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Development of Thermal Stratification Formation Criteria with Applications to PTS Evaluation

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ABSTRACT

The thermal stratification phenomenon of Reactor Coolant System (RCS) piping and the formation of cold water plume of Reactor Pressure Vessel (RPV) downcomer, when High Pressure Safety Injection (HPSI) associated with overcooling transient is under stagnated loop condition, arise due to incomplete mixing. Those behavior presenting temperatures much lower than the bulk average fluid temperature can not be described by system analysis codes such as RETRAN and RELAP. This paper focuses on the development of a numerical analysis model for buoyancy driven thermal stratification criteria using PHOENICS code which can predict the unsteady 3-dimensional mixing for thermal stratified turbulent flow in RCS piping and apply to Pressurized Thermal Shock (PTS) evaluation. The developed model was validated by the test results performed in CREARE 1/2 scale test facility. Richardson (Ri) number was introduced to present the criterion of thermal stratification formation due to the change of cold leg flow rate. The thermal stratification formation line expressed in this paper may be used as the decision criterion for the detailed thermal-mixing analysis recommended in R.G. (Regulatory Guide) 1.154 for plant specific PTS evaluation on a radiation embrittled vessel.

1. INTRODUCTION

When an accident, such as LOCA (Loss of Coolant Accident), arises in a nuclear power plant, a cold HPSI fluid enters the cold legs to protect the core. The HPSI fluid can be well mixed or stratified in the cold legs and the vessel downcomer based on fluid condition and density difference between the cold HPSI fluid and the hot coolant. If the stratified flow enters the vessel downcomer, the cold plume quickly cools down a section of radiation embrittled vessel below the bulk average fluid temperature which increases the failure probability due to severe thermal stress. The transient thermal-hydraulic computer programs available to analyze the effects of pressurized thermal shock transients do not model fluid behavior with sufficient detail to predict the onset of HPSI thermal stratification in the cold leg and the subsequent cold leg and downcomer behavior [1]. Also, previous thermal-mixing programs developed for analyzing these behavior tend to be unreliable due to the calculation limitation and excessive conservatism [2].

This paper focuses on the development of a 3-dimensional thermal-mixing analysis model using PHOENICS code to reduce the excessive conservatism and calculation time and to identify the thermal stratification formation time. The developed model was composed based on a 2-loop Pressurized Water Reactor (PWR) and validated by the CREARE 1/2 scale test. The thermal stratification formation criterion according to the flow rates of reactor coolant and safety injection fluid was evaluated based on the numerical analysis method. And, the formation time of the thermal stratification phenomena was estimated based on dimensionless Ri number.

2. MODEL DESCRIPTION AND VERIFICATION

2.1 *Model Description*

A numerical analysis model using PHOENICS code was developed to analyze the thermal stratification phenomena during HPSI and to suggest the thermal stratification criteria. The model plant is a 2-loop PWR. Figure 1 shows a top view of the reactor vessel for one loop RCS. Figure 2 shows an elevation view of the vessel downcomer region with the cold leg nozzle. To simplify the analysis, a model consisting of one cold leg and half of the reactor vessel was developed. The sections included in this model are the loop seal, cold leg, core barrel, thermal shield, and reactor vessel wall. The safety injection piping was modeled as inclined 45° from top of the cold leg piping approximately 14.85 ft from the reactor vessel wall.

The relevant geometric data of the reactor vessel configuration are provided in Table 1. Figure 3 illustrates the cell divisions, which have limitations of 28 computational cells in the x-direction, 28 cells in the y-direction, and 25 cells in the z-direction, based on BFC (Body Fitted Coordinate) methods used to the conjunction sections between the reactor vessel and cold legs. In the nuclear power plant, there is a horizontal bend in each piping cold leg. Previous studies have shown that there was little effect on the calculated velocity and temperature profiles adjacent to the vessel wall when a cold leg pipe with a horizontal bend was modeled as straight piping [3]. Since it makes little difference in the calculations, input presentation time was saved by modeling the horizontal bend in the cold leg piping as straight piping.

Table 1. Geometric data

(ft)

Items	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter	2.292	11.000	-	-	2.583	9.083	9.606
Length	17.050	20.042	-	-	30.813	25.354	15.000
Base Metal Wall Thickness	0.222	0.542	0.344	0.386	0.248	0.165	0.297
Clad Thickness	0.000	0.010	0.010	-	0.000	-	-
Insulation Thickness	0.250	0.250	0.250	-	0.250	-	-

* Inner diameter of safety injection piping: 0.432 ft

Turbulence was incorporated in the code calculations through the use of single value effective viscosity and thermal conductivity values. The coolant flow to the vessel downcomer is separated by the thermal shield and reattached in the lower plenum. Although the separated and reattached flow behavior may be well predicted by several turbulence viscosity models, such as KE-EP model, Yap KE-EP model, RNG KE-EP model, etc., calculation time is a limiting factor [4]. On the other hand, calculation time is not a problem using the constant viscosity model which utilizes the average domain velocity and constant eddy viscosity values. Therefore, the constant viscosity values were calculated based on the constant viscosity model. The Boussinesq approximation was then used in the model to account for the buoyancy effects.

2.2 *Model Verification*

To verify the developed model, the same model as the CREARE 1/2 scale test facility consisting of one cold leg and half of the reactor vessel was recomposed. The CREARE test (May 106) performed in 1990 was sponsored by the NRC and EPRI [5]. For the test, the safety injection piping is located directly on top of the cold leg and the thermal shield is included in the CREARE test facility. The geometric data of the CREARE test facility are given in Table 2 and the test conditions are as follows:

- Coolant flow is stagnated and density of coolant is 54.8 lb/ft^3
- Cross section area of safety injection piping is 0.11 ft^2
- Flow rate and density of safety injection fluid are 11.4 lb/sec and 62.43 lb/ft^3

Figures 4 and 5 show the comparisons between the CREARE 1/2 scale test results and the calculation results using PHOENICS code. The calculation was performed until 3,000 seconds. And, the calculation results were compared with the test results at the measurement positions in the cold leg as shown in Figures 4 and 5. In both cases, the prediction appear to properly represent the recorded data.

Table 2. Geometric data of CREARE 1/2 scale test facility

(ft)

Items	Cold Leg	Vessel /Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter	1.19	-	-	-	1.25	-	-
Length	12.39	11.59	-	-	8.94	11.59	0.13
Base Metal Wall Thickness	0.07	0.23	0.02	-	0.07	0.23	0.13
Clad Thickness	-	-	-	-	-	-	-
Insulation Thickness	0.17	0.17	0.17	0.17	0.17	0.17	-

2.3 *Boundary Conditions*

Boundary conditions for the analysis performed with the developed model were taken from the data of full power normal operation for a nuclear power plant. In order to estimate the thermal stratification formation time and flow condition according to the safety injection flow rate, when the coolant flow rate entering the cold leg is decreased exponentially as shown in Figure 6, the safety injection flow rates were taken as 10, 30, 50, 70, 80, 90, and 100 lb/sec, respectively. Even though the coolant flow rate was estimated, it seems to properly represent the actual situation. Based on the coolant flow rate of the cold leg inlet, the flow velocity of the coolant can be expressed as Eq. (1):

$$v = \frac{\dot{m} \times e^{(-0.008 \cdot t)}}{\rho \times A} \tag{1}$$

Where, $\dot{m}$ is initial coolant flow rate (700 lb/sec) injected to the cold leg, t is time, ρ is density of coolant, and A is the cold leg cross section area (4.126 ft^2). The temperatures of the coolant and safety injection fluid was taken constant values as 541.4 °F and 80 °F, respectively.

3. RESULTS AND DISCUSSION

When an accident, such as loss of coolant accident, main steam line break, steam generator tube rupture, etc., arises in a nuclear power plant, the coolant flow rate entering the cold legs is decreased exponentially due to the reactor coolant pump trip. The calculation was performed until 600 seconds to identify the thermal stratification formation time and the flow behavior of the cold leg and vessel downcomer according to the variation of safety injection flow rate. The input coolant flow rate was supposed to decrease exponentially.

As time progresses, the changes of flow behavior inside the cold leg piping approximately 3.18 ft from the reactor vessel wall are shown in Figure 7. In this figure, the unstable flow behavior is shown at 100 seconds and the considerable mixing is shown at 300 seconds. The initiation of thermal stratification phenomenon is shown at 500 seconds and the stable thermal stratification phenomenon is shown at 600 seconds. Figure 8 shows the flow behavior in the cold leg piping along the distance from the location connected to the safety injection piping. In this figure, the flow behavior, injected through the safety injection piping, is shown (A) at a distance of 14.86 ft from the reactor vessel wall. And, (B), (C), and (D) show the flow behaviors at a distance of 11.65, 7.41, and 3.18 ft, respectively. As the distance closes to the reactor vessel wall, the thermal stratification phenomenon is appeared apparently, which is shown in the series of flow behavior in Figure 8.

Figure 9 shows the temperature distributions in the vessel downcomer. The temperature distribution between the core barrel and the thermal shield is shown in (A) and the temperature distribution between the thermal shield and the reactor vessel wall is shown in (B) of Figure 9. This figure shows that the stratified flow enters between the core barrel and the thermal shield rather than between the thermal shield and the reactor vessel wall because of the flow velocity in the cold leg. If the stratified flow enters the downcomer of the reactor vessel, the failure probability of a radiation embrittled vessel increases due to the local overcooling. When the cold HPSI fluid enters the cold leg piping, the overlapped temperature and vector distributions on cross section connected to the safety injection piping are shown in Figure 10.

The evaluation position in the cold leg piping approximately 3.18 ft from the reactor vessel wall is shown in Figure 11. As examples for the safety injection flow rates of 30 and 80 lb/sec, the temperature variations with time at the evaluation positions are shown in Figures 12 and 13, respectively. In these figures, as time progresses, the flow behaviors were found initially unstable and fully mixed gradually. After a time, the thermal stratification phenomena were found and the temperatures at each evaluation positions were presented differently. As the same flow behaviors were found in all cases except for the safety injection flow rate of 100 lb/sec, it was identified that the thermal stratification phenomena were not generated in the case of over the flow rate of 100 lb/sec.

To determine the thermal stratification formation criterion, two other dimensionless groups, Ri (Richardson) number and time, were introduced. Ri number in Eq. (2) is expressed in terms of the ratio of Gr number representing the buoyance effect by viscosity effect and Re number representing the inertia force effect by viscosity effect.

$$Ri = \frac{Gr}{Re^2} = \frac{g\,\beta\,\Delta T\,D}{(u_h - u_c)^2} \tag{2}$$

Where, g is the gravity constant, β is the thermal expansion coefficient, ΔT is the temperature difference between hot and cold fluid, D is the diameter of cold leg piping, and u_h and u_c are the velocities of hot and cold fluid. And, the dimensionless time is expressed in the form:

$$Dimensionless\ Time = \frac{t^{*}\,\nu}{D^2} \tag{3}$$

Where, t^* is the real time and υ is the kinematic viscosity.

Figure 14 shows the Ri numbers, which were calculated according to the variations of the coolant and safety injection flow rate, and the thermal stratification formation line expressed as the stratification/mixing boundary which was connected the Ri numbers at the time of thermal stratification formation to point by point. From the fact that, if the safety injection flow rate exceeds 100 lb/sec, the thermal stratification phenomena do not generated in the cold legs, the Ri number between 0.177 and 0.220 was estimated the lower bound of thermal stratification formation. As shown in Figure 14, it was concluded that the thermal stratification phenomena were not generated in the left side (Well Mixed Zone) of the thermal stratification formation line but generated in the right side (Stratified Zone). If the monitoring positions move to the reactor vessel wall, the thermal stratification formation line will be moved to right side. And, if the monitoring positions move to the safety injection piping, the thermal stratification formation line will be moved somewhat to left side. In this sense, it is expected that the thermal stratification formation line may be used as the decision criterion for the detailed thermal-mixing analysis recommended in R.G. 1.154 in pressurized thermal shock evaluation for a radiation embrittled vessel.

4. CONCLUSIONS

A numerical analysis model using PHOENICS code was developed to analyze the thermal stratification phenomena due to incomplete mixing between the cold HPSI fluid entering the cold legs for protecting the core associated with overcooling transient and the hot coolant. The model based on a pressurized water reactor was validated by the test results performed in CREARE 1/2 scale test facility. To estimate the thermal stratification formation time according to the flow rates of the HPSI and cold leg coolant and to understand the flow behavior of the cold leg and vessel downcomer, the coolant flow rate was supposed to decrease exponentially and the safety injection flow rates were taken as 10, 30, 50, 70, 80, 90, and 100 lb/sec, respectively.

To determine the thermal stratification formation criterion, two other dimensionless groups, Ri number and time, were introduced. The thermal stratification formation line, classifying the well mixed zone and the stratified zone, was suggested based on the Ri numbers at the time of the thermal stratification formation. Since the thermal stratification phenomena were generated in all cases except for the safety injection flow rate of 100 lb/sec, the Ri number between 0.177 and 0.220 was estimated the lower bound of thermal stratification formation. Also, it was identified that, even though the flow conditions were satisfied with the criteria of thermal stratification formation, the thermal stratification phenomena were not generated in all location of the cold leg. Depending on the analysis results in this study, it is concluded that the thermal stratification formation line can be used as the decision criterion for the detailed thermal-mixing analysis recommended in R.G. 1.154 for plant specific PTS evaluation on a radiation embrittled vessel.

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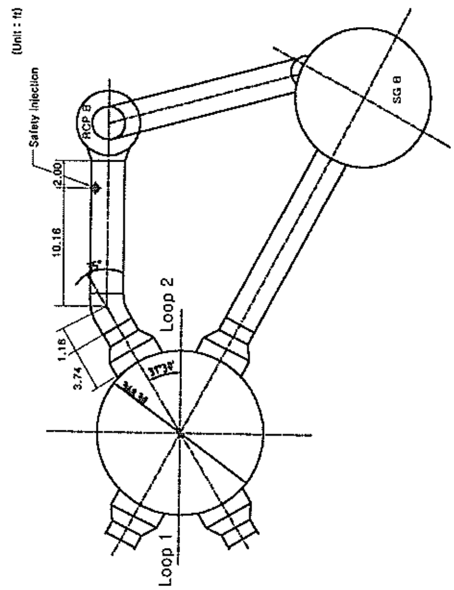


Fig. 1 Top view of RCS loop

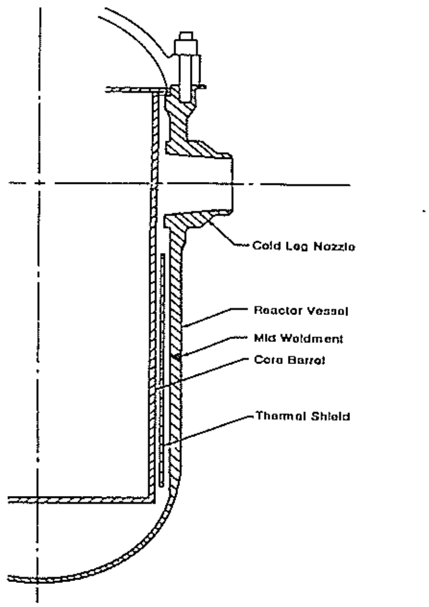


Fig. 2 Elevation view of RPV

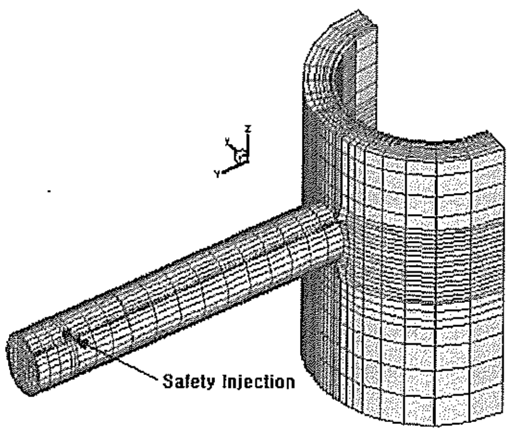


Fig. 3 Cell Divisions

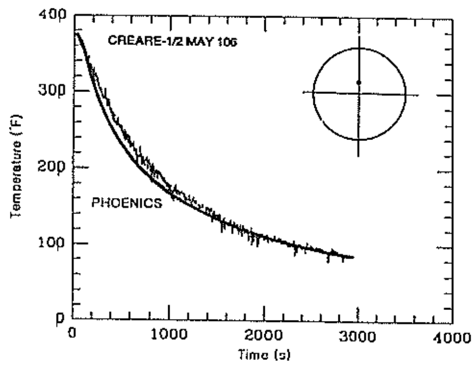


Fig. 4 Comparison of Temp. above the cold leg centerline

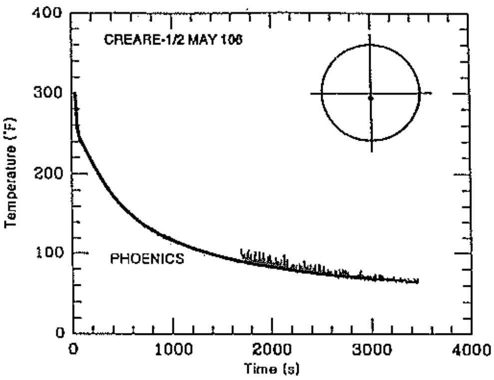


Fig. 5 Comparison of Temp. below the cold leg centerline

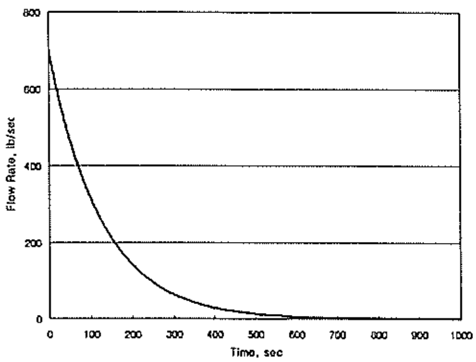
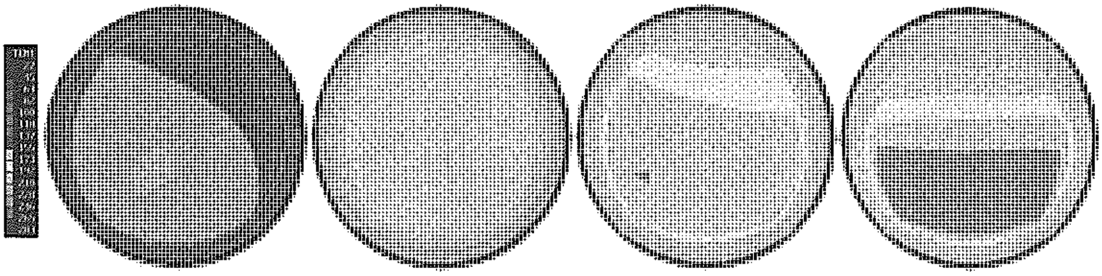
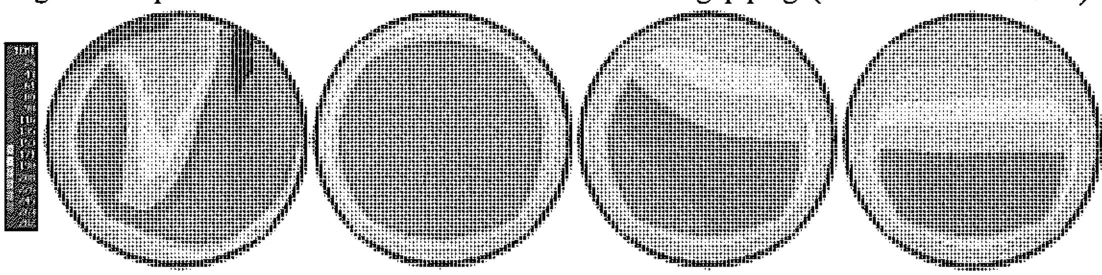


Fig. 6 Input coolant flow rate



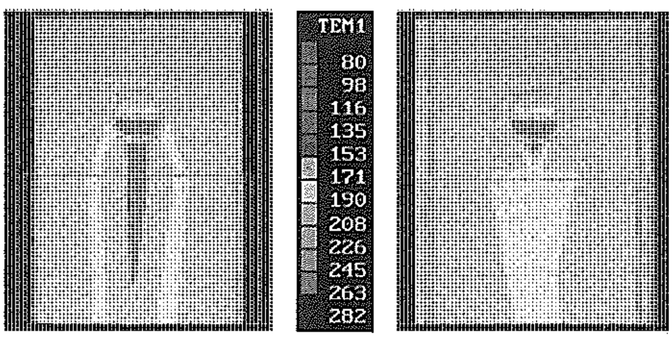
(A) 100 sec. (B) 300 sec. (C) 500 sec. (D) 600 sec.

Fig. 7 Temp. distributions with time inside the cold leg piping (3.18 ft and 50 lb/sec)



(A) 14.86 ft (B) 11.65 ft (C) 7.41 ft (D) 3.18 ft

Fig. 8 Temp. distributions along the distance inside the cold leg piping (600 sec. and 50 lb/sec)



(A) Core Barrel-Thermal Shield (B) Thermal Shield-RPV

Fig. 9 Temp. distributions (600 sec. and 50 lb/sec)

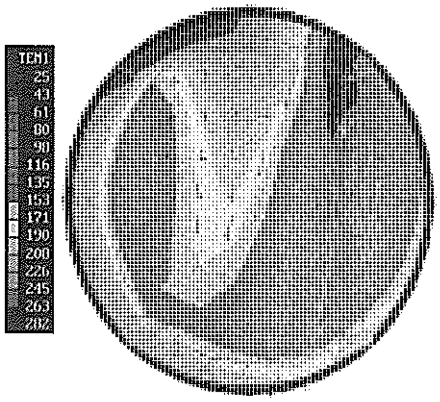


Fig. 10 Temp./vector distribution

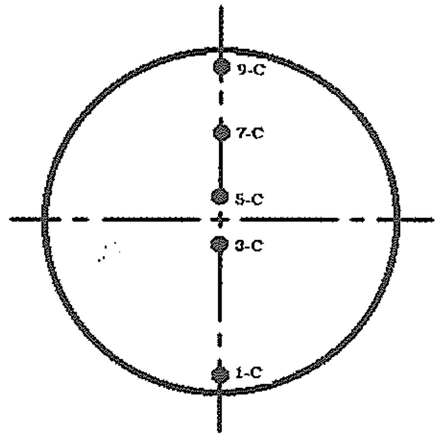


Fig. 11 Temp. evaluation position

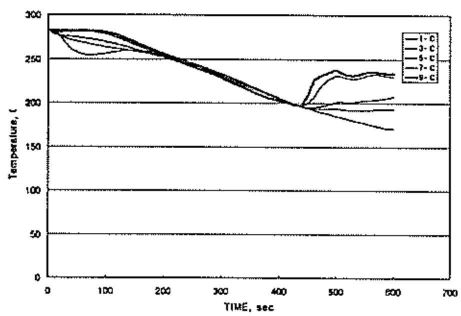


Fig. 12 Temp. profile (SI: 30lb/sec)

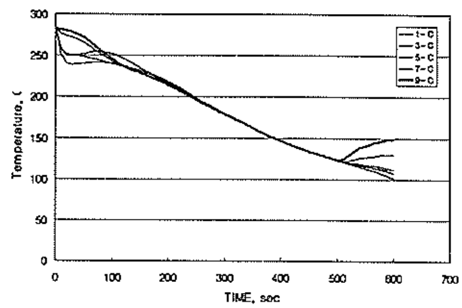


Figure 13. Temp. profile (SI: 80lb/sec)

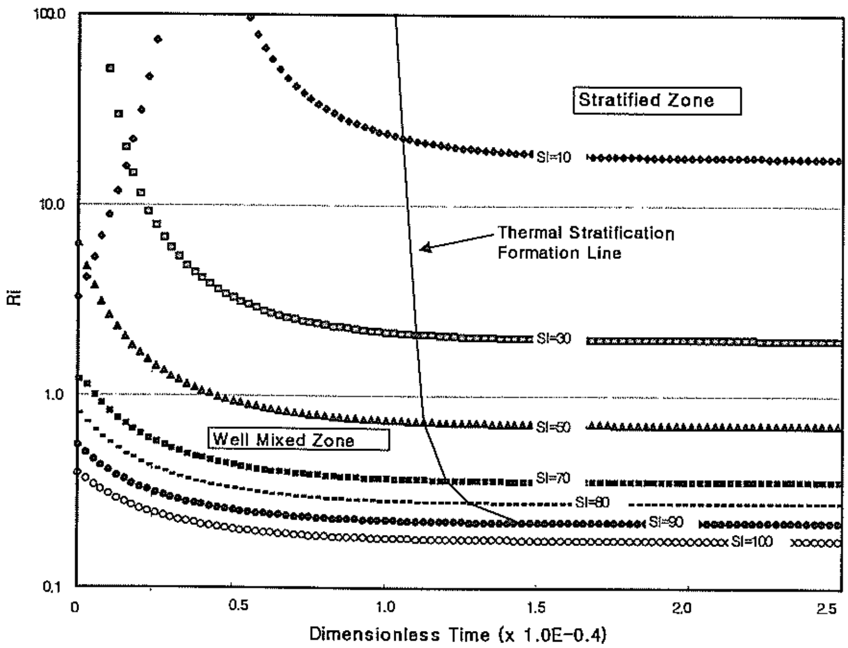


Fig. 14 Thermal stratification formation line overlapped the Ri numbers with time