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FAVOR: A New Fracture Mechanics Code for Reactor Pressure Vessels Subjected to Pressurized Thermal Shock

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ABSTRACT

Probabilistic fracture mechanics (PFM) analysis is a major element of the comprehensive probabilistic methodology endorsed by the NRC for evaluation of the integrity of Pressurized Water Reactor (PWR) pressure vessels subjected to pressurized-thermal-shock (PTS) transients. OCA-P and VISA-II are PTS PFM computer codes (developed at Oak Ridge National Laboratory and Pacific Northwest Laboratory, respectively, in the 1980's with NRC funding) that are currently referenced in Regulatory Guide 1.154 as acceptable codes for performing plant-specific analyses. These codes perform PFM analyses to estimate the increase in vessel failure probability as the vessel accumulates radiation damage over the operating life of the vessel. Experience with the application of these codes in the last few years has provided insights into areas where they could be improved.

It is anticipated that there will be an increasing need for an improved and validated PTS PFM code which is accepted by the NRC and utilities, as more plants approach the PTS screening criteria and are required to perform plant-specific analyses. The NRC funded Heavy Section Steel Technology (HSST) Program at Oak Ridge National Laboratories is currently developing the FAVOR (Fracture Analysis of Vessels: Oak Ridge) PTS PFM code, which is intended to meet this need.

The FAVOR code incorporates the most important features of both OCA-P and VISA-II and contains some new capabilities such as (1) PFM global modeling methodology (2) the capability to approximate the effects of thermal streaming on circumferential flaws located inside a plume region created by fluid and thermal stratification (3) a library of stress intensity factor influence coefficients, generated by the NQA-1 certified ABAQUS computer code, for an adequate range of two and three dimensional inside surface flaws (4) the flexibility to generate a variety of output reports, and (5) user friendliness.

1.0 INTRODUCTION

The NRC PTS rule [1] requires plants that desire to operate beyond the screening criteria established by the PTS rule to submit a plant-specific safety analysis. Regulatory Guide 1.154 [2] recommends the content and format for the plant-specific integrated PTS analyses. The objective of performing the plant-specific PTS analysis is to calculate the probability of vessel failure due to PTS. An important element of performing this analysis is the calculation of the conditional probability of failure of the vessel by performing PFM analyses. The results of such analyses, when compared with limits of acceptable failure probabilities, provide an estimation of the residual life of a reactor pressure vessel. Results of such analyses can be used to evaluate the benefits of plant-specific mitigating actions designed to reduce the probability of failure of a reactor vessel, potentially extending the operating life of the vessel.

FAVOR will continue to mature and evolve in the future, i.e., provide a framework into which future fracture technology developed in the HSST and other programs can be incorporated. It is intended that FAVOR continuously reflect the current state-of-the-art in

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fracture technology, and that it will eventually accurately address all important conditions encountered in plant-specific PTS analyses.

2.0 FAVOR DESIGN OBJECTIVES

Regulatory Guide 1.154 requires that a PFM analysis be performed on the entire vessel beltline. A developed view of a representative RPV beltline region is illustrated in Figure 1. The beltline region (that region of the vessel adjacent to the core active fuel) may consist of distinct regions such as axial and circumferential welds and plates, each of which may have its own distinguishing embrittlement related and flaw geometry parameters and be subjected to different loads. There may also be variations of these parameters inside each distinct region (subregions), particularly axial and azimuthal variations of fluence.

A main objective in the design of FAVOR was to provide the ability to model and analyze the entire vessel beltline region (multiple regions and multiple flaws) in a single PFM analysis. This should make a Regulatory Guide 1.154 - type analysis easier to perform and also totally eliminate the potential conservatism due to "double counting." Double counting is the calculation of more than one failure per simulated vessel. It is inherent to some extent in both the VISA-II [3] and OCA-P [4] probabilistic methodologie due to required adjustments for the correct number of flaws and / or combining results of PFM analyses which were performed for different beltline subregions. FAVOR can be used to model the entire beltline region, or any subset of it, and the degree of detail to be included in the model is at the discretion of the user.

Other design objectives were to incorporate the ability to include the effects of thermal streaming and to incorporate an accurate library of stress intensity factor influence coefficients for an adequate range of two and three dimensional inside surface flaws. Additional design objectives were to make the FAVOR code user-friendly, modularly designed, quality assured, computationally efficient, self contained (no external files required), and well documented.

3.0 FAVOR OVERVIEW

The FAVOR code is divided into 3 separate modules as shown in Figure 2.

FAVL - Load analysis
FAVD - Deterministic fracture mechanics analysis
FAVP - Probabilistic fracture mechanics analysis

This modular design lends itself well to code maintenance and enhancement as well as being more computationally efficient.

The load analysis for a specific PTS event is performed only once and the user-named output file is used repeatedly as input into any deterministic or probabilistic fracture analysis. This structure lends itself well to the common procedures of investigating the fracture reponse of a vessel to a specific PTS event over a range of embrittlement and flaw distribution sensitivities, or conversely, investigating the fracture response of a vessel of specified embrittlement and flaw distribution to different PTS transients.

A brief description regarding the function and capabilities of each of the modules is discussed below.

3.1) FAVL - LOAD ANALYSIS MODULE

The FAVL module accepts a user-friendly user-named input dataset which contains the vessel geometry, thermal-elastic properties of the clad and base materials, and the PTS event definition. There are no embrittlement related data in the FAVL input dataset. The PTS event definition consists of time-history data pairs for the convective heat transfer coefficient, coolant temperature, and pressure. Each of these time histories may be accurately described by using up to 100 discrete time-history pairs. This provides the capability for very accurate descriptions of the pressure and thermal hydraulic boundary conditions imposed on the inner surface of the vessel wall, including those PTS events which exhibit discontinuities, such as the case for pressure transients which have repressurizations.

FAVL generates all the load parameters required to perform a fracture analysis of the entire vessel beltline region in one analysis (computer execution). It consolidates these parameters into a single user-named output file which can be repeatedly used as input into any deterministic or probabilistic fracture analysis. The FAVL module generates a user-named ouput file which contains solutions for the following:

- vessel thermal response
- circumferential stress response
- axial stress response
- stress intensity factors for axial surface flaws (infinite length and semi-elliptical flaws of specified aspect ratio)
- stress intensity factors for circumferential surface flaws (infinite length)

FAVL also has an option for including the effect of thermal streaming on the:

- vessel thermal response
- axial stress response
- stress intensity factors for infinite length circumferential surface flaws

In cases where the thermal streaming option is activated, the FAVL output file will contain solutions for circumferential flaws located in the beltline regions outside and inside of plumes induced by thermal streaming.

FAVL is capable of including the effects of the cladding in both the thermal and stress analyses, as required by Regulatory Guide 1.154. The thermal and stress analysis finite element algorithms are basically the same as those previously used in the OCA-P code [4] and provide highly accurate solutions which have been validated against ADINA [5] and NQA-1 certified ABAQUS [6], both widely recognized general purpose finite element codes.

Stress intensity factors are calculated using influence coefficients and superposition techniques. Stress intensity factor influence coefficients for inside surface axial and circumferential flaws incorporated internally into FAVL were generated using the NQA-1 certified ABAQUS code [6], which employs a highly accurate crack extension technique. The exact geometry used in the ABAQUS models was for a vessel with an internal radius of 86.0 inches and a wall thickness of 8.5 inches, which is a common vessel geometry for commercial US PWRs. The influence coefficients were calculated in a nondimensional form. Therefore, FAVL is capable of applying them to any vessel which has a vessel radius to wall thickness (R / t) ratio of approximately 10.

FAVL also provides the user with the flexibility to specify the transient time period for which the load analysis is to be performed and also to specify the time increment for which the load results are to be stored in the output file. The results of a PFM analysis for some PTS transients, particularly those which exhibit discontinuities, are to some extent dependent on the size of the time step increment.

3.1.1 INCLUSION OF THERMAL STREAMING IN PTS ANALYSES

Section 4.4 of RG 1.154 states that account should be taken of thermal stratification effects; therefore, an objective in the design of FAVOR was to include, as an option, the capability to include the effect of the additional axial load due to the thermal streaming in deterministic and probabilistic analysis of circumferential flaws. OCA-P and VISA-II both perform one-dimensional (1D) thermal and stress analyses, implicitly assuming an axisymmetric thermal hydraulic boundary condition and thus do not include the additional axial load induced by thermal streaming.

The formation of cooling plumes under the cold leg inlet occurs for transients that exhibit fluid / thermal stratification as a result of incomplete mixing of the high pressure injection (HPI) fluid stream and the primary side cold leg fluid as illustrated in Figure 3 [7]. This is referred to as thermal streaming. Plume strength is the temperature differential across the fluid plume width on the inner surface of the vessel wall i.e., it is a measure of the circumferential temperature variation of the cooling plume. The larger the degree of stratification, the greater will be the plume strength and therefore the larger will be the thermally induced axial stress. The plume strength diminishes with transient time and axial distance below the cold leg inlet (z).

German investigators previously performed thermal hydraulic experiments in the now decommisioned superheated steam HDR experimental reactor pressure vessel which resulted in the formation of relatively strong vertical plumes of cooling water beneath the cold leg inlet nozzle. Geib reported [8] that the 1D solutions generated by OCA-P and VISA-II were unconservative with respect to the experimentally determined values for axial stresses, but were in good agreement with the experimentally determined azimuthal stresses.

Analytical techniques for predicting the degree of mixing (stratification) of the HPI and cold leg fluid streams have been developed. These techniques are embodied in the thermal hydraulic simulation code REMIX [9]. REMIX has been validated against several thermal mixing experiments. Therefore, it appears that the degree of stratification can be predicted with a reasonable degree of confidence [7]. Specifically, REMIX predicts the temperature-time history of the fluid on the inner surface of the pressure vessel wall along a centerline below the cold leg inlet (Figure 3) for different axial locations below the cold leg. REMIX also predicts the temperature time history of the fluid in contact with the vessel wall outside of the plume region, i.e., the well mixed fluid temperature time history. Therefore, the plume strength as a function of time for a given axial location, including circumferential welds below the cold leg centerline, can be obtained from the output of REMIX. These data will provide the input into FAVOR when utilizing the option for including the effect of streaming in a fracture analysis of a circumferential flaw located in a plume region.

FAVOR uses an approximate method to calculate the axial stress component induced by the circumferential temperature variation. The FAVOR methodology appears to slightly overestimate the ABAQUS 2D finite element solutions which rigorously model the multidimensional thermal hydraulic boundary conditions caused by thermal streaming.

The present FAVOR methodology for simulating thermal streaming could be further refined to agree even more closely with multidimensional analyses. Such a refinement may be included in FAVOR in the future. FAVOR could also be enhanced to incorporate temperature and stress data generated by rigorous 2D or 3D finite element thermal and stress analyses into both deterministic or probabilistic fracture analyses.

3.2 FAVD MODULE

The FAVD module is the deterministic fracture module which accepts a user-friendly input dataset and a calculated load input dataset (FAVL output) and provides the user with the ability to generate a wide variety of user-tailored deterministic output data.

FAVD allows the user to easily generate specific combinations of load, embrittlement, and fracture toughness parameters in an array format which can be transported to external software packages (LOTUS, Cricket-Graph, etc) for further postprocessing and / or graphics. FAVD has four basic options:

(1) Generation of time histories of load, embrittlement, and fracture toughness parameters for up to 10 user-specified flaw depths and aspect ratios.

(2) Generation of the through wall variation of load, embrittlement, and fracture toughness parameters for up to 10 user-specified transient times. This option is equivalent to the traditional deterministic output data generated by VISA-II [3] and OCA-P [4], although it includes the option of tailoring the output to specified parameters for specified transient times.

In options 1 and 2 above, the user can specify any combination of the following eight time and wall depth dependent load, embrittlement, and fracture toughness parameters to be reported : (1) temperature, (2) hoop stress, (3) axial stress, (4) K_I acting on an axial flaw, (5) K_I acting on a circumferential flaw, (6) K_{Ic}, (7) K_{Ia}, (8) RT_{NDT}.

(3) Generation of output for fracture response of up to 10 specific flaw depths and aspect ratios.

This option examines the fracture response of each specified flaw (does initial initiation occur ?, at what time does it occur ?, does it arrest ?, and reinitiate ?) for specified levels of embrittlement and fracture toughness curves. This option will generate the K_I and K_{Ic} time histories for the specified flaw depths. If an initial initiation occurs ($K_I > K_{Ic}$), the K_I and K_{Ia} variations thru the wall (checking for crack arrest) will be reported.

(4) Fracture parameter minimization option

This option will solve for the minimum value for any of the following six parameters which will result in cleavage fracture (called the incipient value), for a specified flaw orientation, if the remaining 5 parameters are specified: (1) surface fluence (2) copper (3) nickel (4) RT_{NDTO} (5) RT_{NDT} Margin (6) flaw size

3.3 FAVP MODULE

The module FAVP accepts a user-friendly input dataset and a specified load dataset (FAVL output dataset) and generates the results of a probabilistic fracture mechanics (PFM) analysis. The FAVP input dataset primarily contains embrittlement and flaw distribution mapping data, as well as the flaw depth cumulative distribution function. FAVP allows the user to select either the Marshall flaw depth distribution function as a default or to input a user specified distribution function in the form of discrete pairs of flaw depths and values of the cumulative distribution function. Also, the inclusion of Type I warm-prestressing is an available option.

FAVP utilizes a global PFM modeling methodology, which means that it can perform a PFM analysis for the entire vessel beltline region (or any subset thereof) containing any number of flaws, in a single PFM analysis. This methodology provides the user with generality for modeling the fracture characteristics of the vessel and also eliminates the potential for "double counting", which is inherent, to some extent, in the other PTS PFM codes, as explained earlier.

The PFM analysis is based on Monte Carlo techniques, i.e., many deterministic analyses are performed on stochastically generated vessels to determine if each vessel, containing an integer number of flaws, will fail when subjected to a specified PTS event at a particular time in the operating life of the vessel. FAVP contains the required logic to correctly account for "fractional number of flaws". The conditional probability of failure per event, designated as P(F|E), is estimated by dividing the number of vessels which failed by the total number of vessels simulated for a given transient. The term "failure" refers to full penetration of the vessel wall by a propagating flaw. The probability of failure is "conditional" in the sense that the transient is assumed to occur. FAVP will execute until either the user-specified maximum number of vessels has been simulated or until a user-specified convergence tolerance (based on the central limit theorem from the theory of probability) has been satisfied. The results of the PFM analysis are displayed on the computer screen for each 10000 vessels, so that the analyst can monitor the progress of the simulation.

The beltline region of the vessel may be divided into major regions such as plates, axial welds, and circumferential welds. FAVP has the capability to perform PFM analyses on simple models with a small amount of detail or to perform a PFM analysis on the entire beltline region including a considerable amount of detail. Each major region may be further subdivided into subregions, each of which may be assigned its own distinguishing parameters such as:

- surface fluence used for predicting initial initiation
- surface fluence used for predicting arrest
- copper content in weight %
- nickel content in weight %
- volume
- flaw density
- RT_{NDT0}
- RT_{NDT} shift correlaton (Regulatory Guide 1.99 revision 2 for weld or base metal)
- flaw orientation (axial or circumferential)
- flaw aspect ratio to be used for predicting initial initiation
- flaw length to be used in predicting arrest

For the case of circumferential flaws, the thermal response and K_I values for flaws in a subregion may be further distinguished between flaws that exist inside a plume region (as modeled by the thermal streaming parameters in the FAVL input) and those that reside outside the plume region.

The number of flaws in the vessel may be proportionally distributed over the model in any specified manner, since each subregion is also assigned its own flaw density and vessel wall volume. The product of the flaw density and volume of each subregion determines the actual number of flaws in that subregion. The summation of those products over all modeled subregions determines the total number of flaws in the entire model.

For each vessel analyzed, a flaw is located in a specific beltline subregion and a value for each critical parameter is sampled from a normal distribution, truncated at plus and minus three standard deviations. FAVP then steps through the transient time history, and at each time step, the applied K_I at the crack tip is compared to the sampled K_{Ic} at the crack tip. If initiation does not occur ($K_I < K_{Ic}$), the simulation advances to the next time step. If initiation does occur, the crack tip is extended by a small increment and the new K_I value is compared to K_{Ia}. If crack arrest does not occur, the crack tip advances another small increment and again a check is made for arrest. If the crack does arrest, FAVP continues stepping through transient time checking for reinitiation. The simulation continues until the vessel either fails or the transient is over. If the vessel does fail, the code proceeds to generate the next vessel. If the vessel does not fail, the code proceeds to locate another flaw in a subregion of the same vessel and repeats the process until either a flaw causes vessel failure or none of the flaws cause failure. In the analysis, it is assumed that each flaw is independent of all other flaws, i.e., the presence of a flaw in one region of the model has no influence on the fracture response of flaws located in other regions of the model.

The global methodology of analyzing the entire beltline region for any number of flaws neccessaily involves the potential simulation of a very large number of flaws in order to converge to a solution with an acceptably small error, particularly for those cases having relatively low probabilities of failure. An algorithm was developed and incorporated into FAVP which enhances the computational efficiency. This algorithm identifies those combinations of initial flaw sizes, beltline subregions, and transient times for which cleavage could not possibly occur, even for the "minimum worst case" prediction of fracture toughness. This eliminates actually analyzing those combinations which could never possibly cause cleavage fracture. The effectiveness of this algorithm increases as the conditional probability of failure decreases and dramatically reduces the computational effort required for those models which have relatively low probabilties of failure.

4.0 SUMMARY

The FAVOR code is a validated, user-friendly, modularly designed, and well documented PTS fracture mechanics code which incorporates the most important features of existing PTS codes and contains some new features. From lessons learned in previous NRC Regulatory Guide 1.154-type plant specific analyses, one of the main objectives in the design of FAVOR was to provide flexibility in the degree of detail that can be included in a PTS analysis. FAVOR can accomodate simple models; however, is also capable of performing a PFM analysis for the entire beltline region, including a substantial amount of detail in the model. In general, the FAVOR PFM methodology makes Regulatory Guide 1.154-type analyses more accurate, easier, and more computationally efficient to perform.

It is intended that FAVOR will continue to mature and evolve in the future i.e., provide a framework into which future fracture technology developed in the HSST and other programs can be incorporated, such that the code continuously reflects the current state-of-the-art in fracture technology, and that it will eventually accurately address all important conditions encountered in plant-specific PTS analyses.

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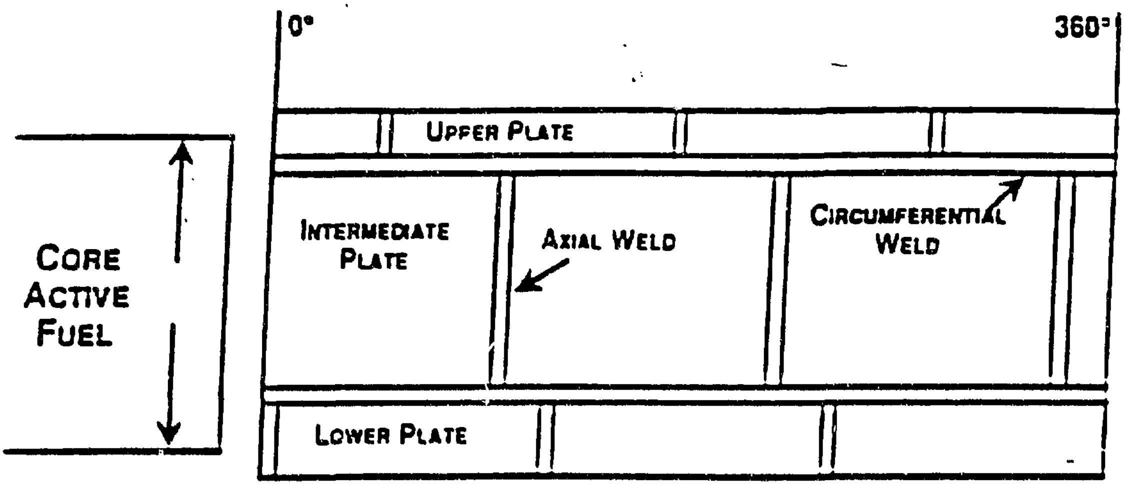

Figure 1. Developed view of RPV Beltline region

FAVOR STRUCTURE
DIVIDE CODE INTO THREE MAIN MODULES:

(1) LOAD ANALYSIS — FAVL
(2) DETERMINISTIC FRACTURE ANALYSIS — FAVD
(3) PROBABILISTIC FRACTURE ANALYSIS — FAVP

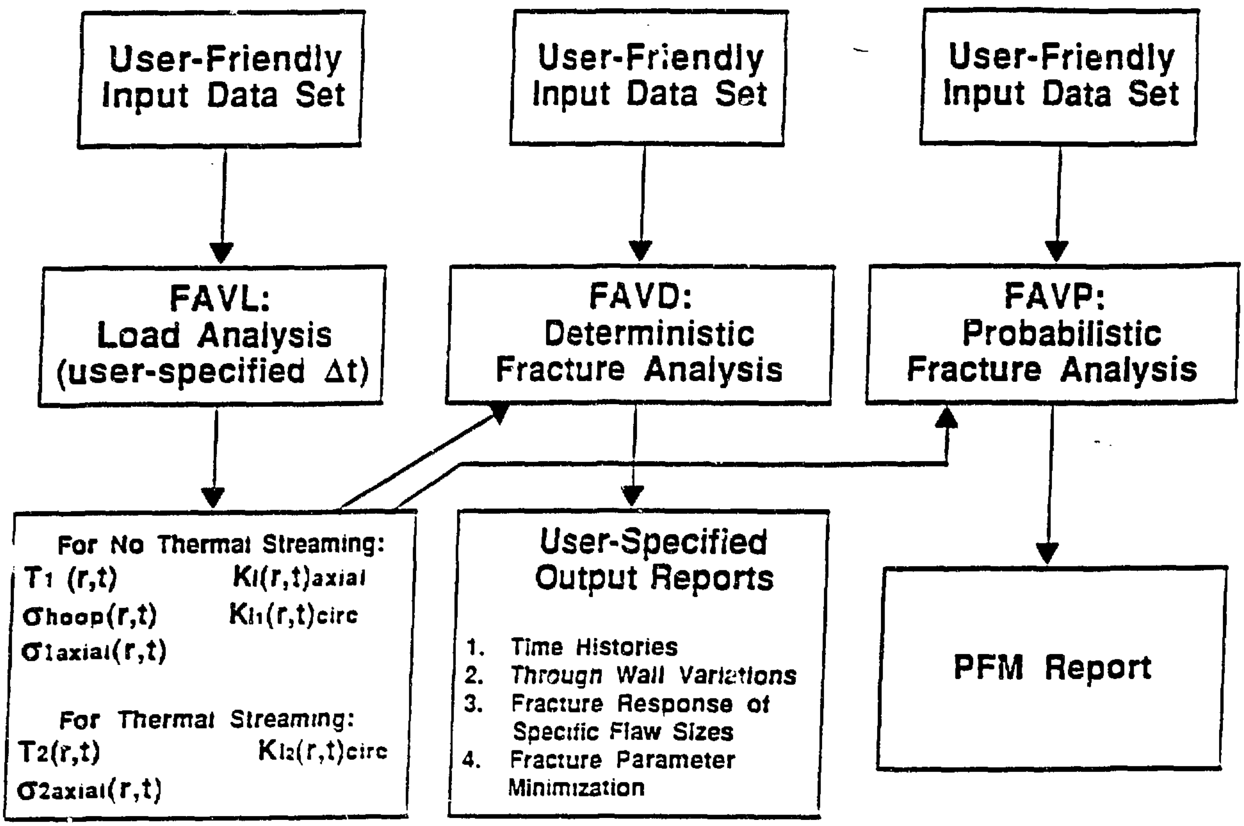

Figure 2. The Favor code is divided Into 3 Separate Modules.

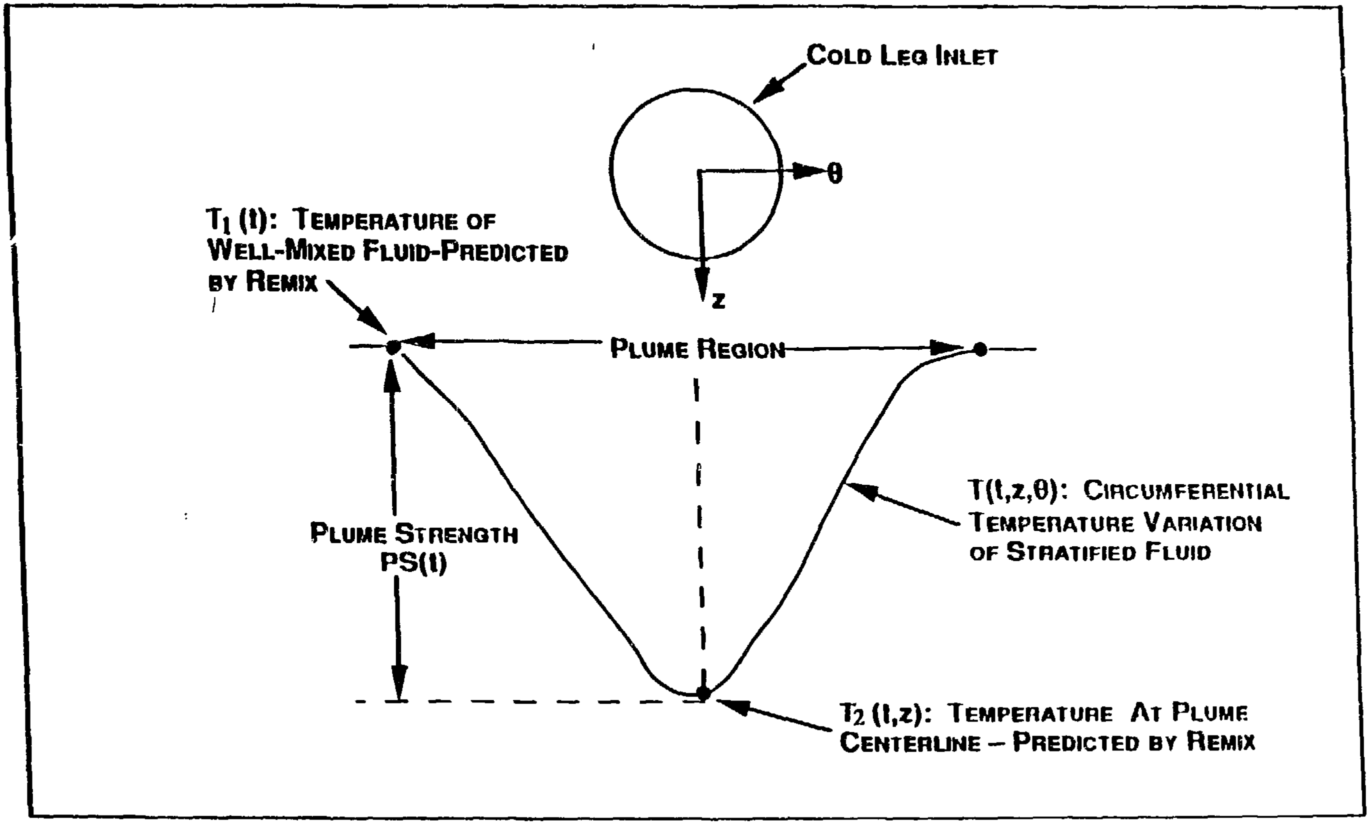

Fig. 3. Thermal streaming results in formation of plume, that is, a circumferential variation of fluid temperature on the inner surface of vessel.