux from the lower plenum decreased the rewet time due to local depressurization at the condensing front within the channels.

3. With sufficient channel heat addition, vapour generation/CCFL interactions within each channel could control liquid delivery from the upper plenum into the channel and the lower plenum. The channels would tend to behave independently of one another with diminished parallel channel interactions.
4. Parallel channel interactions could have both beneficial as well as negative effects. It could permit co-current downflow through the hotter less restricted channel, thus leading to an earlier rewet of this channel. This is highly desirable, and can occur in real reactors if earlier CCFL breakdown at the upper orifices of the hotter channels are promoted via the method of injection the ECCS liquid. With even mixing of steam and water in the upper plenum, for example, a 'stream binding' flow configuration can exist due to parallel channel interactions. The rewet of the hotter channels will be delayed and this is very undesirable.
5. Finally, the interactions of channel internal heat generation, subcool and vapour condensation, lower plenum steam efflux, and parallel channel interactions result in an intermittent liquid delivery into the channels the lower plenum during upper plenum reflood transients. This would normally present difficulties in the transient model development.

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