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DYNAMICS AND DEVELOPING OF NATURAL CIRCULATION COOLING FROM VERTICAL UPFLOW AND DOWNFLOW CONDITIONS

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ABSTRACT

Several research programs have been conducted to evaluate the capability of natural circulation cooling of reactors following a loss of cooling accident. Both experimental and RELAP5 simulation results were obtained for these studies in a facility with vertical heated tube(s) and a unheated bypass channel. The analytical results showed that, under a certain power level, a natural circulation pattern can be developed from both initial upflow and downflow conditions, and maintained for a significant cooling period. This power level, for the discussion of this paper, is defined as the natural circulation cooling (NCC) power limit. Two import factors, namely the pump coastdown rate and the initial flow direction, are examined in this paper.

In the benchmark case, as compared to the experimental results, the RELAP5 simulation program accurately predicted the transient phenomena from forced convection through flow reversal, then, into natural circulation cooling. Generally, the two-phase NCC power limit is higher and also more stable for the cases with initial upflow forced convection than for the cases with initial downflow. The transient phenomena (dynamics) of the natural circulation cooling was examined by varying the pump coast down rate in approaching the flow reversal natural circulation. A significant pump coastdown effect on the NCC power limit was observed for the analytical tests with initial downflow forced convection. For the tests with initial downflow condition, the higher the coastdown rate (or the shorter the coastdown period), the higher the NCC power limit. For the case with initial upflow forced convection, there may be an optimal coastdown rate for a given subcooled condition However, for the subcooled condition used in this study, the effect of pump coast down rate is not as significant as in the downward forced convection.

NOMENCLATURE

G_r = Grashof number
R_e = Reynolds number
P = heat removal limit (w)
A = coolant flow area (m^2)
c = liquid heat capacity (J/kg-K)
λ = latent heat of evaporation (J/kg)
ΔT = subcooling measured by the saturation temperature at the test section exit pressure minus inlet temperature (K)
ρ_g = vapor density (kg/m3)
ρ_l = liquid density (kg/m3)
g = gravity constant (9.8 m/sec2)
L = length of heated section (m)
f = two-phase friction factor (assumed value = 0.005)
D = equivalent channel diameter (m)

BACKGROUND

In some reactors, in the event of loss of cooling accident, such as single - or multiple-failure small breaks, the regulatory procedures may require the operator to turn off the pumps to initiate natural circulation in the primary loop in order to remove the decay heat in the reactor. In a low pressure reactor such as HWNPR or HFBR, two-phase natural circulation flow may develop in the events of pump failure. Following the above transient events, the available hydrostatic pressure between the moderator and the vapor generating hot leg tends to force the flow through the cold leg to the hot leg by means of natural convection. The effects of system operating pressure, degree of subcooled on the two-phase natural circulation cooling limits were examined [1,2]. Fauske et al (1991) [3] developed a theoretical model to predict natural circulation heat removal power limit based upon the channel pressure drop and the available hydrostatic head in the reservoir tank by assuming a steady state conditions with a certain steam quality in the heated section.

$$P = A\left[\frac{2\lambda C\Delta T\rho_\ell\rho_g gL}{1+fL/D}\right]^{1/2} \tag{1}$$

This proposed cooling limit equation has been shown to provide a conservative prediction of test results [4]. If the steam exit quality is unity and the inlet condition is saturated liquid, the equation (1) becomes

$$P = A\lambda\left[\frac{\rho_\ell\rho_g gL}{1+fL/D}\right]^{1/2} \tag{2}$$

Experimental results obtained at the Columbia University Heat Transfer Research Facility (HTRF) under vertical upflow, with a certain coast down procedure, demonstrated that the above model can predict the critical power level for steady state natural convection cooling reasonably well. However, some questions remained to be solved regarding the determination of the power limit below which a transition from forced flow into natural circulation cooling can be successfully established and maintained for a significant period of time. These remaining concerns include: the effect of the rate of flow coast down, the effect of initial flow direction, and the density wave flow oscillation induced during the course of flow reduction.

During the transient from forced flow to natural circulation, after the flow reduced to a certain extend, the forced and free convection effects become comparable when the ratio of G_r/R_e near 1. Under this condition, the effect of buoyancy on heat transfer in the remaining forced flow is affected by the direction of the buoyancy force relative to that of the flow.

In case of initial vertical downflow, the developing of natural circulation cooling in the event of LOF accident involves the reversal of flow direction in the test section. The rate of transient event has a very significant effect on the developing of the natural circulation. During this type of transient, the direction of the residual forced flow in the test section is different from that of the buoyancy-induced natural circulation. It will not only condense the vapor generated in the test section but also suppress the formation of the natural circulation. The developing of natural circulation in the opposite direction (opposing flow) is expected to reduce the rate of heat transfer associated with pure forced convection.

In case of upflow, the developing of natural circulation cooling involves the reversal of flow direction in the less heated bypass channels (cold leg). In the test section, the natural circulation flow is in the same direction with the residual forced flow. The buoyancy induces an assisting flow and is expected to enhance the rate of heat transfer associated with pure forced convection.

INTRODUCTION

In this paper, the dynamics of transient phenomena was examined in a simplified loop to study the developing of the natural circulation flow from an originally forced flow condition. First, the experimental data was used for RELAP5 code verification. Then, the significant variables affecting the transient of two-phase natural circulation were examined which include: the flow coastdown rate as well as the initial forced flow direction.

The modified SRL PC version RELAP codes was benchmarked with experimental results for both vertical downflow and upflow, low pressure operating conditions. In both cases, a circulation pump with electrical control valve were uses to control the rate of LOF event. That is, by controlling the duration of pump coast-down or the valve opening, different transient events with various flow coastdown rates were obtained.

The test configuration used for both experimental testing and RELAP5 simulation was mainly composed of single or multiple electrically heated hot legs and a unheated cold leg. At the absence of forced flow, the water in the hot leg(s) rises due to density difference between the warm water in the hot leg(s) and the cooler water in the cold leg. As the power level in the hot leg gradually increased, voids (steam) begin to form in the hot leg and significantly reduce the hot leg fluid density, resulting in a rapid increase in natural circulation flow. As the power increases further, the pressure drop associated with the two-phase flow begins to have more effect than the increased voids and the increase of natural circulation flow decrease as the power is increased further. Further increase in power will eventually reach a point where an incremental increase in power produces no increase in natural circulation flow. This is the point where the amount of increased natural circulation driving head (buoyancy) is the same as the increased two-phase pressure drop due to the higher steam flow. Beyond this point, further increase of power level may result in a flow instability and eventually lead to a physical burn-out. In case of transient condition, the competing phenomena between the density deriving head and the associated two phase pressure drop becomes much more complicate due to the involvement of additional components, such as rate of steam formation, steam collapsing, as well as frictional and acceleration loss from forced flow.

In case of initial vertical downflow, the results from the RELAP simulation clearly demonstrated a strong effect of the speed of flow coast down on the establishing of natural circulation cooling. The simulation results showed that for the vertical downflow, the faster the flow coast down, the easier for the developing of natural circulation cooling. In case of the upflow, both experimental data and RELAP simulation demonstrated this type of effect to a less degree.

TEST FACILITY

The experimental results used to benchmark the RELAP5 simulation program were obtained in electrically heated test section. A detailed description of this test facility, instrumentation and test procedure was summarized in previous paper [4].

The test section was a 0.625 inch (15.9 mm) diameter circular inconel tube with a heated length of 96 inch (2.44 m) and wall thickness of 0.07 inch (1.778 mm). An unheated bypass line with a 2 inch (50.8 mm) inside diameter was connected in parallel with the heated test section through the inlet and exit plena to serve as a bypass cold leg for the test section.

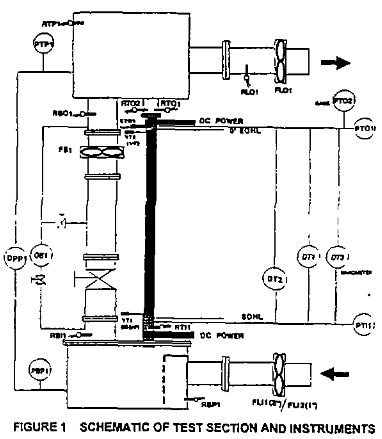


FIGURE 1 SCHEMATIC OF TEST SECTION AND INSTRUMENTS

Figure 1 presents a schematic of the instrumentation layout.

The measurement uncertainty for the major instrument is summarized in the following table (Table 1).

Table 1 Instrument Uncertainty

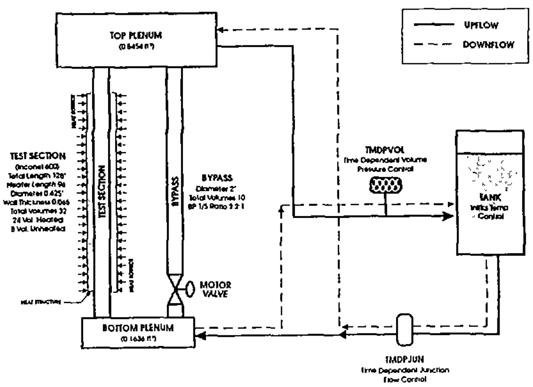
Measurement Parameter	Uncertainty	Full Scale
Absolute pressure	0.049 KPa (0.0071psi)	345 KPa (50 psi)
Diff. pressure	0.01 KPa (0.0015psi)	138 KPa (20 psi)
Power	18 watts	1.6 Mw
Flowrate	0.0012 m^3/min (0.32 gpm)	0.136 m^3/min (36 gpm)

RELAP SIMULATION

In this paper, RELAP5 was used to simulate the dynamics and transient of natural circulation cooling in both upflow and downflow systems. This SRL version of RELAP5 was developed especially to handle low pressure systems.

Two separate models were developed for this study. As shown in the RELAP model loop configuration (Figure 2), the major components in this model include:

FIGURE 2 RELAP5 MODEL FOR UPFLOW AND DOWNFLOW SINGLE TUBE LOOP



- ***Accumulator***: to simulates the tank.
- ***Time Dependent Junction:*** to simulates the pump and controls the flow to the inlet plenum
- ***Test Section and Bypass:*** to simulate the test section and bypass line. The heater is an Inconel 600 tube with 0.625 inches inside diameter, 0.065 inches wall thickness, and 96 inches heated length. With 32 inches of the unheated top and bottom end pieces, the total length of the test section is 128 inches. Axially, total 32 volumes (24 unheated and 8 unheated volumes) were used to simulate the entire test section, each volume is four inch long. A heat structure with constant heat input is attached to the heated section. Bypass is comprised of 10 volumes, and has an inside diameter of 2 inches. Radially, the 0.065 inch heater wall is simulated by three concentric layers with equal thickness of 0.0217 inches.
- ***Bypass Motor Valves***: to simulate the flow split between the test section and bypass. (1 to 2.2 for all tests)
- ***Time Dependent Volume***: to control test section exit pressure.
- ***Top and Bottom Branches***: to simulate the top and bottom plena

Both upflow and downflow models have the same loop components.

Test Conditions

First, a typical natural circulation transient test was used to compare with the RELAP5 simulation. The transient experiment started with an initial steady state upflow at 4 gpm test section flowrate, 122 ^{o}F inlet temperature, 150 psia exit pressure, and 0.15 MBtu/hr-sqft test section heat flux. After established the above steady state condition, the transient was initiated by gradually reducing the overall flowrate to zero. In the experimental testing, a pneumatic control valve located in the inlet line to the inlet plenum was used to control the overall flowrate. The flow split between the test section and the bypass line was set via a valve in the bypass line.

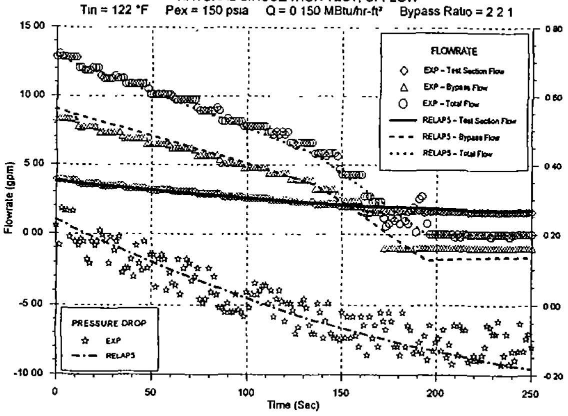
In case of RELAP simulation, the flow transient was controlled by the "Time Dependent Junction Flow Control" located at the inlet line to the inlet plenum. The flow split between the test section and the bypass was simulated by the motorized valve in the bypass line (Figure 2).

In addition, the RELAP5 models were used to examine the effects of the rate of flow coastdown and the initial flow direction. The test conditions covered a range of power inputs from 0.05 to 0.175 MBtu/hr-sqft at test section exit pressure of 90 psia and inlet temperature of 121 ^{O}F. All tests started with initial test section flowrate at 3.7 lb/sec (26.5 gpm) and gradually reduced to zero. The coastdown period, the duration from initial flow to zero flow, examined in this paper includes 1, 10, 20, and 60 seconds.

RESULTS AND DISCUSSION

Figure 3 demonstrates the comparison between the experimental data and the simulation results. In this benchmark case, the flow reduction is completed in two stages with two different coastdown rates. Both experimental data and RELAP5 simulation show that flow reversal occurs in the bypass line before the total flowrate reaches zero. This is due to the combination of difference in density as well as inertia between the cold and hot legs.

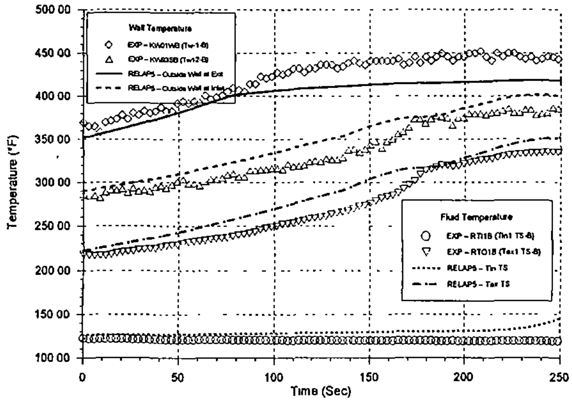
FIGURE 3 EXPERIMENTAL DATA vs RELAP5 CALCULATIONS
NATURAL CIRCULATION TEST, UPFLOW
Tin = 122 °F Pex = 150 psia Q = 0.150 MBtu/hr-ft² Bypass Ratio = 2.2:1



The natural circulation flowrate calculated by RELAP5 is about 1.5 gpm. The experimentally measured test section natural circulation flowrate is the same as the RELAP5 prediction. However, the natural circulation flowrate obtained from the bypass bi-directional flowmeter is only 1.0 gpm. This is due to the failure of the frequency converter used for the bypass bi-directional flowmeter in the reversed flow direction below 1 gpm. This is also verified by the good agreement between the measured and predicted test section pressure drop under both single-phase and two-phase conditions. (Figure 3). The pressure drop presented in this figure is a direct measurement obtained from the differential pressure transducer without any hydraulic head correction. For a single phase pressure drop measurement, the hydrostatic head on the test section side cancels that on the pressure line side. The differential pressure transducers only measured the frictional and acceleration pressure drop. However, for a two-phase pressure drop measurement, different hydrostatic head between the single-phase pressure line and the two-phase test section channel could result in a negative pressure drop reading. The test section pressure drop becomes negative at about 100 seconds after the initiation of the transient. This sign of significant boiling is also observed in the heater wall temperature from both experimental data and simulation results (Figure 4) where the wall temperature reaches a plateau due to boiling.

The wall temperature and fluid temperature for the above benchmark case are presented in the Figure 4. Generally, the predicted temperatures follow the measured temperatures very well. The largest deviation is observed between the measured and predicted wall temperature at the test section exit. This is mainly due to that only three concentric layers were used in RELAP model to simulate entire 0.065 inch thick heater wall. The

FIGURE 4 EXPERIMENTAL DATA vs. RELAP5 CALCULATIONS
NATURAL CIRCULATION TEST, UPFLOW
Tin = 122 °F Pex = 150 psia Q = 0.150 MBtu/hr-ft² Bypass Ratio = 2.2:1



outer wall temperature plotted in this figure actually is the average temperature of the outer layer which is representing the temperature at the center of this layer at 0.054 inch from the heater inner wall surface. Experimentally, the outer wall temperature is measured by thermocouples at the external surface of a heater with actual wall thickness of 0.07 inch. For the inconel heater with 0.15 MBtu/hr-sqft heat flux, this represents approximate 17 ^{O}F difference. Another possible error may be due to the uncertainty of using only three layers (nodes) to simulate the parabolic temperature profile across the radial of the heater wall.

Natural Circulation Power Limit

In this paper, after the benchmark test, the RELAP program is used to simulate different transient conditions and study the effects of flow reduction rate (coastdown period) and the initial flow direction on the natural circulation cooling power limit.

Density wave oscillation was observed in most of two-phase natural circulation developed under low pressure and high subcooled condition.

In certain cases, steam formation and collapsing may induce large amplitude flow and pressure oscillations which eventually lead to a physical burn-out. Experimentally, the power limit above which the natural circulation can not establish was determined by the occurrence of wall temperature excursion. In the RELAP simulation, a sequence of large amplitude and high frequency of flow and pressure oscillation was observed.

Figure 5 shows a typical case of natural circulation (NCC) power limit for a given coast down rate (60 seconds). In this case the NCC was developed from an initial steady state condition with inlet temperature at 121 ^{O}F, exit pressure at 90 psia, bypass ratio of 2.2:1, and coastdown period of 60 seconds. For both the tests with 0.1 and 0.15 MBtu/hr-sqft heat flux, the natural circulation flow was established and maintained for more than 130 seconds (130 seconds after total flow reach zero). However, flow and pressure oscillations were observed for the test with 0.15 Mbtu/hr-sqft hat flux after 60 seconds into NC. The test with 0.175 Mbtu/hr-sqft experienced an early flow instability and the simulation run was terminated due to temperature excursion. This indicates that the power limit for establishing a NCC from the above initial conditions is between 0.15 and 0.175 Mbtu/hr-sqft (or between 58 kW to 68 kW). This prediction agrees with the experimental data. For the same test condition, equation (1) calculates a low power limit about 52 kW and the equation (2) calculates a high power limit about 79 kW.

Effect of flow direction

NCC Power Limit

The effect of initial forced flow direction on the NCC power limit is illustrated in Figures 5 and 6. In the Figure 6, for the same given set of initial condition in a vertical downflow system, the NCC power limit is about 0.15 Mbtu/hr-sqft instead of 0.175 Mbtu/hr-sqft as in the initial upflow system. As shown in figure 6, both tests with 0.075 and 0.1 MBtu/hr-sqft recover from initial slight oscillation and maintain for more than 120 second NCC. However, in case of 0.15 Mbtu/hr-sqft, a series of

FIGURE 5 RELAP5 CALCULATIONS FOR UPFLOW TEST
TEST SECTION FLOWRATE
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Coast Down =60 sec

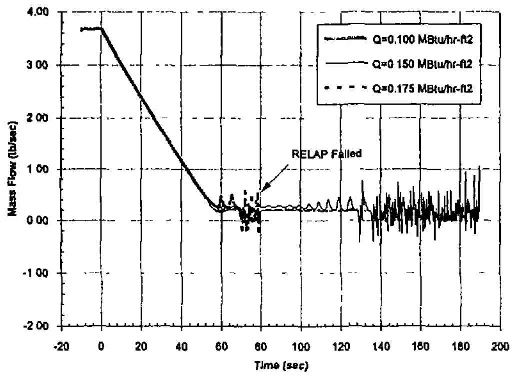
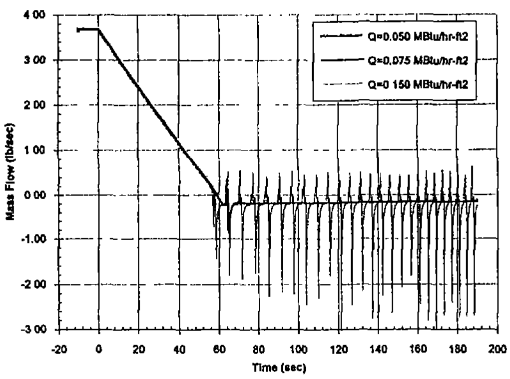


FIGURE 6 RELAP5 CALCULATIONS FOR DOWNFLOW TEST
TEST SECTION FLOWRATE
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Coast Down =60 sec



large amplitude flow instability oscillation is observed and eventually leads into a temperature excursion which does not show in the initial upflow case. This flow direction effect is not predicted by equation (1) or (2). This is due to that both equations (1) and (2) were developed [3] based upon the channel pressure drop and the available hydrostatic head in the reservoir tank under a steady state conditions with a certain steam quality in the heated section. No dynamic factor is included in these equations.

NCC Flow Instability

For the test with initial upward forced flow, the remaining forced flow during the coastdown period is in the same direction as the developing NC. However, for the test with initial downflow, the remaining forced flow during the coastdown period introduces an instability factor in addition to the density wave oscillation due to the fact that the forced flow is working against the free conventional flow in the opposite direction. As shown in Figure 7, for the test with 0.15 Mbtu/hr-sqft, large amplitude flow oscillation is observed with a 0.17 Hz fundamental frequency for the test with initial downflow. For the same test condition, the test with initial upflow does not experience this type of flow instability oscillation (Figure 8).

Effect of Flow Coastdown Rate

Another parameter examined in this paper is the coastdown effect on the NCC power limit.

For the initial downflow case, the developing of natural circulation involves a transition of flow reversal in the heated section. Depend on the rate of flow coast down as well as the rate of heat input and steam

FIGURE 7 RELAP5 CALCULATIONS FOR DOWNFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q=0.150 MBtu/hr-ft² Coast Down = 60 Sec

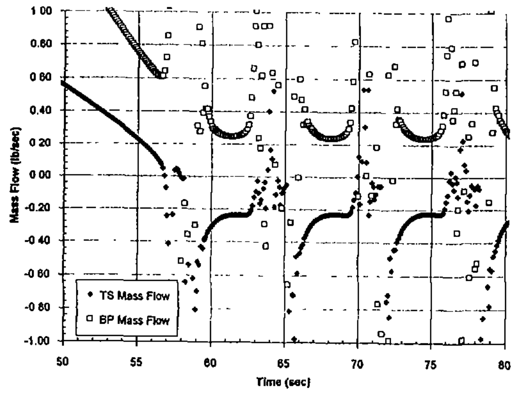
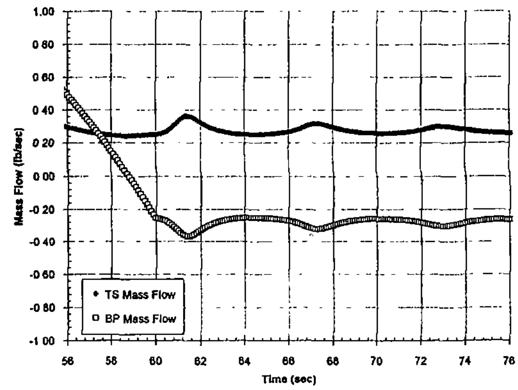


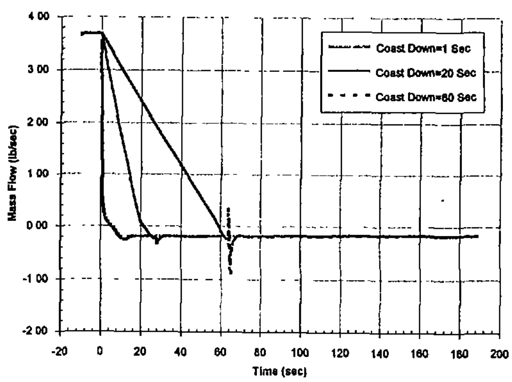
FIGURE 8 RELAP5 CALCULATIONS FOR UPFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q=0.150 MBtu/hr-ft² Coast Down = 60 Sec



formation, a flow and pressure oscillation may result during the transition from forced convection into natural circulation.

As shown in Figure 9, with the same initial downflow test condition, the tests with 1 and 20 seconds coastdown period develop NCC without any oscillation while the test with 60 second coastdown period experiences an initial flow excursion.

FIGURE 9 RELAP5 CALCULATIONS FOR DOWNFLOW TEST
TEST SECTION FLOWRATE
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q = 0.075 MBtu/hr-ft² (29 KW)



For the test with initial upward forced flow, the remaining forced flow during the coastdown period may enhance the establishing of natural circulation because the forced flow and free convection flow are in the same direction. However, the longer the coastdown period, the higher the exit coolant temperature. This affects the duration that the natural circulation can substation.

FIGURE 10 RELAP5 CALCULATIONS FOR UPFLOW TEST
TEST SECTION FLOWRATE
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q = 0.175 Btu/hr-ft² (67 KW)

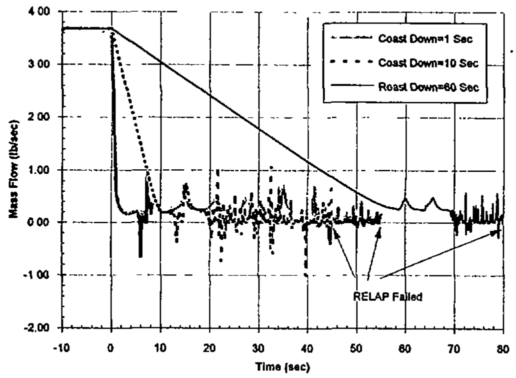
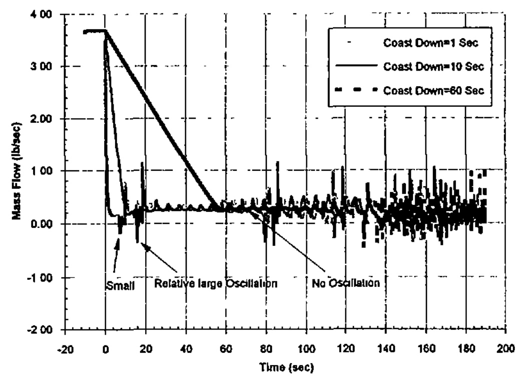


FIGURE 11 RELAP5 CALCULATIONS FOR UPFLOW TEST
TEST SECTION FLOWRATE
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q = 0.150 MBtu/hr-ft² (57.5 KW)



As shown in Figure 10, for the same initial test conditions, the test with long coastdown period (60 seconds) does not experience any significant flow oscillation at initial 10 seconds of NCC, while relative larger amplitude and high frequency oscillation are observed in the tests with 1 and 10 seconds coastdown period. However, the NCC in the tests with long coastdown period (60 seconds) terminated quicker than the test with shorter coastdown period (1 or 10 seconds). This is due to that the exit temperature at the beginning of NCC is higher for the test with longer coastdown period. The same pattern of coastdown effect is also observed in the tests with 0.15 Mbtu/hr-sqft (Figure 11).

Other Parameters

Figures 12, 13, 14, 15 and 16 present different parameter values throughout the transient from forced flow to natural circulation flow. As shown in these figures, all variables correspond to each excursion event very consistently. Without any prolonged flow coastdown period, immediately after the pump trips (about 1 second), the bypass flow reversal occurs and leads to a natural circulation flow. At the beginning of the transient, the exit temperature rises gradually until reaches the saturation temperature at about 6 seconds after the pump trips. However, the inlet temperature stays very low until a suddenly increase takes place, at about 6 seconds into NCC, due to that the entire heater channel boils off and fills with large volume of steam (see Figure 16). The rapidly expanding steam tends to push hot fluid toward both upward and downward directions and will result in another flow reversal in the bypass line. Immediately follows this flow reversal, the bypass flow reverses again due to the large density gradient between the cold and hot leg. The

FIGURE 12 RELAP5 CALCULATIONS FOR UPFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q=0.175 MBtu/hr-ft² Coast Down = 1 sec

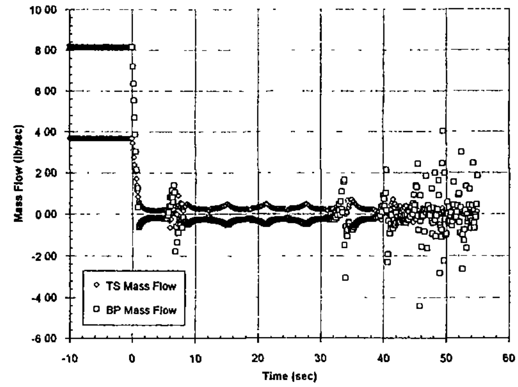


FIGURE 13 RELAP5 CALCULATIONS FOR UPFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q=0.175 MBtu/hr-ft² Coast Down = 1 sec

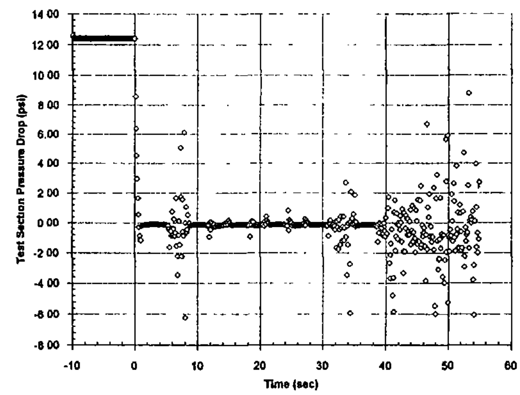
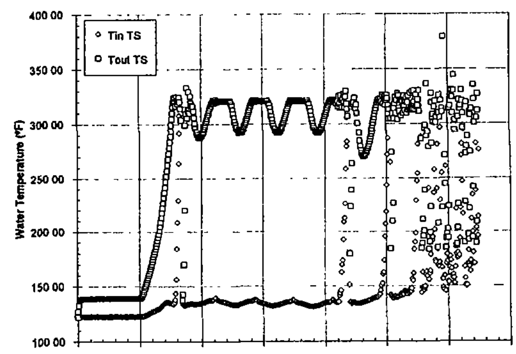


FIGURE 14 RELAP5 CALCULATIONS FOR UPFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2.2:1
Q=0.175 MBtu/hr-ft² Coast Down = 1 sec



flowrate of this reversal flow in the bypass line further accelerated by the large suction effect in the heater section caused by the large volume of steam collapsed in the heater section. This event takes place about 7 second after the pump trip and followed by a series of low frequency oscillation (Figure 12). The frequency of this cycle is dependent on the relaxation time, the loop time constant and the heat input rate. The same event is also observed in the heater wall temperatures (Figure 15), test section pressure drop (Figure 13), and heater channel void fraction (Figure 16).

FIGURE 15 RELAP5 CALCULATIONS FOR UPFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2 2:1
Q=0.175 MBtu/hr-ft² Coast Down = 1 sec

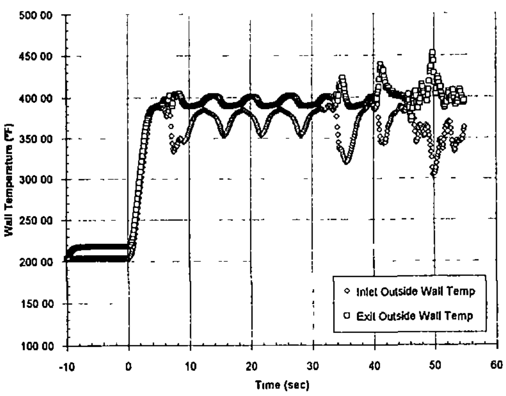
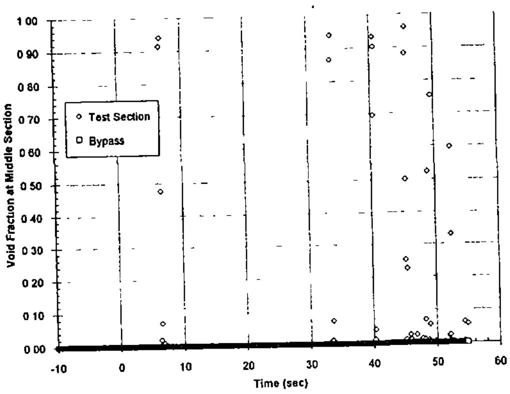


FIGURE 16 RELAP5 CALCULATIONS FOR UPFLOW TEST
Tin = 121 °F Pex = 90 psia Bypass Ratio = 2 2:1
Q=0.175 MBtu/hr-ft² Coast Down = 1 sec



CONCLUSION

The analytical results showed that a natural circulation cooling pattern can be established and that a significant cooling period can be maintained for both initial upflow and downflow conditions. In the benchmark case, the RELAP simulation program predicts the transient phenomena from forced convection into natural circulation cooling very well.

Both the initial flow direction and the rate of forced flow reduction (coastdown rate) have effects on the development and the stability of the natural circulation cooling.

The two-phase natural circulation cooling limit is higher for the test started with upflow forced convection than for the tests with initial downflow. In addition, the NCC developed from an initial downflow system subject to greater flow oscillation than that developed from an initial upflow system.

The rate of flow reduction, or pump coast down, is identified as a significant factor in the establishing of natural circulation from an initially forced flow condition. The effect of pump coast down is also dependent on the initial flow direction. In case of vertical downflow, the results from the RELAP simulation clearly demonstrated a strong effect of the speed of flow coast down on the establishing of natural circul;ation cooling. The simulation results showed that for an initial vertical downflow, the faster the flow coast down, the easier for the developing of natural circulation cooling. For the test with initial upflow force convection, the effect of pump coast down rate is not as significant. This may be due to the cancellation between the two major contributing factors, namely, the test section exit temperature and the flow direction between the residual forced flow and the developing natural circulation flow.

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