

JAERI - M
92-006

DESCRIPTION OF CODE SYSTEM PLES/PTS FOR
EVALUATION OF PRESSURE VESSEL INTEGRITY DURING PTS EVENTS

February 1992

Masashi HIRANO and Atsuo KOHSAKA

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-M レポートは、日本原子力研究所が不定期に公刊している研究報告書です。入手の問合せは、日本原子力研究所技術情報部情報資料課（〒319-11茨城県那珂郡東海村）あて、お申しこしください。なお、このほかに財団法人原子力弘済会資料センター（〒319-11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費領布をおこなっております。

JAERI-M reports are issued irregularly.

Inquiries about availability of the reports should be addressed to Information Division, Department of Technical Information, Japan Atomic Energy Research Institute, Tokaimura, Naka-gun, Ibaraki-ken 319-11, Japan.

© Japan Atomic Energy Research Institute, 1992

編集兼発行 日本原子力研究所
印 刷 核原子力資料サービス

Description of Code System PLES/PTS for
Evaluation of Pressure Vessel Integrity during PTS Events

Masashi HIRANO and Atsuo KOHSAKA⁺

Department of Reactor Safety Research
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

(Received January 13, 1992)

A code system PLES/PTS has been developed at the Japan Atomic Energy Research Institute (JAERI) to evaluate the integrity of the pressure vessel during plant thermal-hydraulic transients related to pressurized thermal shock (PTS) in a pressurized water reactor (PWR). The code system consists of several member codes to analyse the thermal-mixing behavior of emergency core cooling (ECC) water and primary coolant, transient stress distribution within the vessel wall, and crack growth behavior at the inner surface of the vessel. The crack growth behavior is evaluated by comparing the stress intensity factor (k_I) with the crack initiation toughness (k_{Ic}) and crack arrest toughness (k_{Ia}), taking into account the fast neutron irradiation embrittlement.

This report describes the methods and models applied in PLES/PTS and the input data requirements.

Keywords: PLES/PTS, Pressurized Thermal Shock (PTS), Integrity of Pressure Vessel, Thermal-Mixing, Crack Growth

+ Office of Planning

加圧熱衝撃事象時圧力容器健全性評価コードシステム PLES/PTSの記述

日本原子力研究所東海研究所原子炉安全工学部

平野 雅司・鴻坂 厚夫⁺

(1992年1月13日受理)

加圧水型軽水炉 (PWR : Pressurized Water Reactor) における加圧熱衝撃 (PTS : Pressurized Thermal Shock) 事象時の原子炉圧力容器健全性を評価する計算コードシステム PLES/PTS を開発した。このコードシステムは、非常用炉心冷却 (ECC : Emergency Core Cooling) 水と一次冷却水との熱混合解析と圧力容器壁内の応力分布の過渡解析、亀裂進展解析を行う複数のメンバーコードで構成されている。亀裂進展挙動は、応力拡大係数 (k_t) と速中性子照射脆化を考慮した破壊靱性 (k_{t_c} 及び k_{t_a}) とを比較して評価される。

本報告書では、本コードシステムで用いている解析手法と入力規約について述べる。

Contents

1.	Introduction	1
2.	Overall Description of PLES/PTS	2
3.	Methods and Models in PLES/PTS	6
3.1	Plant Thermal-hydraulic Analysis	6
3.2	Thermal-Mixing Analysis	6
3.2.1	Empirical Bulk Mixing Model by EPRI	8
3.2.2	Regional Mixing Model (RMM) by Theofanous	10
3.2.3	Empirical Correlation by MHI	16
3.3	Stress Analysis	18
3.4	Fracture Mechanics Analysis	21
3.4.1	Fracture Toughness Properties	21
3.4.2	Stress Intensity Factor	24
4.	Code Organization	27
4.1	Structure of Code System	27
4.2	Driver Program	27
5.	Summary	29
	Acknowledgment	29
	References	30
	Appendix A Input Data Requirements for PLES/PTS	32
	Appendix B Data Transfer and Environmental Programs	50
	Appendix C Sample Inputs and Outputs	60

目 次

1.はじめに	1
2.PLES/PTSの概要	2
3.PLES/PTSの解析モデルと解法	6
3.1 プラントの熱水力解析	6
3.2 热混合解析	6
3.2.1 EPRIのバルク混合モデル	8
3.2.2 Theofanousの領域混合モデル	10
3.2.3 MHIの実験式	16
3.3 応力解析	18
3.4 破壊力学解析	21
3.4.1 破壊革性	21
3.4.2 応力拡大係数	24
4.コードシステムの概要	27
4.1 コードシステムの構造	27
4.2 Driver プログラム	27
5.まとめ	29
謝辞	29
参考文献	30
付録A 入力規約	32
付録B データの流れと付属プログラム	50
付録C サンプル入出力	60

1. Introduction

Under certain postulated accidents such as small-break loss-of-coolant accidents (SBLOCAs), main steam line breaks (SLBs) and other overcooling scenarios, reactor pressure vessels (RPVs) of pressurized water reactors (PWRs) undergo a large cooling rate keeping significantly high internal pressure, especially after high pressure injection (HPI) system is actuated. This combination of thermal stressing and high internal pressure, called pressurized thermal shock (PTS), could pose a serious challenge to the integrity of RPV. The PTS problem was designated as Unresolved Safety Issue A-49⁽¹⁾ by the U.S. Nuclear Regulatory Commission (USNRC) in 1981. Since then, a lot of experimental and analytical efforts have been made to resolve the problem mainly in U.S.A., as shown, for example, in Ref. (2).

The RPV is recognized as one of the critical components which may limit the plant life. Among various threats to challenge the RPV integrity, PTS is one of the most important ones in view of plant life extension because it involves cumulative effects of neutron irradiation, i.e. neutron embrittlement of RPV material. Although early research showed that no PTS concern existed on Japanese RPVs because they have lower copper contents, further research programs have been continued to obtain a public acceptance for RPVs integrity and to provide the data base for their life extension⁽³⁾.

Under these circumstances, the code system PLES/PTS⁽⁴⁾ has been developed at the Japan Atomic Energy Research Institute (JAERI) with the objectives to establish the methodology for the evaluation of RPV integrity under the PTS conditions, and to supply a part of the technical basis for the plant life extension. This code system is also aimed to be a prototype software to synthesize analytical techniques, data bases, etc. of various fields relating to plant life extension.

In order to evaluate the integrity of pressure vessel during a transient related to PTS, first of all, the thermal-hydraulic condition at the downcomer region has to be identified and then the structural integrity can be evaluated against the condition. In the evaluation procedure with PLES/PTS, therefore, analyses of the following items are performed:

- (1) the plant thermal-hydraulic behavior during the PTS event to obtain the pressure transient and overall coolant behavior at the cold leg and downcomer,
- (2) the local behavior of coolant temperature at the inner surface of the RPV wall,
- (3) the transient stress distribution within the RPV wall, which is composed of the thermal stress and stress due to the internal pressure, and
- (4) the crack growth behavior at the inner surface of the RPV wall resulting from the stress transient.

The severity of the event under consideration could be defined by whether or not the crack, which is assumed to exist initially, grows. This can be done by comparing the stress intensity factor to the crack and the fracture toughness of the RPV material in the analysis. If any kinds of probabilities are not taken into consideration in the courses of analyses from 1) to 4), the evaluation is called deterministic. In this case, the evaluation is done assuming a certain geometry of the initial crack under a certain plant transient condition related to PTS. In the probabilistic evaluation, on the other hand, various kinds of probabilities and frequencies, such as the initial crack existing probability which depends on its geometry, probabilities that the initial crack is escaped from detection in pre-service and/or in-service inspections, occurrence frequencies of the plant transients under consideration, etc., might be considered.

PLES/PTS has capabilities to analyze items 2) to 4) only in a deterministic way. The item 1) is designated to be analyzed with existing transient thermal-hydraulic codes. This document provides the description of the methods and models applied in PLES/PTS in addition to the input data requirements to be served as the user's manual.

2. Overall Description of PLES/PTS

The code system PLES/PTS consists of several member codes, not subroutines in a single program. Each member code plays its role along the evaluation flow shown in Fig.2.1. In the PTS evaluation, it is indispensable to analyze transient thermal-hydraulic responses of the plant to miscellaneous transients which may cause a serious overcooling of the primary system. This should be done with transient thermal-hydraulic analysis codes such as TRAC-PF1⁽⁵⁾, RETRAN⁽⁶⁾, etc. This calculation step is corresponding to item 1) stated in Sec.1 and is called the plant thermal-hydraulic analysis.

In the thermal-hydraulics related to PTS, the natural circulation termination, which is abbreviated to NCT in the following, plays an important role because it deteriorates the mixing of high pressure injection (HPI) water with primary coolant and the HPI water may conform a cold stratified layer in the cold leg. Then, the cold layer may directly contact the RPV wall in the downcomer as schematically shown in Fig.2.2. However, the transient thermal-hydraulic analysis codes cannot predict such local behavior since they assume complete mixing in a large computational mesh cell. The cold leg and downcomer are usually discretized only several mesh cells considering the running cost.

The first member code in PLES/PTS evaluates the temperature transient of the cold layer, when NCT is calculated to occur in the plant thermal-hydraulic analysis. This analysis is corresponding to item 2) in Sec.1 and is called the thermal-mixing analysis. There may be two ways to do this analysis. One is to perform a multi-dimensional single phase flow analysis to obtain detailed coolant temperature distribution within downcomer region. The other way is to utilize the empirical correlations or models based on experi-

The severity of the event under consideration could be defined by whether or not the crack, which is assumed to exist initially, grows. This can be done by comparing the stress intensity factor to the crack and the fracture toughness of the RPV material in the analysis. If any kinds of probabilities are not taken into consideration in the courses of analyses from 1) to 4), the evaluation is called deterministic. In this case, the evaluation is done assuming a certain geometry of the initial crack under a certain plant transient condition related to PTS. In the probabilistic evaluation, on the other hand, various kinds of probabilities and frequencies, such as the initial crack existing probability which depends on its geometry, probabilities that the initial crack is escaped from detection in pre-service and/or in-service inspections, occurrence frequencies of the plant transients under consideration, etc., might be considered.

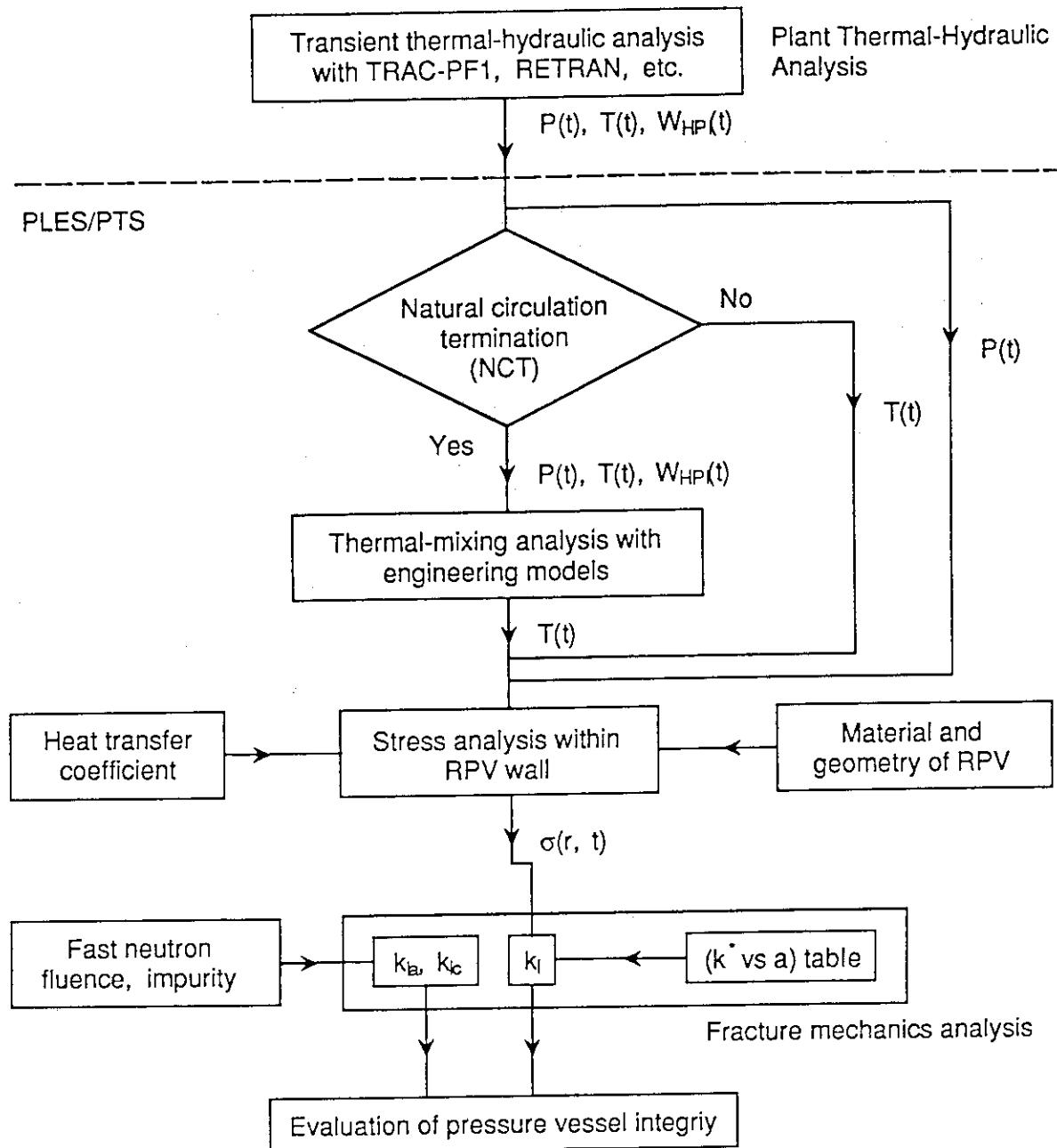
PLES/PTS has capabilities to analyze items 2) to 4) only in a deterministic way. The item 1) is designated to be analyzed with existing transient thermal-hydraulic codes. This document provides the description of the methods and models applied in PLES/PTS in addition to the input data requirements to be served as the user's manual.

2. Overall Description of PLES/PTS

The code system PLES/PTS consists of several member codes, not subroutines in a single program. Each member code plays its role along the evaluation flow shown in Fig.2.1. In the PTS evaluation, it is indispensable to analyze transient thermal-hydraulic responses of the plant to miscellaneous transients which may cause a serious overcooling of the primary system. This should be done with transient thermal-hydraulic analysis codes such as TRAC-PF1⁽⁵⁾, RETRAN⁽⁶⁾, etc. This calculation step is corresponding to item 1) stated in Sec.1 and is called the plant thermal-hydraulic analysis.

In the thermal-hydraulics related to PTS, the natural circulation termination, which is abbreviated to NCT in the following, plays an important role because it deteriorates the mixing of high pressure injection (HPI) water with primary coolant and the HPI water may conform a cold stratified layer in the cold leg. Then, the cold layer may directly contact the RPV wall in the downcomer as schematically shown in Fig.2.2. However, the transient thermal-hydraulic analysis codes cannot predict such local behavior since they assume complete mixing in a large computational mesh cell. The cold leg and downcomer are usually discretized only several mesh cells considering the running cost.

The first member code in PLES/PTS evaluates the temperature transient of the cold layer, when NCT is calculated to occur in the plant thermal-hydraulic analysis. This analysis is corresponding to item 2) in Sec.1 and is called the thermal-mixing analysis. There may be two ways to do this analysis. One is to perform a multi-dimensional single phase flow analysis to obtain detailed coolant temperature distribution within downcomer region. The other way is to utilize the empirical correlations or models based on experi-



- P : Pressure
- T : Temperature
- W : Mass flow rate
- σ : Stress
- k' : Stress intensity factor for unit load
- k_f : Stress intensity factor
- k_a, k_b : Fracture toughness
- a : Crack depth
- HPI : High pressure injection

Fig. 2.1 Calculation flow in PLES/PTS

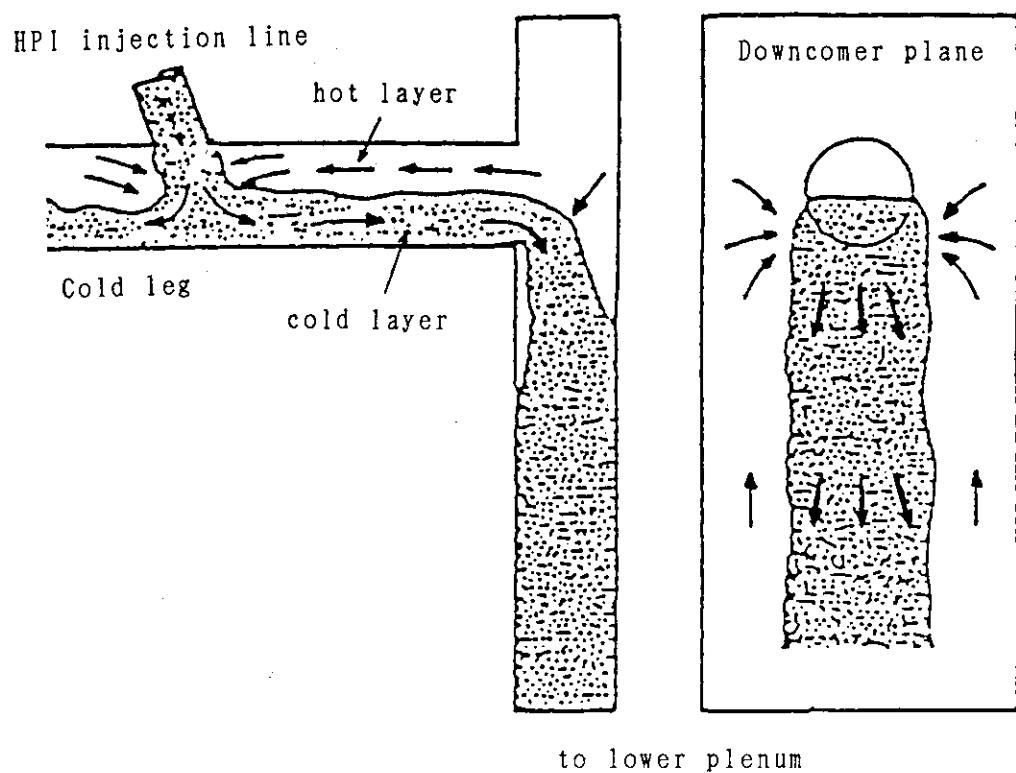


Fig. 2.2 Schematic explanation of thermal stratification phenomenon

ments, which are called engineering models in contrast to the multi-dimensional fluid flow analysis. In PLES/PTS the latter way is adopted. The models presently implemented are the model proposed by Theofanous⁽⁷⁾, the empirical correlation developed base on the 1/3 scale thermal-mixing test conducted by MHI⁽⁸⁾, and the those proposed by EPRI^(9,10,11). In these models, the temperature transients at the cold leg and/or downcomer, and ECC injection flow rate obtained by the plant thermal-hydraulic analysis are used as the initial and/or boundary conditions.

The second member code in PLES/PTS calculates the transient stress distribution within RPV wall. This step is corresponding to item 3) in Sec.1 and is called the stress analysis. In this calculation, the transient temperature distribution is obtained by solving the one-dimensional thermal conduction equation with using the temperature of the cold layer as the boundary condition. Then, the transient stress distribution is calculated based on the temperature and pressure transients which are obtained in the plant thermal-hydraulic analysis.

The third member code in PLES/PTS calculates the FM parameters such as the stress intensity factor k_I and fracture toughness parameters k_{Ia} and k_{Ic} . This step is corresponding to item 4) in Sec.1 and is called the FM analysis. The k_I value is obtained based on the model applied in the OCA-I code⁽¹²⁾. In this model, an infinitely long axial flaw is assumed to exist at beginning and the unit-load k_I values (k^*) for a selected crack depth are summed with weighting in accordance with the crack-free stress distribution associated with the equivalent problem. The k^* value for a certain flaw depth is given as a table, which can be generated by using, for example, an existing code with finite element method (FEM). A built-in table of (k^*), which is applicable to a pressure vessel to a typical Westinghouse PWR, being used in OCA-I, is implemented in PLES/PTS. The fracture toughness parameters k_{Ia} and k_{Ic} are evaluated with an existing empirical correlation, which is either the ASME Sect. XI lower-bound curves⁽¹²⁻¹⁵⁾, ORNL mean curve or USNRC mean curve⁽¹⁴⁾. As for the reference temperature for nil-ductility transition RT_{NDT} to be used to evaluate the fracture toughness parameters k_{Ia} and k_{Ic} , the curve in US Regulatory Guide 1.99(Rev.1)^(12,16) and so called the Guthrie equation^(15,17,23-26) are implemented.

As stated above, the code system PLES/PTS consists of several member codes, not subroutines in a program, and therefore, the job control language (JCL) cards and the input data are rather complicated. Therefore, for ease of the users, the driver program⁽¹⁸⁾ which has been developed at the Oak Ridge National Laboratory (ORNL) is applied to control the execution of member programs including data transfer between them.

3. Methods and Models in PLES/PTS

3.1 Plant Thermal-Hydraulic Analysis

The plant thermal-hydraulic analysis is to supply the following quantities to the further calculation steps by PLES/PTS as shown in Fig.2.1 :

- 1) system pressure transient,
- 2) coolant temperature and flow transients at upstream of ECC injection point,
- 3) flow transients of HPI water(temperature is assumed constant),
- 4) time of natural circulation termination.

In PLES/PTS, this analysis is designated to be done by the TRAC-PF1 or RETRAN02 code. When these codes are used, the output data of 1) to 3) can be retrieved from the output file(s) and transferred to the further steps by PLES/PTS. If these quantities are calculated by using other codes or known in advance, they can be specified as input time tables.

3.2 Thermal-Mixing Analysis

The schematic drawing of the flow configuration under consideration is already shown in Fig.2.2. In PLES/PTS, the thermal stratification is assumed to occur just after NCT takes place. The time of NCT is either given by an input or defined by an input threshold value of flow rate at cold leg. It is shown in this figure that the injected HPI water is not well mixed with primary coolant and stratified into hot and cold layers after natural circulation is terminated. This situation is called thermal stratification phenomenon. The thermal-mixing analysis is to supply the temperature transient of the cold layer based on the temperatures and flow rates of the primary coolant at upstream of the ECC injection point and HPI-water, which are obtained in the plant thermal-hydraulic analysis. This temperature is used as that at the inner surface of the pressure vessel as a boundary condition to solve the thermal conduction equation within the vessel wall. This means that the heat from the vessel wall to coolant is neglected to obtain conservative results for the purpose of PTS evaluation.

If a temperature transient is given in advance, this step can be omitted. In this case, time-dependent temperature of the cold layer is specified by inputs as time table in the stress calculation.

The following four kinds of models are provided in the present version of PLES/PTS:

- 1) Empirical bulk mixing model proposed by EPRI⁽⁹⁾,
- 2) Regional mixing model proposed by Theofanous⁽⁷⁾,
- 3) Empirical correlation proposed by MHI⁽⁸⁾, and
- 4) Model proposed by Kim⁽¹¹⁾.

Among the models listed above, the model in 4) is not sufficiently assessed, and therefore, is not recommended to be used at present. Thus, only the three models in 1) to 3) are described in the following. The model in 2) has been extensively used in the United States relating to the Unresolved Safety Issue A-49. The empirical correlation in 3) was developed based on the experiment which took into account the specific features to Japanese plant designs (See Ref. (8)).

3.2.1 Empirical Bulk Mixing Model by EPRI⁽⁸⁾

The empirical bulk mixing model proposed by the Electric Power Research Institute (EPRI) in the United States is implemented in PLES/PTS. The temperature T_C that is used to evaluate the temperature distribution within the RPV wall in the next step is calculated by the following empirical correlations :

$$T_C = T_m + (T_{CL} - T_m) \cdot e^{-t(Q_{HPI} + Q_{CL}) \cdot V_{CL}} \quad (1)$$

where

$$T_m = \min(T_{m0}, T_n),$$

$$T_{m0} = \frac{\frac{\rho_{HPI}}{\rho_{CL}} \cdot T_{HPI} + \frac{Q_{CL}}{Q_{HPI}} \cdot T_{CL}}{\frac{\rho_{HPI}}{\rho_{CL}} + \frac{Q_{CL}}{Q_{HPI}}},$$

$$T_n = T_m + (T_{CL} - T_{HPI}) \left(\frac{0.01}{60} \cdot \frac{\frac{V_{CL}}{V_{HPI}}}{\frac{(\rho_{HPI} - \rho_{CL})}{\rho_{HPI}}} \right) - 0.07,$$

and

$$V_{CL} = L_{CL} \left(\frac{D_{CL}}{2} \right)^2 \pi.$$

$$\left. \begin{array}{l} T_{CL} : \text{Coolant temperature at cold leg } (\text{°C}) \\ T_{HPI} : \text{Temperature of HPI water } (\text{°C}) \\ \rho_{CL} : \text{Coolant density at cold leg } (\text{kg/m}^3) \\ \rho_{HPI} : \text{Density of HPI water } (\text{kg/m}^3) \\ Q_{CL} : \text{Volumetric flow rate at cold leg } (\text{m}^3/\text{s}) \\ Q_{HPI} : \text{Volumetric flow rate of HPI water } (\text{m}^3/\text{s}) \\ L_{CL} : \text{Length of cold leg } (\text{m}) \\ D_{CL} : \text{Diameter of cold leg } (\text{m}) \end{array} \right\}$$

The temperature T_C is corresponding to the lower bound of that measured in region II in Fig.3.1 in the scaled experiment. As for detailed physical meaning of the equations, their uncertainties, etc., reference should be made to Ref.(9).

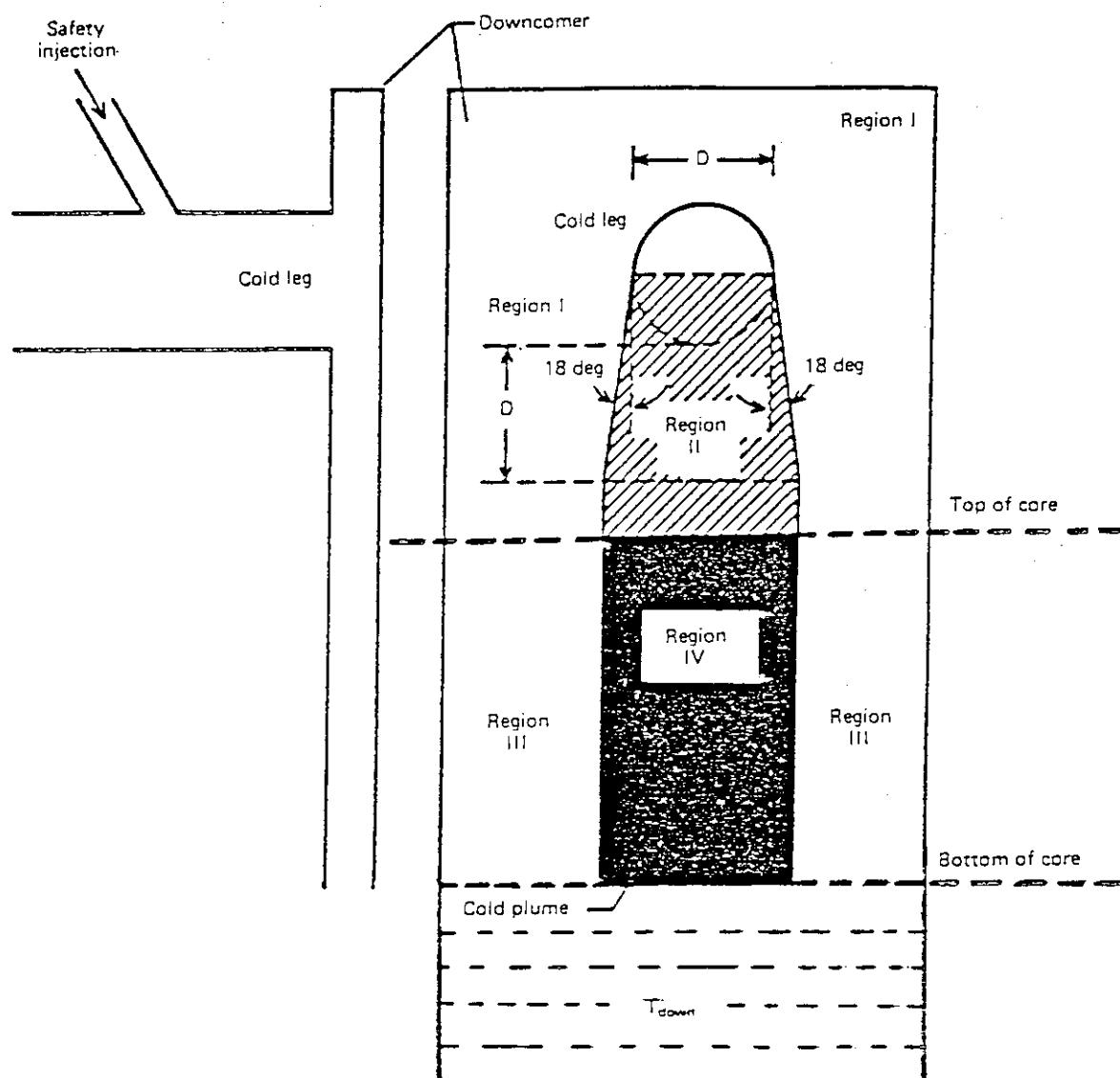


Fig. 3.1 Schematic explanation of bulk mixing model proposed by EPRI⁽⁹⁾

3.2.2 Regional Mixing Model (RMM) by Theofanous⁽⁷⁾

Conceptual drawing of the system under consideration in RMM is shown in Fig.3.2. This model can be applied after NTC takes place. First of all, the temperature transient at downcomer is obtained by solving the simplified energy equation assuming complete mixing as follows :

$$V \rho_m^n \cdot \frac{h_m^{n+1} - h_m^n}{\Delta t} = Q_{HPI}^n \rho_{HPI}^n (h_{HPI} - h_m^n) + Q_w^n , \quad (2)$$

$$\begin{pmatrix} h_{HPI} & = & C_{ref} T_{HPI} \\ h_m & = & C_{ref} T_m \\ \rho_m & = & f(T_m) \end{pmatrix}$$

where

$$V = V_{CL} + V_{add} .$$

$$\left. \begin{array}{ll} h_m & : \text{Enthalpy of mixture (J/kg)} \\ \rho_m & : \text{Density of mixture (kg/m}^3\text{)} \\ Q_w & : \text{Heat input (J/s)} \\ C_{ref} & : \text{Reference specific heat (J/kg°C)} \\ f & : \text{Function} \\ V_{add} & : \text{Additional volume (m}^3\text{)} \\ V_{CL} & : \text{Cold leg volume (m}^3\text{)} \\ V & : \text{Total volume (m}^3\text{)} \\ \Delta t & : \text{Time step width (s)} \\ n & : \text{Time step} \end{array} \right\}$$

The initial conditions are as follows :

$$h_{m0} = C_{ref} T_{CL0} \quad (3)$$

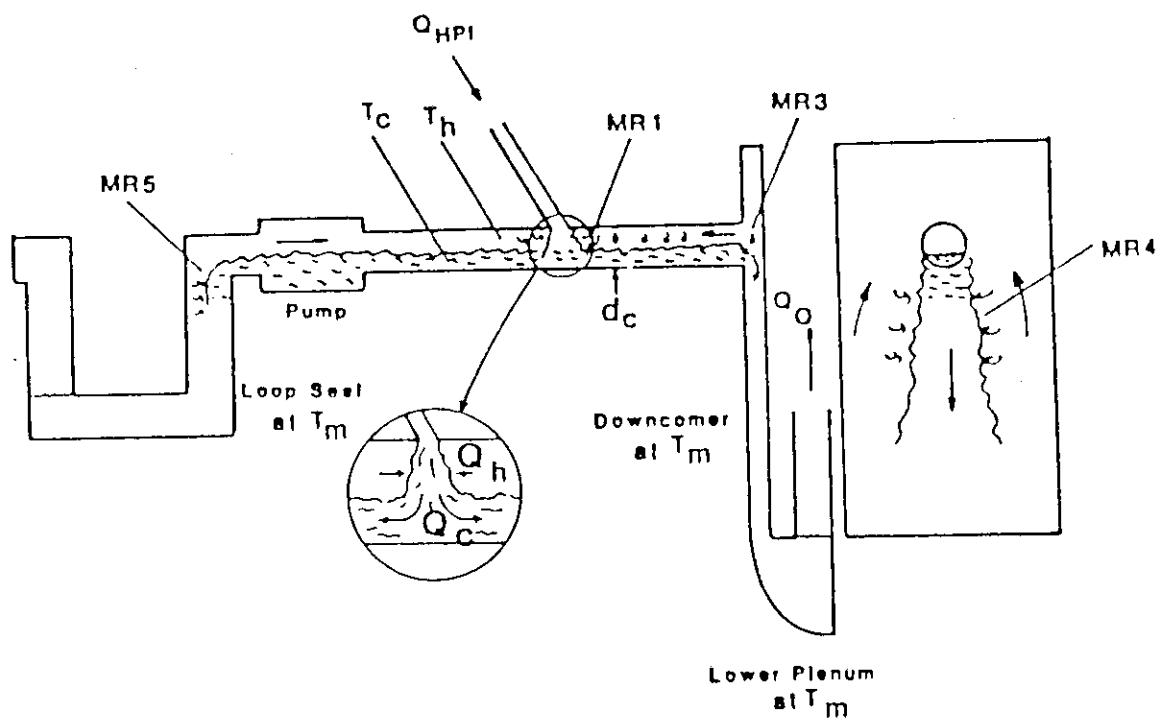


Fig. 3.2 Schematic explanation of RMM proposed by Theofanous⁽⁷⁾

and

$$\rho_{m0} = f(T_{CL0}), \quad (4)$$

where T_{CL0} is an initial temperature at cold leg. This step is called the bulk mixing model.

In the next step, the temperature transient of the cold layer is evaluated base on the density and enthalpy of mixture at $n+1$ time level obtained in the step stated above. In the following, the subscripts h , c and m denote, respectively, the hot layer, cold layer and mixture. The equations to be solved are shown as follows.

Mass balance :

$$Q_{HPI} \rho_{HPI} + Q_h \rho_h = Q_c \rho_c. \quad (5)$$

Energy balance :

$$Q_{HPI} \rho_{HPI} h_{HPI} + Q_h \rho_h h_h = Q_c \rho_c h_c \quad (6)$$

and

$$V_c \rho_c h_c + V_h \rho_h h_h = (V_c + V_h) \rho_m^{n+1} h_m^{n+1}. \quad (7)$$

The temperature T_C to be evaluated is calculated from h_C . The volumes V_c and V_h for cold and hot layers, respectively, are expressed as follows :

$$V_c = A_c L_{CL} \quad (8)$$

and

$$V_h = (A_{CL} - A_c) L_{CL} + V_{add} \quad (9)$$

where

$$A_c = \alpha \cdot \frac{D_{CL}^2}{4} - (0.5 \cdot D_{CL} - H_c) H_c^{\frac{1}{2}} (D_{CL} - H_c)^{\frac{1}{2}},$$

and

$$\alpha = \tan^{-1} \frac{H_c^{\frac{1}{2}} (D_{CL} - H_c)^{\frac{1}{2}}}{0.5 \cdot D_{CL} - H_c} \quad \text{for } H_c \leq \frac{D_{CL}}{2}$$

or

$$A_c = (\pi - \alpha) \frac{D_{CL}^2}{4} + (0.5 \cdot D_{CL} - H_h) H_h^{\frac{1}{2}} (D_{CL} - H_h)^{\frac{1}{2}},$$

and

$$\alpha = \tan^{-1} \frac{H_h^{\frac{1}{2}} (D_{CL} - H_h)^{\frac{1}{2}}}{0.5 \cdot D_{CL} - H_h} \quad \text{for } H_c > \frac{D_{CL}}{2}.$$

It is noted that :

$$H_c + H_h = D_{CL}, \quad (10)$$

and

$$A_c + A_h = A_{CL}. \quad (11)$$

$$\left(\begin{array}{l} H_c : \text{Thickness of cold layer (m)} \\ H_h : \text{Thickness of hot layer (m)} \\ A_c : \text{Flow area of cold layer (m}^2\text{)} \\ A_h : \text{Flow area of hot layer (m}^2\text{)} \\ A : \text{Total flow area of cold leg (m}^2\text{)} \end{array} \right)$$

In addition to these equations, the following flooding condition is assumed to be fulfilled :

$$Fr_c^2 + Fr_h^2 = 1 \quad (12)$$

where

$$Fr_c = \frac{Q_c^*}{A_c} \left(g \cdot \frac{A_c}{w} \cdot \frac{\rho_c - \rho_h}{\rho_c} \right)^{-\frac{1}{2}},$$

$$Fr_h = \frac{Q_h^*}{A_h} \left(g \cdot \frac{A_h}{w} \cdot \frac{\rho_c - \rho_h}{\rho_c} \right)^{-\frac{1}{2}},$$

$$Q_c^* = Q_c - 0.5 \cdot Q_h,$$

$$Q_h^* = 0.5 \cdot Q_h,$$

and

$$w = 2 \left[\frac{D_{CL}^2}{4} - \left\{ \frac{1}{2} D_{CL} - \min(H_h, H_c) \right\}^2 \right]^{\frac{1}{2}}.$$

As for the flow rate of hot layer, the following correlation is applied

$$Q_h = Q_c$$

$$= 0.5176 \cdot Q_{HPI} \left(\frac{H_h}{D_{HPI}} \right)^{1.236} Fr_I^{-0.414} \quad (13)$$

where

$$Fr_I = \frac{Q_{HPI}}{\frac{1}{4} \pi \cdot D_{HPI}^2} \left(g \cdot D_{HPI} \cdot \frac{\rho_{HPI} - \rho_{CL}}{\rho_{HPI}} \right)^{-\frac{1}{2}}$$

The numerical solution procedure is as follows. First of all, h_m^{n+1} and ρ_m^{n+1} , which are the mixture enthalpy and density at new time level to be solved, are obtained from Eq.(2). If the thickness of the hot layer H_h is assumed to be a certain value, the hot layer flow rate Q_h is obtained from Eq.(13) and hence the cold layer flow rate Q_c is obtained from Eq.(5). Then, h_c and h_h , which are the enthalpies of cold and hot layers, respectively, can be obtained from Eq.(6) and (7). However, Eq.(12), which is the flooding condition, may not be fulfilled. Thus, the problem can simply be expressed to solve the following equation :

$$F(H_h) = 0$$

where

$$F(H_h) = Fr_c^2 + Fr_h^2 - 1.$$

In PLES/PTS, the above equation is solved by a simple conventional method.

3.2.3 Empirical Correlation by MHI⁽⁸⁾

This model can be applied after NTC takes place. Before that, complete mixing is assumed. The empirical correlation developed by MHI is shown as follows :

$$\begin{aligned} \frac{(T_c - T_l)}{(T_{HPI} - T_l)} &= 1 - 0.526 R_i^{0.101} \exp(-0.0186 R_i^{-0.146} t^*) \\ &\quad \text{for } R_i \leq 100, \\ &= 1 - 0.838 \exp(-0.0095 t^*) \\ &\quad \text{for } R_i > 100. \end{aligned} \tag{14}$$

where

$$t^* = \frac{U_{CL} t}{L_{CL}} : \text{non-dimensional time},$$

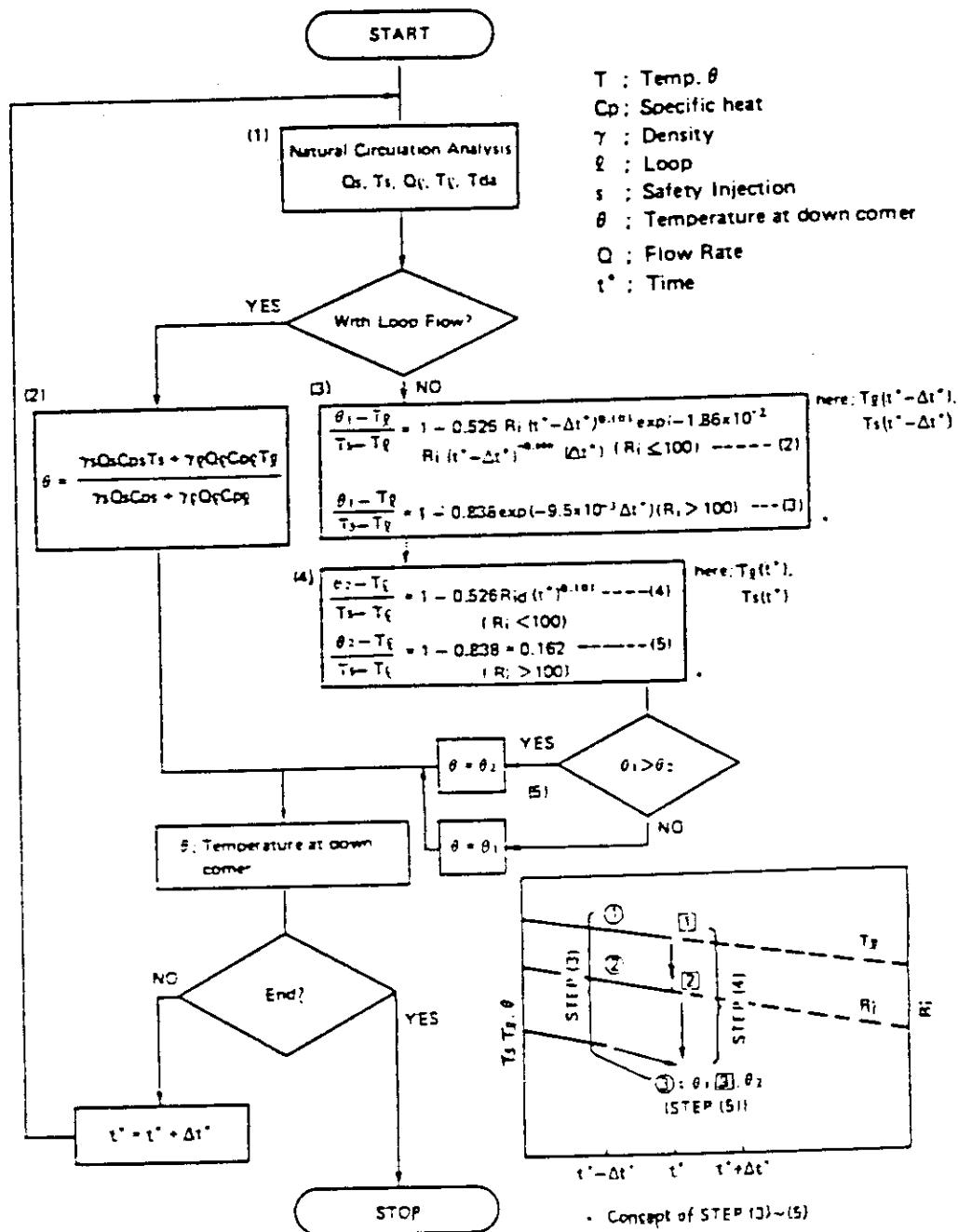
$$R_i = g D_{CL} \frac{\rho_{HPI} - \rho_l}{\rho_{HPI} U_{CL}^2} : \text{Richardson number},$$

and

$$U_{CL} = \frac{Q_{HPI}}{A_{CL}} : \text{velocity at cold leg.}$$

$$\left(\begin{array}{l} T_l : \text{Temperature of primary coolant } (\text{°C}) \\ \rho_l : \text{Density of primary coolant } (\text{kg/m}^3) \\ g : \text{Gravitational acceleration } (\text{m/s}^2) \end{array} \right)$$

The method to apply this correlation to evaluate the downcomer coolant temperature is shown in Fig.3.3⁽⁸⁾.

Fig. 3.3 Calculation flow to use MHI correlation⁽⁸⁾

3.3 Stress Analysis

The stress analysis is to supply the transient of the total stress distribution within the RPV wall to evaluate the stress intensity factor to a initial crack in the FM analysis. The total stress imposed on the RPV wall is composed of thermal stress and stress due to difference in static pressures at inner and outer surfaces of RPV wall. In order to obtain the transient of thermal stress distribution within the RPV wall, one-dimensional thermal conduction equation is solved :

$$\rho_v C_{pv} \frac{\partial T_v}{\partial t} = \frac{1}{r} \cdot \frac{\partial}{\partial r} (k_v r \frac{\partial T_v}{\partial r}) . \quad (15)$$

$$\left(\begin{array}{l} T_v : \text{Temperature within pressure vessel wall } (\text{°C}) \\ \rho_v : \text{Density of pressure vessel wall } (\text{kg/m}^3) \\ C_{pv} : \text{Specific heat of pressure vessel wall } (\text{J/kg} \cdot \text{°C}) \\ k_v : \text{Thermal conductivity of pressure vessel wall } (\text{J/m} \cdot \text{s} \cdot \text{°C}) \\ r : \text{Radial coordinate } (\text{m}) \end{array} \right)$$

The boundary conditions at the inner and outer surfaces of the pressure vessel are assumed as follows :

$$\phi = h_{tc} (T_b - T_w) \quad \text{at inner surface, and} \quad (16)$$

$$\frac{\partial T_w}{\partial r} = 0 \quad \text{at outer surface.} \quad (17)$$

$$\left(\begin{array}{l} T_w : \text{Vessel wall surface temperature } (\text{°C}) \\ h_{tc} : \text{Heat transfer coefficient } (\text{J/m}^2 \cdot \text{s} \cdot \text{°C}) \\ \phi : \text{Heat flux } (\text{J/m}^2 \cdot \text{s}) \\ T_b : \text{Fluid bulk temperature} \end{array} \right)$$

where T_b is taken as T_c which is the temperature of the cold layer evaluated by the thermal-mixing calculation.

The heat transfer coefficient h_{tc} is given as an input constant or evaluated by the following correlation⁽¹⁰⁾ :

$$h_{tc} = \frac{k_f}{D_e} N_{U\phi} \frac{N_u}{N_{u\phi}}$$

where the reference Nusselt Number $N_{u\phi}$ is given by the Petukhov and Kirrilov correlation⁽¹⁹⁾ :

$$N_{u\phi} = R_{ef} P_{rf} \left(\frac{C_f}{2} \right) / \left\{ 12.7 \left(\frac{C_f}{2} \right) \left(P_{rf}^{\frac{2}{3}} - 1 \right) + 1.07 \right\} . \quad (18)$$

The skin friction coefficient C_f is given by

$$C_f = 1 / (3.64 \log_{10} Ref - 3.28)^2 \quad (19)$$

and the Nusselt number ratio is given by the Jackson and Fewster correlation⁽²⁰⁾ :

$$\frac{N_u}{N_{u\phi}} = \left(1 + 4500 - G_{rf} / R_{ef}^{\frac{21}{8}} P_{rf}^{\frac{1}{2}} \right)^{0.31} \quad (20)$$

where

$$G_{rf} = G_{rfo} \frac{T_f - T_w}{\Delta T_{ref}} .$$

$$\left. \begin{array}{l} k_f : \text{Thermal conductivity of fluid } (\text{J/m} \cdot \text{s} \cdot {}^\circ\text{C}) \\ D_e : \text{Equivalent diameter } (\text{m}) \\ R_{ef} : \text{Reynolds number of fluid} \\ P_{rf} : \text{Prandtl number of fluid} \\ G_{rfo} : \text{Grashof number of fluid} \\ \Delta T_{ref} : \text{Reference temperature difference } ({}^\circ\text{C}) \end{array} \right\}$$

Based on the calculated temperature distribution within the pressure vessel wall, the thermal stress σ_T is evaluated by the following equation⁽¹⁹⁾ :

$$\sigma_T = \frac{\alpha E}{1 - \gamma} \cdot \frac{1}{r^2} \left[\frac{r_1^2 + r_0^2}{d^2 - r_0^2} \int_{r_0}^d Tr dr + \int_{r_0}^{r_1} Tr dr - Tr_1^2 \right]. \quad (21)$$

$$\left. \begin{array}{l} \alpha : \text{Thermal expansion ratio } (1/{}^\circ\text{C}) \\ E : \text{Young's modulus } (\text{Pa}) \\ \gamma : \text{Poisson's ratio} \\ r_0 : \text{Inner radius } (\text{m}) \\ r_1 : \text{Outer radius } (\text{m}) \\ d : \text{Wall thickness } (\text{m}) \end{array} \right\}$$

The stress σ_P due to pressure difference between inner and outer surfaces is evaluated as follows :

$$\sigma_P = \frac{r_0^2 P}{d^2 - r_0^2} \left(1 + \frac{d^2}{r_1^2} \right), \quad (22)$$

where the inner pressure P is given as a result of the transient thermal-hydraulic analysis or by an input table. Thus, the total stress σ is given as :

$$\sigma = \sigma_P + \sigma_T. \quad (23)$$

3.4 Fracture Mechanics Analysis

The fracture mechanics (FM) analysis is to obtain the transient of the stress intensity factor to an initial crack on the inner surface of the RPV wall and to estimate the fracture toughness parameters of the vessel material by using empirical correlations.

3.4.1 Fracture Toughness Properties

The following three empirical correlations are implemented to evaluate material fracture toughness properties k_{Ia} and k_{Ic} .

- 1) ASME Section XI lower-bound curve⁽¹³⁾

$$k_{Ic} = 36.5 + 3.084 e^{0.036(T'+56)} \quad (MPa\sqrt{m}), \quad (24)$$

and

$$k_{Ia} = 29.5 + 1.344 e^{0.0261(T'+89)} \quad (MPa\sqrt{m}) \quad (25)$$

where

$$T' = T - (RT_{NDT0} + \Delta RT_{NDT})$$

$$= T - RT_{NDT}$$

$$\left(\begin{array}{ll} T & : \text{Actual temperature from thermal analysis } (^{\circ}\text{C}) \\ RT_{NDT} & : \text{Reference temperature for nil ductility transition } (^{\circ}\text{C}) \\ RT_{NDT0} & : RT_{NDT} \text{ for unirradiated material } (^{\circ}\text{C}) \\ \Delta RT_{NDT} & : \text{Change in RT}_{NDT} \text{ caused by radiation damage } (^{\circ}\text{C}) \end{array} \right)$$

Figure 3.4 shows the k_{Ia} and k_{Ic} vs $(T - RT_{NDT})$ from ASME Section XI(Appendix A)^(12,14).

2) Mean curves by ORNL⁽¹⁵⁾

$$k_{Ic} = 1.43 \cdot k_{Ic} \text{ evaluated by Eq.(24)} \quad (26)$$

and

$$k_{Ia} = 1.25 \cdot k_{Ia} \text{ evaluated by Eq.(25).} \quad (27)$$

3) Mean curves by NRC⁽¹⁵⁾

$$\begin{aligned} k_{Ic} &= 39.8 + 54.3 e^{0.0187T'} \quad \text{for } T' \leq -28, \\ &= 60.6 + 30.8 e^{0.0385T'} \quad \text{for } T' > -28, \end{aligned} \quad (28)$$

and

$$\begin{aligned} k_{Ia} &= 21.9 + 48.2 e^{0.0179T'} \quad \text{for } T' < 28, \\ &= 77.0 + 7.14 e^{0.0353T'} \quad \text{for } T' > 28. \end{aligned} \quad (29)$$

The value of ΔRT_{NDT} is evaluated by either the correlation proposed in US Regulatory Guide 1.99 (Rev. 1)^(12,16) :

$$\begin{aligned} \Delta RT_{NDT} &= \\ &\frac{1}{1.8} [40 + 1000 (\%C_u - 0.08) + 5000 (\%P - 0.008) (F \cdot 10^{-19})^{\frac{1}{2}}] \quad (^{\circ}C) \end{aligned} \quad (30)$$

or by so called the Guthrie equation ^(15,17,23-26) :

$$\Delta RT_{NDT} = \frac{1}{1.8} [38 + 470 \%C_u + 350 \%N_i \cdot \%C_u (F \cdot 10^{-19})^{0.27}] \quad (^{\circ}C)$$

(31)

Whichever is used, the lesser one is used compared with the following equation

$$\Delta RT_{NDT} = \frac{1}{1.8} [283 (F \cdot 10^{-19})^{0.194}] \quad (^{\circ}C).$$

(32)

The attenuation of the fast-neutron fluence through the wall of vessel is given by^(12,13)

$$F = F_0 e^{-3.38a}.$$

(33)

F	: Fast neutron fluence (neutron energy > 1Mev) (n/cm^2)
F_0	: Fluence at inner surface of wall (n/cm^2)
a	: Radial distance from inner surface of cylinder (m)
$\%P$: Weight percentage of copper content
$\%C_u$: Weight percentage of phosphorus content
$\%N_i$: Weight percentage of nickel content

Figure 3.5 shows the ΔRT_{NDT} vs fast neutron fluence data taken from USNRC Regulatory Guide 1.99(Revision 1)^(12,16).

3.4.2 Stress Intensity Factor⁽¹²⁾

The method to evaluate the stress intensity factor k_I is the same as that used in the OCA-I code, where a one-dimensional axial flaw is assumed to exist. The method is to calculate k_I curves separately for each of several unit load applied at specified points along a crack surface. The unit load k_I values k^* for a selected crack depth are weighted in accordance with the crack-free stress distribution associated with the equivalent problem. Then the actual k_I value is obtained by superposition as follows :

$$k_I(a) = \sum_{i=1}^n \sigma_i \Delta a_i k_i^*(a'_i, a) \quad (34)$$

where

(Δa_i : an increment of a about a')

$$\sum_{i=1}^n \Delta a_i = a,$$

a a'_i σ_i k_i^* n	: crack depth (radial distance from open end of crack) : radial distance from open end of crack (cylinder surface) to point of application of unit load, : average stress over Δa_i for equivalent problem, : stress intensity factor per unit load applied at a'_i per unit length of cylinder, and : number of points along length of crack for which k^* values are available.
---	---

Figure 3.6 shows the conceptual illustration of stress along crack line in uncracked cylinder and application of unit load to crack surface along with the table of k^* used in OCA-I⁽¹²⁾. The same model and table are used in PLES/PTS.

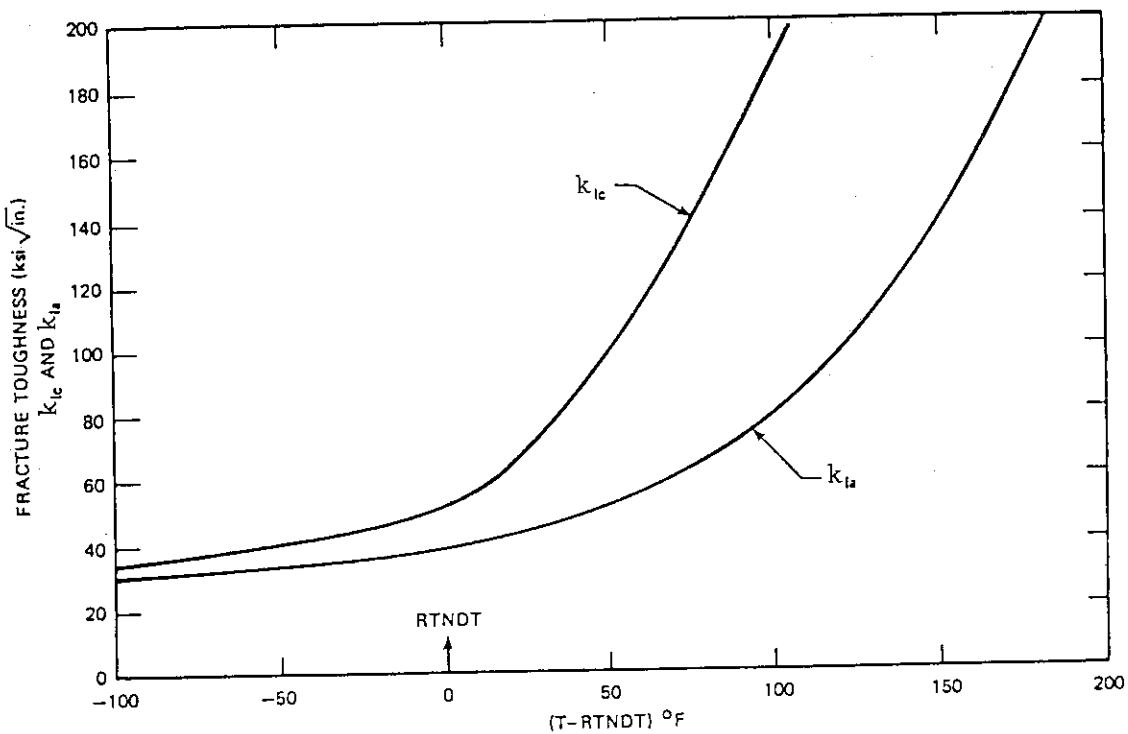


Fig. 3.4 k_{Ia} and k_{Ic} vs $(T - \text{RTNDT})$ from ASME Section XI (Appendix A)
(Appendix A)^(12, 14)

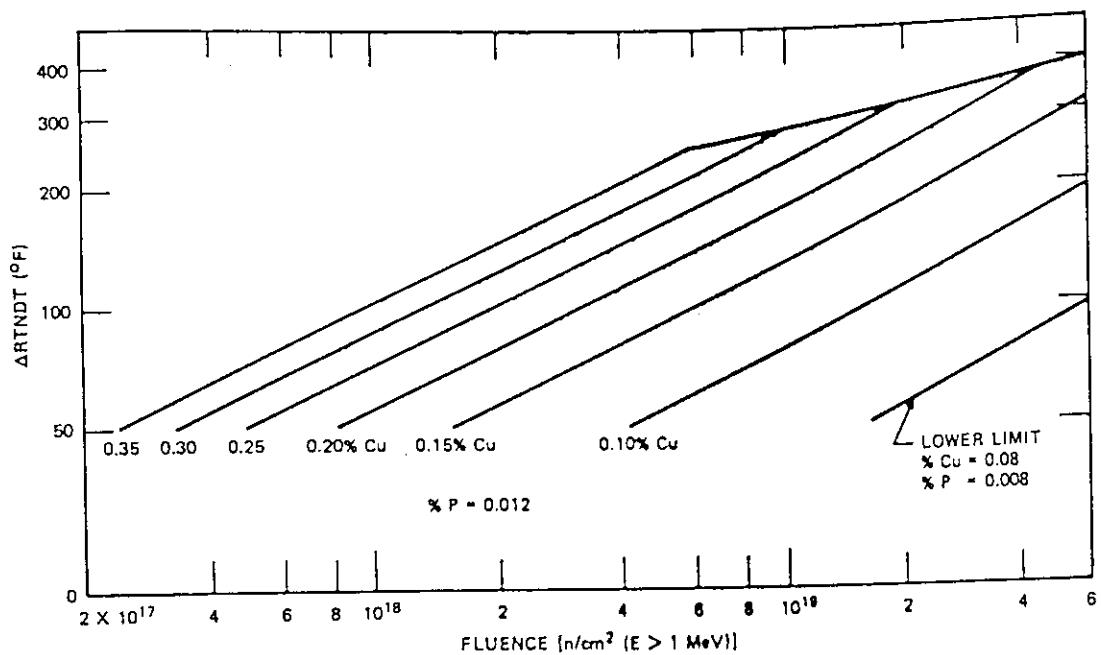
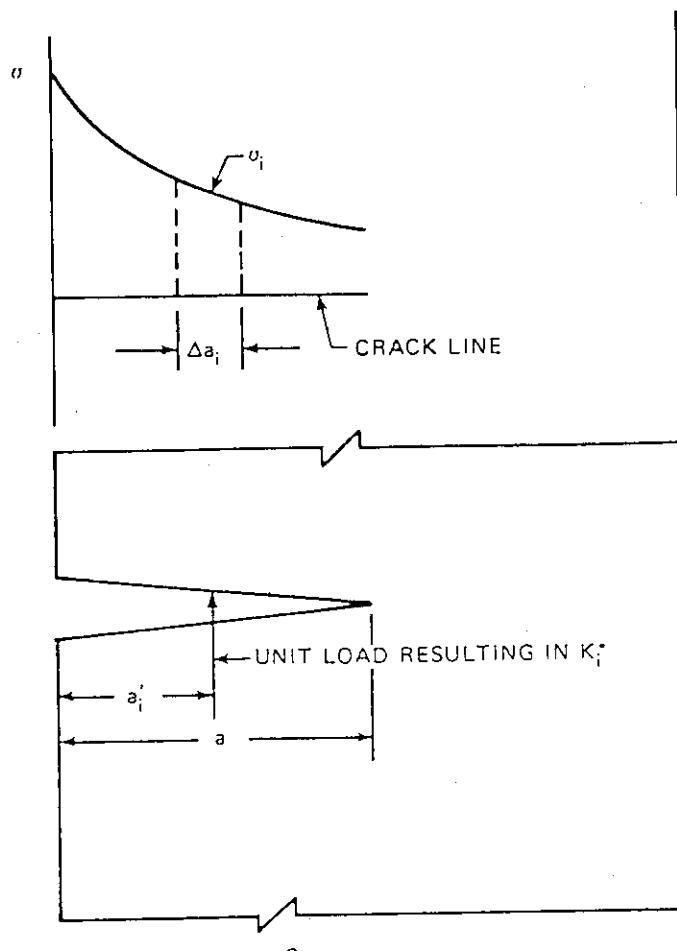


Fig. 3.5 ΔRTNDT vs fast neutron fluence data taken from NRC
Regulatory Guide 1.99(Revision 1)^(12, 16)



$$K_i(a) = \sum_{i=1}^n \sigma_i \Delta a_i K_i^*(a'_i, a)$$

Crack-depth identification No. ^b	Fractional crack depth (a/w)	Number of K^* values
1	0	0
2	0.02647	6
3	0.05588	11
4	0.07641	14
5	0.10147	16
6	0.1500	17
7	0.20147	19
8	0.2500	21
9	0.3011	23
10	0.40147	25
11	0.5000	27
12	0.60012	31
13 ^c	0.70735	34
14	0.8000	37
15	0.8500	37
16	0.9000	37
17		

^aCylinder has a 172-in. ID × 189-in. OD.

^bUsed internally in OCA-I.

^cNot used.

Fig. 3.6 Illustration of stress along crack line in uncracked cylinder and application of unit load to crack surface⁽¹²⁾

4. Code Organization

4.1 Structure of Code System

Figure 4.1 shows the structure of the code system. The code system PLES/PTS consists of :

- (1) Member codes to perform the calculations described in Subsecs. 3.2 to 3.4 and to display the results, which conform the main body of PLES/PTS, and
- (2) Programs to control the execution of the member codes in the main body of PLES/PTS and data transfer between them, which is called the driver program.

Each member code in the main body of PLES/PTS can be executed independently. In the case where a user desires to perform only the thermal-mixing analysis, for example, it is enough to execute only one of the member codes. The driver program⁽¹⁸⁾, which is supplied for ease of users, is helpful to perform a combined calculations with several member codes such as a once-through calculation from the thermal-mixing analysis to fracture mechanics analysis including the plotting of the calculated results.

The input data requirements to the main body of PLES/PTS is supplied in Appendix A. The data flow and sample inputs and outputs are shown in Appendeces B and C, respectively.

4.2 Driver Program

As described in Subsec. 4.1, the driver program is used to execute several member codes simultaneously. The driver program can reduce such endeavor that users have to set up rather complicated JCL, which includes the data transfers to link the calculations with member codes. The driver program has been developed at the Oak Ridge National Laboratory (ORNL) in U.S.A. for the code system SCALE to design and evaluation of transportation casks of nuclear fuels. The driver program is used in pair with a program called the control module, as shown in Fig.4.1. The control module determine the order of programs to be executed and the data transfers between them and the driver program executes the programs one by one following the order. At each execution, it returns the completion code to the control module and then the control module generate the next order to the driver program. The control module to be used to execute each member code in PLES/PTS is incorporated together with the driver program as a part of PLES/PTS.

As for more detailed information on the driver program, reference should be made to Ref.(18).

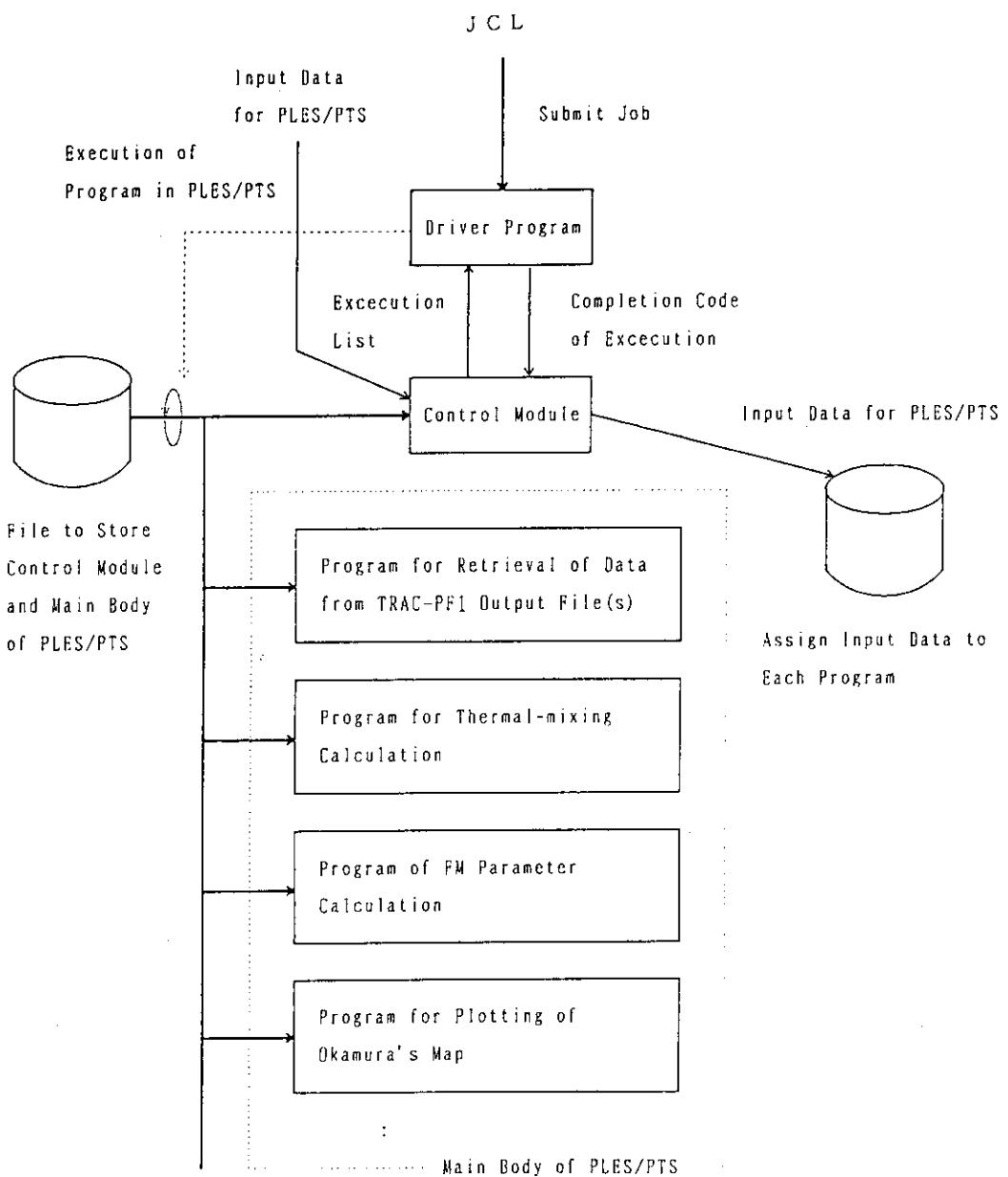


Fig. 4.1 Structure of PLES/PTS

5. Summary

The code system PLES/PTS has been developed at JAERI for evaluation of the integrity of the pressure vessel in PWR during miscellaneous transients related to PTS. The code system handles the combined calculation of the thermal-mixing analysis, stress analysis and fracture mechanics analysis. The major methods and models applied in the present version of PLES/PTS were described in this report in addition to the input data requirements.

Acknowledgment

The authors would like to express their sincere thanks to Mr. K. Abe, Head of Risk Analysis Laboratory, Dept. of Reactor Safety Research, JAERI, for his critical reading, and Miss. K. Aizawa, I.S.L Co. Ltd., for typing the manuscript.

5. Summary

The code system PLES/PTS has been developed at JAERI for evaluation of the integrity of the pressure vessel in PWR during miscellaneous transients related to PTS. The code system handles the combined calculation of the thermal-mixing analysis, stress analysis and fracture mechanics analysis. The major methods and models applied in the present version of PLES/PTS were described in this report in addition to the input data requirements.

Acknowledgment

The authors would like to express their sincere thanks to Mr. K. Abe, Head of Risk Analysis Laboratory, Dept. of Reactor Safety Research, JAERI, for his critical reading, and Miss. K. Aizawa, I.S.L Co. Ltd., for typing the manuscript.

References

- (1) USNRC, "NRC Staff Evaluation of Pressurized Thermal Shock," SECY-82-465, (Nov., 1982).
- (2) D.L. Selby, et al., "Pressurized Thermal Shock Evaluation of the Calvert Cliffs Unit 1 Nuclear Power Plant," NUREG/CR-4022 (1985).
- (3) K. Koyama, et al., "PTS Research in Japan," Proc. 2nd Int. Topical Mtg. on Nucl. Power Plant Thermal Hydraulics and Operation, Tokyo, Japan (April 15-17, 1986).
- (4) M. Hirano and A. Kohsaka, "Dominant Factors in Evaluation of Pressure Vessel Integrity during PTS Events," Proc. Int. ENS/ANS Conf. on Thermal Reactor Safety, Avignon, France, Vol.1 (Oct. 1988) PP.82.1-82.10.
- (5) "TRAC-PF1: An Advanced Best Estimate Computer Program for Pressurized Water Reactor Analysis," NUREG/CR-3567, LA-9944-MS (1984).
- (6) J.H. McFadden and et al., "RETRAN02-A Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow System," NP-1850-CCMA, EPRI(1981).
- (7) T.G. Theofanous, et al., "Decay of Buoyancy Driven Stratified Layers with Applications to Pressurized Thermal Shock," NUREG/CR-3700, U.S. Nuclear Regulatory Commission (May 1984).
- (8) S. Yoshimura, et al., "Mixing Behavior of Safety Injection Water within the Cold Leg and the Downcomer under Postulated Accidents," Proc. 3rd Int. Topical Mtg. on Reactor Thermal Hydraulics, 13.D-(1-8) (1985).
- (9) B.K.H. Sun, et al., "Transient Time of Mixed HPI Water and Primary Loop Water in PWR Cold Legs," Nucl. Tech. Vol.64 (1985).
- (10) V.K. Chexal, et al., "An Empirical Mixing Model for Pressurized Thermal Shock Applications," Nucl. Tech. Vol.69 (April, 1985) pp/94-99.
- (11) J.H. Kim, "An Analytical Mixing model for Buoyant Jet Injected into Pipe Flow," Trans. ASME, Vol.107 (Aug., 1985) pp 630-636.
- (12) S.K. Iskander, et al., "OCA-I, A Code for Calculating the Behavior of Flaws on the Inner Surface of a Pressure Vessel Subjected to Temperature and Pressure Transients," NUREG/CR-2113, ORNL/NUREG-84 (AUG., 1981).
- (13) D.G. Ball et al, "OCA-II, A Code for Calculating the Behavior of 2-D and 3-D Surface Flaws in a Pressure Vessel Subjected to Temperature and Pressure Transients, NUREG/CR-3491, ORNL-5934 (Feb., 1984).

- (14) T.U. Marston, "Flaw Evaluation Procedures: ASME Section XI," EPRI NP-719-SR (Aug., 1978).
- (15) "OCA-P, A Deterministic and Probabilistic Fracture-Mechanics Code for Application to Pressure Vessels," NUREG/CR-3618 (May, 1984).
- (16) USNRC, "Effects of Residual Elements on Predicted Radiation Damage to Reactor Pressure Vessel Materials," Regulatory Guide 1.99, Rev.1 (1976).
- (17) P.N. Randall, U.S.Nuclear Regulatory Commission, personal communication to R.D. Cheverton (see Ref.15), Oak Ridge National Laboratory (April 1982).
- (18) L.M. Petrie, "SCALE System DRIVER," NUREG/CR-0200, Vol. 3, Sec. M1, ORNL/NUREG/CSD-2/v3 (Oct., 1978).
- (19) B.S. Petukhov, "Heat Transfer and Friction in Turbulent Pipe Flow with Variable Properties," Adv. Heat Transfer, 6, 503 (1970).
- (20) "Seminar on Turbulent Buoyant Convection," Proc. Int. Conf. Heat and Mass Transfer, Beograd, Yugoslavia, 1976, D.B. Spalding and Afgan, Eds.
- (21) S. Timoshenko, "Strength of Materials," Part II, 2nd ed.(Clarendon Press, Oxford, England, 1959).
- (22) Okamura, et al., "An Expert-Interactive Algorithm of Structural Evaluation and Its Application to Pressurized Thermal Shock," Proc. Int. Conf. SMiT-9 (1987).
- (23) G.L. Guthrie, "Charpy Trend Curves Based on 177 PWR Data Points," in "LWR Pressure Vessel Surveillance Dosimetry Improvement Program," NUREG/CR-3391, Vol.2, prepared by Hanford Engineering Development Laboratory, HEDL-TME 83-22 (April 1984).
- (24) G.R. Odette et al., "Physically Based Regression Correlations of Embrittlement Data from Reactor Pressure Vessel Surveillance Programs," Electric Power Research Institute, NP-3319 (January 1984).
- (25) USNRC, "Radiation Embrittlement of Reactor Vessel Materials", Regulatory Guide 1.99 Rev.2) (1988).
- (26) Code of Federal Regulations, 10 CFR Part 50, Section 50.61, "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events."

Appendix A Input Data Requirements for PLES/PTS

The input data set for PLES/PTS consists of 4 data blocks corresponding to the following 4 programs.

Identifier	Program
1. TRAC	Retrieval of data from TRAC-PF1 output file(s)
2. ENG1	Thermal-mixing calculation
3. FRAC	Stress and fracture mechanics(FM) parameter calculations
4. OAK2	Plotting of Okamura's map

Each data block must be started by a card which contains DATAID and IEXEC. The variable DATAID is an identifier to select which program is to be executed. When IEXEC is not 0, the corresponding program is executed. When IEXEC = 0, it is not executed. In this case, therefore, the residual input data in the data block have to be omitted. In the following, the input data requirements to each data block are summarized.

1. Input Data for Retrieving Data from TRAC-PF1 Output Data File(s)

When the temperature and pressure transients are to be read from the output data file(s) for plotting from the TRAC-PF1 code, this program is to be executed.

Record-01 (A4, I4)

DATAID	Must be TRAC.
IEXEC	= 0 : Not to be executed. ≠ 0 : To be executed.

Record-02 (A72)

TITLE	Title : Any words
-------	-------------------

Record-03 (I4)

NFILE	Number of TRAC-PF1 output files to be used
-------	--

Record-04 (2F8.3)

TSTART	Start time for data retrieval(s)
TEND	End time for data retrieval(s)

Record-05 (F8.3, I4)

TSTEP	Interval for data retrieval(s)
NSTEP	Interval for data retrieval
TSTEP>0 : every TSTEP seconds(NSTEP is not used.)	
TSTEP<0 : every NSTEP time steps(TSTEP is not used.)	

Record-06 (I4)

NUMCMP Component number of data to be retrieved

2. Input Data for Thermal-Mixing Calculation

When the thermal-mixing calculation with the engineering models is to be performed, this program is executed. The input data block for this program consists of 10 sub-blocks of input data. Each sub-block must be started by a card with an identifier IDSB and be ended by a card with a character string FIN, for example, as follows:

```

TIME : Sub-block identifier
&TIME MT=0,DT=10.0,NTP=1,NTDAT=10, : Input data by namelist statement
      TINIT=0.0,TEND=2000.0, &END
FIN : Must be closed by a character string FIN.

```

In the above example, the identifier IDSB is TIME. In-between the identifier IDSB and FIN, the input data are given by a namelist statement and/or by cards with fixed formats.

Record-01 (A4, I4)

DATAID	Must be ENGL.
IEXEC	= 0 : Not to be executed. ≠ 0 : To be executed.

Sub-block 1 : Calculation title

IDSB	Must be TITL.
TITLE (A72)	Title : Any words
FIN	Must be FIN.

Sub-block 2 : Controlling parameters

IDSB	Must be TIME.
NAMELIST &TIME	
FIN	Must be FIN.

NAMELIST &TIME:

MT Number of time steps
 DT Time step width
 NTP Printout interval(steps)
 TINIT Start time of calculation(s)
 TEND End time of calculation(s)
 NTDAT Number of data points

Sub-block 3 : Options

IDSB Must be OPTN.

Option input card(414)

Namelist &QQW

FIN Must be FIN.

Namelist &QQW:

ICALC Option flag for method to be applied:

- = 1 : Empirical correlation proposed by EPRI
- = 2 : Theofanous' bulk mixing model (Not supported)
- = 3 : Theofanous' regional mixing model
- = 4 : Kim's method(Not supported)
- = 5 : Empirical correlation proposed by MHI

IPNO Option flag for calculation:

- = 0 : Wall temperature transient is read from NAMELIST &QQW and time dependent data are read from sub-block 9.)
- > 1 : Time dependent data are read from Fortran Unit 3(See Table A.1) and heat from wall cannot be considered.)

IDEBUG Option flag for printing for debugging:

- = 1 : Printing for debugging is given on Fortran Unit 8.

ITERMX Maximum iteration number for RMM calculation(see sample input in Appendix C)

NAMELIST &QQW(When IPNO = 0):

QW Wall temperature(°C)

Sub-block 4 : Convergence criteria

IDSB Must be EPSC.

NAMELIST &EPSC

FIN Must be FIN.

NAMELIST &EPSC:

EPSIN Convergence criterion for inner loop in RMM calculation
 EPS2 Convergence criterion for outer loop in RMM calculation
 QLMIN Criterion of NCT (Natural Circulation Termination)(m^3/sec)
 (When cold leg flow < QLMIN, NCT is assumed to occur.)

Sub-block 5 : Physical variables

IDSB Must be QTDE.

NAMELIST &QTDE

FIN Must be FIN.

NAMELIST &QTDE:

TCL Coolant temperature at cold leg ($^{\circ}\text{C}$)
 QCL Volumetric flow rate at cold leg(m^3/s)
 RHOCL Coolant density at cold leg (kg/m^3)
 THPI HPI water temperature ($^{\circ}\text{C}$)
 QHPI HPI volumetric flow rate (m^3/s)
 RHOHPI HPI water density (kg/m^3)
 TDC Coolant temperature at downcomer ($^{\circ}\text{C}$)

Sub-block 6 : Geometrical data

IDSB Must be SIZE.

NAMELIST &SIZE

FIN Must be FIN.

NAMELIST &SIZE:

DCL Cold leg diameter (m).
 ALCL Cold leg length (m)
 VADD Additional volume (m^3) (Normally 1/4 of pump volume)
 DHPI HPI leg diameter
 THETA Angle of HPI leg to cold leg
 VSYC Total volume (m^3) (Except pump volume)

Sub-block 7 : Physical properties

IDSB Must be CNST.

NAMELIST &CNST

FIN Must be FIN.

NAMELIST &CNST:

CREF	Reference specific heat (kcal/kg°C)
NTEMP	Number of points in temperature and density tables
FTEMP	Temperature (°C) (NTEMP points)
FDENS	Density (kg/m³) (NTEMP points)
NSHEAT	Number of points in temperature and specific heat tables
FHTEMP	Temperature (°C) (NSHEAT points)
FCREF	Specific heat (kcal/kg) (NSHEAT points)

Sub-block 8 : Input data for Kim's model

Although the calculation model is implemented, it has not been well verified. Thus, this model is currently not recommended to be used.

IDSB Must be CALC.

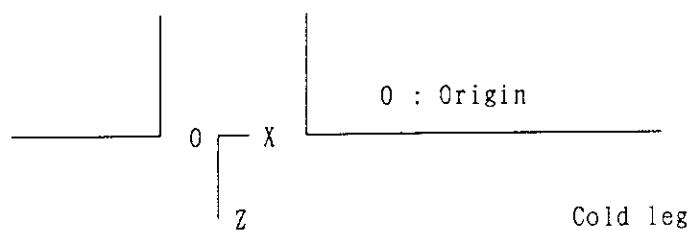
NAMELIST &CALC

FIN Must be FIN.

NAMELIST &CALC

LCALCP	Number of data points (≤ 201)
Z	Z-coordinate of data point (m)
X	Z-coordinate of data point (m)

HPI leg



Sub-block 9 : Time dependent data

If IPNO>1, only IRHOPT should be specified. The other data are read from Fortran Unit 3(See Table A.1).

IDSB Must be TQTD.

NAMELIST &TQTD

FIN Must be FIN.

NAMELIST &TQTD

TTITME	Time (s) (NTDAT Points)
TTCL	Coolant temperature at cold leg ('C) (NTDAT Points)
TQCL	Volumetric flow rate at cold leg (m^3/sec) (NTDAT Points)
TRHOCL	Coolant density at cold leg (kg/m^3) (NTDAT Points)
TTDA	Coolant temperature at downcomer ('C) (NTDAT Points)
TTHPI	HPI water temperature ('C) (NTDAT Points)
TQHPI	HPI volumetric flow rate (m^3/sec) (NTDAT Points)
TRHOHP	HPI water density (kg/m^3) (NTDAT Points)
IRHOPT	Option flag for cold leg density calculation: = 1 : Cold leg density is to be calculated.

The input variables required for each engineering model specified by option flag ICALC in Sub-block 3 are summarized in Table A.2.

Table A.1 Format of input file(Flow and flow rate data)
to thermal-mixing culation

Record-01

NTDAT I*4 Number of data points

Record-02 (NTDAT Records)

TTIME(I)	R*8	Time (s)
TQHPI(I)	R*8	HPI volumetric flow rate (m^3/s)
TTHPI(I)	R*8	HPI water temperature ('C)
TRHOHP(I)*	R*8	HPI water density (kg/m^3)
TQCL(I)	R*8	Volumetric flow rate at cold leg (m^3/s)
TTCL(I)	R*8	Coolant temperature at cold leg ('C)
TRHOCL(I)*	R*8	Coolant density at cold leg (kg/m^3)
TTDA(I)	R*8	Coolant temperature at downcomer ('C)

*)When IRHOPT=1, TRHOHP and TRHOCL are not used.

Table A.2 List of input variables required for each engineering model specified by option flag ICALC

Variables	NAMELIST	Option flag ICALC				
		= 1	= 2	= 3	= 4	= 5
MT	&TIME			△ *1	△ *1	
DT	&TIME	○	○	○		○
NTP	&TIME	○	○	○		
TINIT	&TIME	○	○	○		○
TEND	&TIME	○	△ *1	△ *1		○
NTDAT	&TIME		○ *2	○ *2		○ *2
TCL	&QTDE	○			○	
QCL	&QTDE	○			○	
RHOCL	&QTDE	○			○	
THPI	&QTDE	○			○	
QHPI	&QTDE	○			○	
RHOHPI	&QTDE	○			○	
TDC	&QTDE		○ *3	○ *3		○ *3
DCL	&SIZE	○	○	○	○	○
ALCL	&SIZE	○	○	○		
VADD	&SIZE			○		
DHPI	&SIZE	○		○	○	
THETA	&SIZE				○	
VSYC	&SIZE		○	○		
CREF	&CNST		○	○		
NTEMP	&CNST		○	○	○	○
FTEMP	&CNST		○	○	○	○
FDENS	&CNST		○	○	○	○
NSHEAT	&CNST					○
FHTEMP	&CNST					○
FCREF	&CNST					○
LCALCP	&CALC				○	
Z	&CALC				○	
X	&CALC				○	
EPSIN	&EPSC			○	○	
EPS2	&EPSC			○	○	
QLMIN	&EPSC		○	○		○

*1) Either TEND or MT is to be given. When TEND ≠ 0.0, MT = (TEND - TINIT) / DT + 1.

*2) Not necessary, when IPNO > 1 in namelist &QQW.

*3) Not necessary, when IPNO = 1 in namelist &QQW.

Table A.2 List of input variables required for each engineering option flag ICALC (Continued)

Variables	NAMELIST	Option flag ICALC				
		= 1	= 2	= 3	= 4	= 5
TTIME* ¹	&TQTD		○	○		○
TTCL* ¹	&TQTD		○	○		○
TQCL* ¹	&TQTD		○	○		○
TRHOCL* ¹	&TQTD		○* ²	○* ²		○* ²
TTDA* ¹	&TQTD		○	○		○
TTHPI* ¹	&TQTD		○	○		○
TQHPI* ¹	&TQTD		○	○		○
TRHOHP* ¹	&TQTD		○* ²	○* ²		○* ²
IRHOPT	&TQTD		○	○		○
QW	&QQW	○* ³	○* ³	○* ³	○* ³	○* ³

*1) To be read from Fortran Unit 3, when IPNO>1.

*2) Not necessary, when IRHOPT = 1 in namelist &TQTD.

*3) Necessary, when IPNO = 0 in namelist &QQW.

Table A.3 Format of input file (pressure data) to stress calculation

Record-01

IBCP I*4 Number of data points

Record-02 (IBCP Records)

BCTIME(I) R*4 Time(min)

BCPRES(I) R*4 Pressure(ksi or MPa)

3. Input Data for Stress and Fracture Mechanics(MF) Parameter Calculation

Record-01 (A4, 14)

DATAID Must be FRAC.
 IEXEC = 0 : Not to be executed.
 ≠ 0 : To be executed.

Record-02 (4X, 2I4)

KOPT Option flag for execution:
 = 0 : Both FM parameter calculation and plotting are to be
 executed.
 > 0 : Only FM parameter calculation is to be executed.
 < 0 : Only plotting is to be executed.
 NUNT Option flag for units:
 = 1 : Both calculation and plotting are done by British units.
 = 2 : Both calculation and plotting are done by MKS units.
 = 3 : Calculation is done by British units and plotting is
 done by MKS units.

Records from 03 to 25 must be inserted when KOPT ≥ 0 .

Record-03 (4X, 18A4)

TITL Title : Any word

Record-04 (4X, 4I4, F8.0)

NOD Number of mesh points for thermal conduction calculation

Record-05 (4X, 6F12.4)

RATE Ratio of i-th mesh length to i-1-th mesh length
 RIN Vessel wall inner diameter (in or m)
 ROUT Vessel wall outer diameter (in or m)

Record-06 (4X, 6F12.4) (When RATE<0.0)

R(J), J=1, NOD Coordinates at mesh points (in or m)

Record-07 (4X, 6F12.4)

RHO (1) Specific weight of cladding (lb/in³ or kg/m³)
 SP1 (1) Specfiic heat of cladding (Btu/lb·°F or kJ/kg·°C)
 COND(1) Thermal conductivity of cladding (Btu/min·in·°F or
 kJ/min·m·°C)
 TCINI Initial temperature of cladding (°F or °C)

Record-08 (4X, 6F12.4)

RHO (2) Specific weight of vessel wall (lb/in³ or kg/m³)
 SP1 (2) Specific heat of vessel wall (Btu/lb·°F or kJ/kg·°C)
 COND(2) Thermal conductivity of vessel wall (Btu/min·in·°F or
 kJ/min·m·°C)
 TVINI Initial temperature of vessel wall (°F or °C)

Record-09 (4X, 6F12.4)

RCR Outer diameter of cladding (in or m)

Record-10 (4X, I4, 5F12.4)

IHT Option flag for heat transfer coefficient(HTC):
 = 0 : HTC is given by input.
 = 1 : HTC is to be calculated.
 HTA HTC (Btu/min·in²·°F or kJ/min·m²·°C) (When IHT=0)

Record-11 (4X, 6F12.4) (When IHT=1)

DIAM Equivalent diameter of downcomer (in or m)
 RE Reynolds number
 PR Prandtl number
 GR Grashof number
 DTREF Reference temperature (°F or °C)

Record-12 (4X, 4I4, F8.0)

IHF Option flag for fluid temperature transient input:
 = 0 : To be read from cards.
 = 1 : To be read from TRAC-PF1 output file(s).
 = -1 : To be read from TRAC-PF1 output file(s) before
 TFSTOP and be read from results of thermal-
 mixing calculation after that.
 = 2 : To be calculated by defaulted function(see
 record-13).
 = 3 : To be read from results of thermal-mixing
 calculation.

IBCT Number of data points for temperature transient(≤ 500)
 (When IHF=0)
 IST Sampling interval (steps)(When IHF=1)
 TFSTOP Time of natural circulation termination (min)(When IHF=-1)

Record-13 (4X, 6F12.4) (IF IHF=2)

TAUT Time constant (min)
 TINIT Initial temperature (°F or °C)
 TFINAL Terminal temperature (°F or °C)

The defaulted function is defined as follows:

$$\text{TEMP} = \text{TFINAL} + (\text{TINIT} - \text{TFINAL}) \exp(-\text{Time}/\text{TAUT})$$

Record-14 (4X, 6F12.4) (When IHF=0)

BCT(J), TEMP(J), J=1, IBCT

BCT : Time (min)

TEMP : Fluid temperature ('F or 'C)

Record-15 (4X, 3F12.4)

DTI Time step width (min)

TIMS Start time (min)

TIML End time (min)

Record-16 (4X, 2I4)

IKV Option flag for K_{ia} and K_{ic} calculations:

= 1 : ASME Section XI lower-bound curve

= 2 : ORNL mean curve

= 3 : NRC mean curve

IRT Option flag for DRTNDT calculation:

= ± 1 : Regulatory Guide 1.99 (If positive, impurity concentrations are assumed to be zero).

= ± 2 : Randall's (Guthrie's correlation) correlation
(If positive, impurity concentrations are assumed to be zero).

Record-17 (4X, 6F12.4)

RTNDT RTNDT ('F or 'C)

UPKIA Maximum value of K_{ia} (ksi·in^{1/2} or MPa·m^{1/2})

UPKIC Maximum value of K_{ic} (ksi·in^{1/2} or MPa·m^{1/2})

F0 Fast neutron fluence at inner surface

CCU Copper concentration (w%) (If blank, 0.25.)

CCP Phosphorus concentration for IRT= ± 1 (w%) (If blank, 0.012.)

Nichel concentration for IRT= ± 2 (w%)

Record-18 (4X, 6F12.4)

E Young's modulus (ksi or MPa)

UYN Poisson's ratio

ALPHA Coefficient of thermal expansion (1/'F or 1/'C)

Record-19 (4X, 4I4)

IPF Option flag for pressure transient input:

= 0 : To be read from cards.

= 1 : To be read from TRAC-PF1 output file(s).

= 2 : To be calculated by defaulted function
(see record-20).

= 3 : To be read from external file (See Table A.3).

IBCP Number of data points(≤ 500) (When IPF=0)
 IC Starting record(When IPF=1)
 IST Data sampling interval(When IPF=1)

Record-20 (4X, 3F12.4) (When IPF $\neq 0$)

TAUP Time constant (min)
 PINIT Initial pressure (ksi or MPa)
 PFINAL Terminal pressure (ksi or MPa)

The defaulted function is defined as follows:

$$\text{PRES} = \text{PFINAL} + (\text{PINIT} - \text{PFINAL}) \exp(-\text{Time}/\text{TAUP})$$

Record-21 (4X, 6F12.4) (When IPF=0)

BCP(I), PRES(I), I=1, IBCP
 BCP : Time (min)
 PRES : Pressure (ksi or MPa)

Record-22 (4X, 2I4)

KTIM K_t -value is to be calculated at every KTIM steps.
 ICOPT Option flag for K_t -value calculation:
 = 0 : Thermal conduction calculation is to be executed
 but K_t -value is not to be calculated.
 = 1 : K_t -value is to be calculated.

Record-23 (4X, 1I4) (When DTI ≤ 0.0)

IDMAX Number of time step width for thermal conduction
 calculation(≤ 20)

Record-24 (4X, 6F12.4) (When DTI ≤ 0.0 in record-15)

DT(I), I=1, IDMAX
 Time step width for thermal conduction calculation (min)

Record-25 (4X, 6F12.4) (When DTI ≤ 0.0 in record-15)

DTSTOP(I), I=1, IDMAX
 Maximum time (min)

Records from 26 to 52 must be inserted, when KOPT ≤ 0 .

Record-26 (A4, 7I4) Option flags for plotting:

DATAID Must be IPLO.
 IPLOT1 Critical-crack-depth curve:
 = 1 : To be plotted.
 = 0 : Not to be plotted.

I PLOT2 K_I , K_{Ic} , K_{Ia} , wall temperature(TEMP), thermal stress(SIGMAT), stress due to inner pressure(SIGMAP), total stress(SIGMA) vs normalized crack depth(a/W) curves:
 = 1 : To be plotted.
 = 0 : Not to be plotted.

I PLOT3 K_I , K_{Ic} , K_{Ia} vs a/W curves:
 = 1 : To be plotted.
 = 0 : Not to be plotted.

I PLOT4 SIGMAT, SIGMAP, SIGMA vs a/W curves:
 = 1 : To be plotted.
 = 0 : Not to be plotted.

I PLOT5 K_{Ic} , K_{Ia} vs TEMP curves(Okamura's map):
 = 1 : To be plotted.
 = 0 : Not to be plotted.

I PLOT6 Fluid temperature transient:
 = 1 : To be plotted.
 = 0 : Not to be plotted.

I PLOT7 Pressure transient:
 = 1 : To be plotted.
 = 0 : Not to be plotted.

Record-27 (4X, 2F8.0)

XLONG Length of X-axis (mm)(300mm, when ≤ 0.0)
 YLONG Length of Y-axis (mm)(250mm, when ≤ 0.0)

Records from 28 to 30 must be inserted when I PLOT1 $\neq 0$.

Record-28 (4X, 2F8.0)

TMIN Minimum value of X-axis (min)
 TMAX Maximum value of X-axis (min)
 (X-axis is automatically scaled, when TMAX \leq TMIN.)

Record-29 (4X, I4)

N DATA Number of data points(≤ 100)

Record-30 (4X, 3F8.0) (Must be repeated N DATA times, when N DATA > 0 .)

X DATA(I) Time data (min)
 Z DATA(I, 1) Normalized flaw depth(a/W) at initiation
 Z DATA(I, 2) Normalized flaw depth(a/W) at arrest

Records from 31 to 37 must be inserted, when IPLOT2 \neq 0.

Record-31 (4X, 7I4)

JPLOT(I), I=1, 7

Option flags for plotting:

JPLOT(1) : K_1 vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

JPLOT(2) : K_{1c} vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

JPLOT(3) : K_{1a} vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

JPLOT(4) : TEMP vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

JPLOT(5) : SIGMAT vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

JPLOT(6) : SIGMAP vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

JPLOT(7) : SIGMA vs a/W curve:

= 1 : To be plotted.

= 0 : Not to be plotted.

Record-32 (4X, 14)

ITMAX Number of time data to be plotted

(To be plotted at all time steps, when ITMAX \leq 0.)

Record-33 (4X, 8F8.0) (When ITMAX>0)

TIME(I), I=1, ITMAX

Time data (min)

Record-34 (4X, 2I4)

JMAX Option flag for plotting

(When JMAX>0, plotting is done.)

NDATA Number of data points to be plotted(\leq 100)

Record-35 (4X, 8F8.0) (When JMAX>0)

XDATA(I), I=1, NDATA

Normalized flaw depth (a/W) or r-coordinate (in or m)

Record-36 (4X, 2F8.0, I4) (When JPLOT(K) ≠ 0)

YMIN(K) Minimum value of Y-axis
 YMAX(K) Maximum value of Y-axis (Y-axis is automatically scaled, when
 YMAX ≤ YMIN.)
 JMAX(K) Number of data points in one curve(≤100)

K must be repeated from 1 to 7.

Record-37 (4X, 8F8.0) (When JMAX>0)

YDATA(!), I=1, JMAX(K)
 Variables to be plotted:
 K = 1 : K₁
 K = 2 : K_{1c}
 K = 3 : K_{1a}
 K = 4 : TEMP
 K = 5 : SIGMAT
 K = 6 : SIGMAP
 K = 7 : SIGMA

Records from 38 to 42 must be inserted when IPLOT3≠0.

Record-38 (4X, 2F8.0)

YMIN Maximum value of Y-axis
 YMAX Minimum value of Y-axis (Y-axis is automatically scaled when
 YMAX ≤ YMIN.)

Record-39 (4X, 18I4)

NTMAX Number of time data to be plotted(≤100)
 NDATA Number of data points in one curve(≤100)

Record-40 (4X, 8F8.0)

TIME(I), I=1, NTMAX
 Time data (min)

Record-41 (4X, 8F8.0) (When NDATA>0)

XDATA(I), I=1, NDATA
 Normalized flaw depth or r-coordinate (in or m)

Record-42 (4X, 8F8.0) (When NDATA>0)

(YDATA(I, J), I=1, NDATA), J=1, 3
 Variable to be plotted:
 J = 1 : K₁.
 J = 2 : K_{1c}.
 J = 3 : K_{1a}.

Records from 43 to 47 must be inserted when IPLOT4 \neq 0.

Record-43 (4X, 2F8.0)

YMIN	Minimum value of Y-axis
YMAX	Maximum value of Y-axis (Y-axis is automatically scaled, when YMAX \leq YMIN)

Record-44 (4X, 18I4)

NTMAX	Number of time data to be plotted (\leq 100)
NDATA	Number of data points in one curve (\leq 100)

Record-45 (4X, 8F8.0)

TIME(I), I=1, NTMAX	Time data (min)
---------------------	-----------------

Record-46 (4X, 8F8.0) (When NDATA>0)

XDATA(I), I=1, NDATA	Normalized flaw depth or r-coordinate (in or m)
----------------------	---

Record-47 (4X, 8F8.0) (When NDATA>0)

(YDATA(I, J), I=1, NDATA), J=1, 3	Variable to be plotted:
J = 1 : SIGMAT	
J = 2 : SIGMAP	
J = 3 : SIGMA	

Records from 48 to 50 must be inserted when IPLOT5 \neq 0.

Record-48 (4X, 4F8.0)

XMIN	Minimum value of X-axis ('F or 'C)
XMAX	Maximum value of X-axis ('F or 'C)
YMIN	Minimum value of Y-axis (ksi·in $^{1/2}$ or MPa·m $^{1/2}$)
YMAX	Maximum value of Y-axis (ksi·in $^{1/2}$ or MPa·m $^{1/2}$) (Axis is automatically scaled when corresponding MAX \leq MIN.)

Record-49 (4X, 16I4)

KIPL	Option flag for Okamura's map:
= 0	: Not to be plotted.
= 1	: Both upper and lower curves are to be plotted.
= 2	: Only lower curve is to be plotted.

KIACPL Option flag for K_{ic} , K_{is} vs TEMP curve:
 = 0 : Not to be plotted.
 = 1 : K_{ic} vs TEMP and K_{is} vs TEMP curves are to be
 plotted in one figure.
 = 2 : K_{ic} vs TEMP and K_{is} vs TEMP curves are to be
 plotted separately in two figures.

ISIG Number of time data to draw line to connect points at
 equal time (≤ 10). (Not necessary, when $KIPL \neq 0$.)

Record-50 (4X, 8F8.0) (When ISIG>0)

TIMEI(I), I=1, ISIG
 Times when points are connected by lines (min).

Record-51 must be inserted, when IPLOT6 $\neq 0$.

Record-51 (4X, 4F8.0)

XMIN Maximum value of X-axis (min)
 XMAX Minimum value of X-axis (min)
 YMIN Maximum value of Y-axis ('F or 'C)
 YMAX Minimum value of X-axis ('F or 'C)
 (Axis is automatically scaled, when corresponding
 MAX \leq MIN.)

Record-52 must be inserted, when IPLOT7 $\neq 0$.

Record-52 (4X, 8F8.0)

XXMIN Maximum value of X-axis (min)
 XMAX Minimum value of X-axis (min)
 YMIN Maximum value of Y-axis (psi or MPa)
 YMAX Minimum value of X-axis (psi or MPa)
 (Axis is automatically scaled, when corresponding
 MAX \leq MIN.)

When plotting the temperature and/or pressure transients, interpolation is performed if data points are less than 20. Symbol marks are also attached if data points are less than 20.

4. Input Data for Plotting Okamura's map

Record-01 (A4, I4)

DATAID Must be OAK2.
 IEXEC = 0 : Not to be executed.
 $\neq 0$: To be executed.

Record-02 (4X, 18A4)

TITL Title : Any words

Record-03 (4X, F8.0)

ADMM Flaw depth (mm)

Record-04 (4X, I4)

JCASE Number of curves to be plotted (≤ 10)

Record-05 must be repeated JCASE times.

Record-05 (4X, 2I4)

IF9 Number of Fortran Unit to read data.

IPLOT Option flag for plotting:

= 0 : Data points are connected by line with symbol.

= 1 : Only symbols are plotted at data points.

Record-06 (4X, 4F8.0)

XMIN Minimum value of X-axis ('C)

XMAX Minimum value of X-axis ('C)

YMIN Maximum value of Y-axis (MPa·m^{1/2})YMAX Minimum value of X-axis (MPa·m^{1/2})(Axis is automatically scaled when corresponding
MAX \leq MIN.)

Record-07 (4X, 14I4)

KIPL Option flag for plotting of K_I vs TEMP curve:

= 0 : To be plotted.

= 1 : Not to be plotted.

KIA CPL Curves to be plotted:

= 0 : No variable.

= ±1 : K_{Ic} and K_{Ia} vs TEMP curves.= ±2 : K_{Ic} and K_{Ia} vs TEMP curves.= ±3 : K_I , K_{Ic} and K_{Ia} vs TEMP curves.

(Only one curve is plotted when sign is negative.)

ISIG Number of time data to draw line to connect points at equal
time (≤ 10) (Not necessary, when KIPL ≠ 0.)NOKIA K_{Ia} curve is not outputted, when NOKIA ≠ 0.

Record-08 (4X, 8F8.0) (When ISIG > 0)

TIME(I), I=1, ISIG

Times when points are connected by line (min).

Appendix B Data Transfer and Environmental Programs

B.1 Data Transfer

The data flows in PLES/PTS are shown in Fig.B.1. In order to perform the thermal-mixing calculation and the stress calculation, the initial and boundary conditions such as coolant temperature and flow rate at cold leg are necessary. They can be supplied either input time tables or through the data written on files (see App.A) which are shown in Fig.B.1 as the temperature and flow rate data, and pressure data. The formats of the former and latter files are shown in Tables A.1 and A.3 in Appendix A, respectively. When using TRAC-PF1, the files can be generated from the TRAC-PF1 output file(s) by one of the member codes in PLES/PTS. When using RETRAN02, a supplemental program is included in PLES/PTS to generate the files from the RETRAN02 output file(s). The procedure to do this is described in B.2.

PLES/PTS has its own plotting programs to plot the calculated results of the stress and fracture mechanics calculations. In order to plot the input data and/or calculated results in the thermal-mixing calculation, however, the SPLPLOT program⁽¹⁾ is designed to be used as shown in Fig.B.1. The SPLPLOT program is a plotting program for general purpose which has been developed in JAERI. The program has a capability to read data from a file(s) with fixed-format, which is called SPL format, and draw figures. The conversion program from the PLES/PTS output data file(see Table B.1 and B.2) to SPL-format data file is included in the PLES/PTS. The information on the variables converted and to be plotted with SPLPLOT is shown in Table B.3. The user can select the variables to be plotted in the JCL cards to perform the SPLPLOT program. The sample JCL cards to for conversion and plotting, please see Appendix C (sample inputs and outputs). The users manual of SPLPLOT is included in Ref.(1) in this appendix.

Except for plotting with SPLPLOT, all the calculations in PLES/PTS can be executed by a single JCL cards shown in Fig.B.2, because the driver program is used as stated in the text. The information on the Fortran Units used in the JCL cards are summarized in Table B.4.

B.2 Procedure to generate input files to PLES/PTS from the RETRAN02 output file(s)

In order to generate the input files to PLES/PTS from the RETRAN02 output file(s), the re-edit capability of RETRAN02 is used. First of all, the transient calculation is performed with RETRAN02. Next, the following calculated variables are retrieved from the RETRAN02 output file(s) by using the re-edit capability :

- (1) system pressure,
- (2) coolant temperature at cold leg,
- (3) mass flow rate at cold leg,
- (4) coolant temperature at downcomer, and
- (5) HPI mass flow rate.

It should be noted that the major edit frequency (MAJOR) must be larger than the time span of interest in the transient calculation with RETRAN02. In the re-edit calculation, the output must be written on a file as shown, for example, as follow :

```
//FT06F001 DD DSN=Jxxxx.xxxxxxx.xxxxxx,DISP=(NEW,CATLG,DELETE),
//           SPACE=(TRK,(10,5),RLSE),UNIT=TSSWK,
//           DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043)
```

The JCL cards to execute the job to generate the input files to PLES/PTS from the output file from the above re-edit calculation is shown in Fig.B.3. The information on Fortran Units used in the JCL cards are summarized in Table B.5. It should be noted that IRHOPT in the thermal-mixing calculation must be 1, when using this capability.

References

- (1) Muramatu, K., et al., "Users Manual for SPLPLOT-1: A Program for Plotting and Editing of Experimental and Analytical Data of Various Transient Systems," ,JAERI-M 83-166, (1983)(in Japanese, but English version of user's manual is included.).

Table B.1 Format of output file from thermal-mixing calculation

Record-01	TITLE	A*72	Title
Record-02	MT	I*4	Number of data points
Record-03	TIME	R*4	Time(s)
Record-04	TDCC	R*4	Coolant temperature at downcomer (Cal.) (°C)
Record-05	TDCI	R*4	Coolant temperature at downcomer (Input) (°C)
Record-06	QHPI	R*4	HPI volumetric flow rate (m³/s)
Record-07	THPI	R*4	HPI water temperature (°C)
Record-08	RHODC	R*4	Coolant density at downcomer (kg/m³)
Record-09	QHPDC	R*4	Volumetric flow rate at downcomer (m³/s)
Record-10	HD	R*4	Height of cold layer at Cold leg (m)
Record-11	TEMPND	R*4	Non-dimensional temperature
Record-12	TSNT	R*4	Non-dimensional time

Table B.2 Contents of output file from thermal-mixing calculation depending on model to be used

Variables	Option flag ICALC				
	= 1	= 2	= 3	= 4	= 5
TITLE	○	○	○	-	○
MT	○	○	○	-	○
TIME	○	○	○	-	○
TDCC	○	○	○	-	○
TDCI	△	○	○	-	○
QHPI	△	○	○	-	○
THPI	○	○	○	-	○
RHODC	△	○	△	-	△
QHPDC	△	○	△	-	△
HD	△	△	○	-	△
TEMPND	△	△	△	-	○
TSNT	△	△	△	-	○

(○) : To be written.

(△) : To be set 0.0.

(-) : Not to be written.

Table B.3 Information on variables converted to SPL-format data

Variable Name	Label Information	Unit Name	Unit Name	Description
TIME	TIME	TIME	SEC	Time
TDCC	DC TEMP. (CALCULATED)	TEMP	DEGC	Coolant temp. at downcomer(Cal.)
TDCI	DC TEMP. (INPUT)	TEMP	DEGC	Coolant temp. at downcomer(Input)
QHPI	HPI FLOW RATE	VFLW	M3/SEC	HPI volumetric flow rate
THPI	HPI WATER TEMP.	TEMP	DEGC	HPI water temperature
RHODC	DC DENSITY	DENS	KG/M3	Coolant density at downcomer
QHPDC	HPI FLOW TO DC	VFLW	M3/SEC	Volumetric flow rate at downcomer
HD	COLG STREAM HIGHT	LNGT	M	Height of cold layer at cold leg
NDTEMP	TEMP. (NON-DIM.)	-	-	Non-dimensional temperature
TSNT	TIME (NON-DIM.)	-	-	Non-dimensional time

Table B.4 Description of Fortran Units in JCL cards

DD NAME	RECFM	LRECL	BLOCKL	Description
FT01F001	VBS	X	32760	Work file for TRAC-PF1 data handling program
FT02F001	VBS	X	32760	Output pressure data file from TRAC-PF1 handling program to be used for stress calculation
FT11F001	VBS			TRAC-PF1 output file(When more than two files are used, the number of Fortran Units should be increased by one by one.)
FT70F001	VBS	X	32760	Work file for TRAC-PF1 data handling program(When more than two TRAC-PF1 output files are used, the number of Fortran Units should
FT03F001	VBS			Input temperature and flow rate data file to be used for thermal-mixing calculation
FT08F001	FBA	137	19043	Output file for debugging from thermal-mixing calculation
FT21F001	VBS			Output data file from thermal-mixing calculation
FT26F001	FB	80	3200	Output data file from mesh generation prggram for K1 calculation
FT27F001	FB	80	3200	Output data file from K1 calculation program
FT31F001				Work file for K1 calculation
FT32F001	FB		816	Work file for K1 calculation
FT37F001	FB		144	Work file for K1 calculation
FT38F001	FB		144	Work file for K1 calculation
FT50F001	FBA	137	19043	Output file for debugging from K1 calculation
FT09F001	FB	80	3200	Output data file from fracture mechanics caclulation to be used to Okamura's plot
FT04F001	VBS			Input pressure data file to be used for stress calculation

Table B.5 Fortran Units used in JCL cards to generate input files
to PLES/PTS from RETRAN02 re-edit calculation

Fortran Unit	Description
FT10F001	Output from RETRAN02 re-edit calculation
FT20F001	Resulted input temperature and flow rate data file to PLES/PTS
FT30F001	Resulted input pressure data file to PLES/PTS
FT05F001	Input data to control the calculation

CARD-01 (2F10.0)

TNCT : Time of natural circulation termination (s)
TEND : End time of file output (s)

CARD-02 (F10.0)

HPTMP : HPI water temperature (°C)

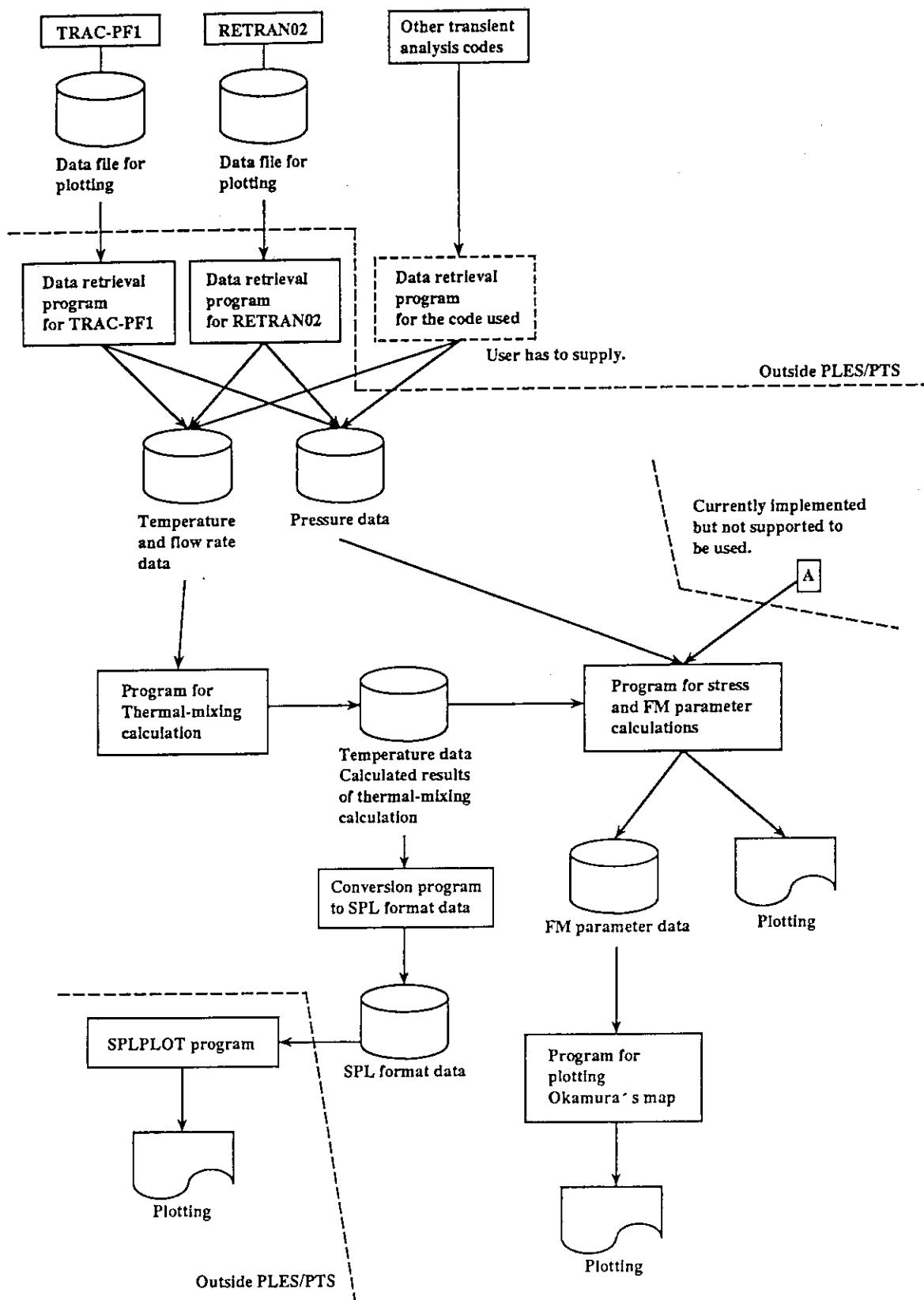


Fig. B.1 Data flow in PLES/PTS

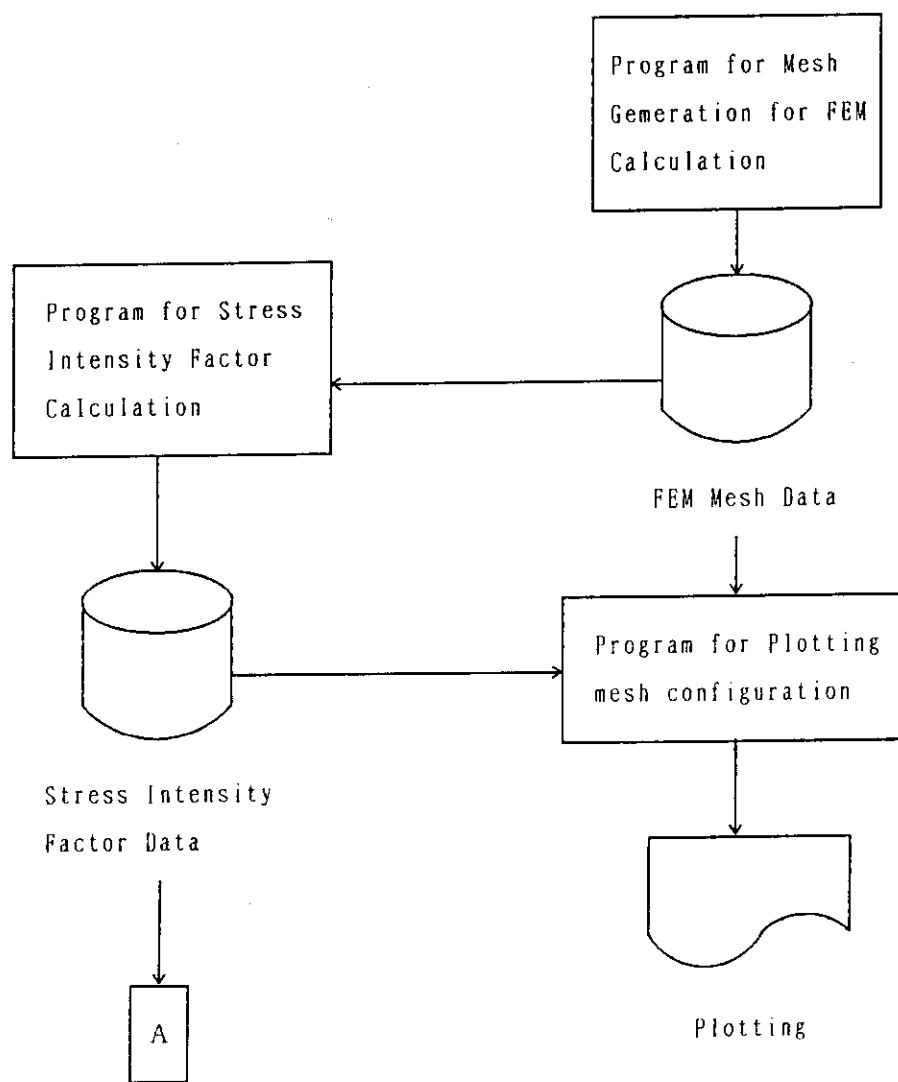


Fig. B.1 Data flow in PLES/PTS (Continued)

```

.....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8
00001 : //JCLG JOB                                     00010000
00002 : //JCLG EXEC JCLG                           00020000
00003 : //SYSIN DD DATA,DLM='++'                   00030000
00004 : // JUSER 99999999,XX,XXXXXX,8888,77      00040000
00005 :     T.4 C.2 W.4 I.5 SRP GRP               00050000
00006 :     OPTP PASSWORD=XXXXXXXXX,NOTIFY=J9999   00060000
00007 : //*****                                         00070000
00008 : /* EXECUTE PLES/PTS SYSTEM *              00080000
00009 : //*****                                         00090000
00010 : //PLESPTS EXEC PGM=LPCNTROL             00100000
00011 : //STEPLIB DD DSN=J3149.DRIVER.LOAD,DISP=SHR 00110000
00012 : //          DD DSN=J3149.PLESPTS.LOAD,DISP=SHR 00120000
00013 : //PRINT  DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00130000
00014 : //FT05F001 DD UNIT=WK10,SPACE=(480,(200,100)),DCB=BLKSIZE=480 00140000
00015 : //*****                                         00150000
00016 : /* COMMON FILE(S) *                      00160000
00017 : //*****                                         00170000
00018 : //FT06F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00180000
00019 : //MPTMST  DD DSN=SYS1.KPATNL18,DISP=SHR    00190000
00020 : //GDFILE  DD SYSOUT=G,OUTLIM=0            00200000
00021 : //*****                                         00210000
00022 : /* INTERFACE FILE(S) *                  00220000
00023 : //*****                                         00230000
00024 : //FT41F001 DD DSN=&TRAC,SPACE=(TRK,(5,2)),UNIT=WK10,        00240000
00025 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00250000
00026 : //FT42F001 DD DSN=&&ENGI,SPACE=(TRK,(5,2)),UNIT=WK10,        00260000
00027 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00270000
00028 : //FT43F001 DD DSN=&&FRUP,SPACE=(TRK,(5,2)),UNIT=WK10,        00280000
00029 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00290000
00030 : //FT44F001 DD DSN=&&K1RA,SPACE=(TRK,(5,2)),UNIT=WK10,        00300000
00031 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00310000
00032 : //FT45F001 DD DSN=&&PLOT,SPACE=(TRK,(5,2)),UNIT=WK10,        00320000
00033 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00330000
00034 : //FT46F001 DD DSN=&&OAKP,SPACE=(TRK,(5,2)),UNIT=WK10,        00340000
00035 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00350000
00036 : //FT47F001 DD DSN=&&OAK2,SPACE=(TRK,(5,2)),UNIT=WK10,        00360000
00037 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00370000
00038 : //*****                                         00380000
00039 : /* TRAC DATA HANDLING PROGRAM *          00390000
00040 : //*****                                         00400000
00041 : //FT01F001 DD SPACE=(TRK,(20,10)),UNIT=WK10,        00410000
00042 : //          DCB=(LRECL=X,BLKSIZE=32760,RECFM=VBS)         00420000
00043 : //FT02F001 DD DSN=&TRAC,SPACE=(TRK,(20,10)),UNIT=WK10,        00430000
00044 : //          DCB=(LRECL=X,BLKSIZE=32760,RECFM=VBS)         00440000
00045 : //FT11F001 DD DSN=J3149.TRACOUT.DATA,DISP=SHR,LABEL=(,,,IN) 00450000
00046 : //FT70F001 DD SPACE=(TRK,(20,10)),UNIT=WK10,        00460000
00047 : //          DCB=(LRECL=X,BLKSIZE=32760,RECFM=VBS)         00470000
00048 : //*****                                         00480000
00049 : /* ENGINEERING MODEL PROGRAM *          00490000
00050 : //*****                                         00500000
00051 : //FT03F001 DD DSN=J3149.MIHAMA.TEMPBC.DATA,DISP=SHR,LABEL=(,,,IN) 00510000
00052 : //FT08F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00520000
00053 : //FT21F001 DD DSN=J3149.MIHAMA.ENGMHI.DATA,DISP=(NEW,CATLG/DELETE), 00530000
00054 : //          SPACE=(TRK,(20,10),RLSE),UNIT=TSSWK          00540000
00055 : //*****                                         00550000
00056 : /* KI MESH DIVISION PROGRAM *          00560000
00057 : //*****                                         00570000
00058 : //FT26F001 DD DSN=&MESH,SPACE=(TRK,(10,2),RLSE),UNIT=WK10,        00580000
00059 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00590000
00060 : //*****                                         00600000
00061 : /* KI VALUE CALCULATION PROGRAM *        00610000
00062 : //*****                                         00620000
00063 : //FT27F001 DD DSN=&KI,SPACE=(TRK,(10,2),RLSE),UNIT=WK10,        00630000
00064 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00640000
00065 : //FT31F001 DD SPACE=(TRK,(20,5),RLSE),UNIT=WK10          00650000
00066 : //FT32F001 DD SPACE=(16,(500,10),RLSE),UNIT=WK10          00660000
00067 : //FT37F001 DD SPACE=(14,(500,10),RLSE),UNIT=WK10          00670000
00068 : //FT38F001 DD SPACE=(14,(500,10),RLSE),UNIT=WK10          00680000
00069 : //FT50F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00690000
00070 : //*****                                         00700000
00071 : /* FRACTURE MECHANICS PROGRAM *        00710000
00072 : //*****                                         00720000
00073 : //FT09F001 DD DSN=&FRUOUT,SPACE=(TRK,(20,5),RLSE),UNIT=WK10,        00730000
00074 : //          DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)           00740000
00075 : //FT04F001 DD DSN=J3149.MIHAMA.PRESBC.DATA,DISP=SHR,LABEL=(,,,IN) 00750000
00076 : //*****                                         00760000
00077 : /* INPUT DATA FOR PLES/PTS SYSTEM *        00770000
00078 : //*****                                         00780000
00079 : //SYSIN  DD *                                00790000
00080 : =PLESPTS                                     00800000
00081 : //          DD DSN=J3149.PLESPTS.DATA(ALL),DISP=SHR,LABEL=(,,,IN) 00810000
00082 : DD *                                         00820000
00083 : END                                         00830000
00084 : /*                                         00840000
00085 : ++                                         00850000
00086 : //                                         00860000
.....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8

```

Fig. B.2 JCL cards to execute PLES/PTS

```

.....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8
00001 : //JCLG JOB                                     00010000
00002 : //JCLG EXEC JCLG                           00020000
00003 : //SYSIN DD DATA,DLM='++'                   00030000
00004 : // JUSER 99999999,XX.XXXXXX,8888.77       00040000
00005 :     T.4 C.2 W.1 I.4 SRP                   00050000
00006 :     OOPTP PASSWORD=XXXXXXXXX,NOTIFY=J9999  00060000
00007 : //***** PLES/PTS BOUNDARY INPUT FROM RETRAN CALCUALTION RESULT * 00070000
00008 : //* GENERATE PLES/PTS BOUNDARY INPUT FROM RETRAN CALCUALTION RESULT * 00080000
00009 : //*****                                         00090000
00010 : //----- COMPILE STEP                         00100000
00011 : //FORT77  EXEC PGM=JZKA FORT,REGION=1024K,PARM='OPT(2),NOSOURCE' 00110000
00012 : //SYSUT2  DD SPACE=(TRK,(30,10)),DCB=BLKSIZE=3200,UNIT=WK10    00120000
00013 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00130000
00014 : //SYSTEM  DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043)  00140000
00015 : //SYSLIN   DD DSN=&&OBJ,DISP=(NEW,PASS),UNIT=WK10,                00150000
00016 : //           SPACE=(TRK,(30,10),RLSE),DCB=BLKSIZE=3200            00160000
00017 : //SYSIN    DD DSN=J3149.PLESPTS.FORT77(RET2PTS),DISP=SHR        00170000
00018 : //----- LINK STEP                           00180000
00019 : //LINK    EXEC PGM=JQAL,REGION=1024K,COND=(4,LT),PARM='NOMAP,LET' 00190000
00020 : //SYSLIB   DD DSN=SYS2.FORTLIB,DISP=SHR      00200000
00021 : //SYSPRINT DD SYSOUT=*,DCB=(BLKSIZE=4840)      00210000
00022 : //SYSTEM   DD SYSOUT=*
00023 : //SYSUT1   DD UNIT=VID,SPACE=(TRK,(30,10))      00230000
00024 : //SYSLMOD  DD DSN=&&LM,DISP=(NEW,PASS),          00240000
00025 : //           SPACE=(TRK,(20,5,1),RLSE),UNIT=WK10    00250000
00026 : //SYSLIN   DD DSN=&&OBJ,DISP=(OLD,DELETE)        00260000
00027 : //           DD *
00028 :     ENTRY MAIN                                00280000
00029 :     NAME TEMPNAME(R)                          00290000
00030 : /*
00031 : //RUN    EXEC PGM=TEMPNAME,COND=(4,LT)          00310000
00032 : //STEPLIB DD DSN=&&LM,DISP=(OLD,DELETE)        00320000
00033 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00330000
00034 : //FT06F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043)  00340000
00035 : //FT10F001 DD DSN=J3149.MIHAMA.NBASE2SG.BC.OUTLIST,          00350000
00036 : //           DISP=SHR,LABEL=(,,,IN)             00360000
00037 : //FT20F001 DD DSN=J3149.MIHAMA.TEMPBC.DATA,DISP=(NEW,CATLG,DELETE), 00370000
00038 : //           SPACE=(TRK,(5,2),RLSE),UNIT=D0950      00380000
00039 : //FT30F001 DD DSN=J3149.MIHAMA.PRESBC.DATA,DISP=(NEW,CATLG,DELETE), 00390000
00040 : //           SPACE=(TRK,(5,2),RLSE),UNIT=D0950      00400000
00041 : //FT05F001 DD *
00042 :     1500.0   3600.0                            00410000
00043 :     27.0                               00420000
00044 : /*
00045 : ++
00046 : /
.....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8

```

Fig. B.3 JCL cards to generate input files to PLES/PTS from RETRAN02 re-edit results

Appendix C Sample Inputs and Outputs

This appendix contains the sample inputs and outputs to perform the thermal-mixing calculations with the empirical correlation proposed by MHI and RMM proposed by Theofanous based on the calculated results of plant system thermal-hydraulic calculation with RETRAN02, to perform the stress and fracture mechanics calculations based on the results of the thermal-mixing calculation with the MHI correlation.

Figure C.1(a) shows the JCL cards to execute the thermal-mixing calculation, stress calculation and fracture mechanics calculation to be shown in this appendix. Figures C.1(b), (c) and (d) show the input data sets for the thermal-mixing calculations with the MHI correlation, Bulk Mixing Model (BMM) and Regional Mixing Model (RMM), respectively. Before performing RMM calculation, BMM calculation has to be done. Figure C.1(e) shows the sample JCL cards to plot the calculated results of the thermal mixing calculation by using the SPLPLOT program. The resulted output figures from SPLPLOT are shown in Figs.C.1(f) to C.1(h).

Figure C.2(a) shows the input data for the stress and fracture mechanics calculation based on the thermal-mixing calculation with the MHI correlation. In this case, the calculated results are automatically plotted as shown in Fig.C.2(b)-(o), if desired. When the Okamura plot is desired, an additional input data, for example, shown in Fig.C.3(a) is needed. The resulted plot is shown in Fig.C.3(b). The Okamura plot is useful to examine whether or not the postulated initial crack grows. The margin to the crack growth could be quantified by the distance between the stress intensity factor (k_I) and crack initiation toughness (k_{Ic}) (See Fig.C.3(b)).

```

....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8

00001 : //JCLG JOB                                     00010000
00002 : //JCLG EXEC JCLG                           00020000
00003 : //SYSIN DD DATA,DLM='*'                   00030000
00004 : // JUSER 99999999,XX.XXXXXX,888B.77          00040000
00005 :   T_4 C_2 W_4 I_5 SRP GRP                  00050000
00006 :   OPTP PASSWORD=XXXXXXXXX,NOTIFY=J9999      00060000
00007 : //*****                                     00070000
00008 : /* EXECUTE PLES/PTS SYSTEM *               00080000
00009 : //*****                                     00090000
00010 : //PLESPTS EXEC PGM=LPCNTROL                00100000
00011 : //STEPLIB DD DSN=J3149,DRIVER,LOAD,DISP=SHR 00110000
00012 :   // DD DSN=J3149,PLESPTS,LOAD,DISP=SHR     00120000
00013 : //PRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00130000
00014 : //FT05F001 DD UNIT=WK10,SPACE=(480,(200,100)),DCB=BLKSIZE=480 00140000
00015 : //*****                                     00150000
00016 : /* COMMON FILE(S) *                         00160000
00017 : //*****                                     00170000
00018 : //FT06F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00180000
00019 : //MPTNST DD DSN=SYS1,KPATNLIB,DISP=SHR    00190000
00020 : //GDFILE  DD SYSOUT=G,OUTLIM=0             00200000
00021 : //*****                                     00210000
00022 : /* INTERFACE FILE(S) *                     00220000
00023 : //*****                                     00230000
00024 : //FT41F001 DD DSN=&TRAC,SPACE=(TRK,(5,2)),UNIT=WK10,        00240000
00025 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00250000
00026 : //FT42F001 DD DSN=&ENGI,SPACE=(TRK,(5,2)),UNIT=WK10,        00260000
00027 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00270000
00028 : //FT43F001 DD DSN=&FRUP,SPACE=(TRK,(5,2)),UNIT=WK10,        00280000
00029 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00290000
00030 : //FT44F001 DD DSN=&X1RA,SPACE=(TRK,(5,2)),UNIT=WK10,        00300000
00031 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00310000
00032 : //FT45F001 DD DSN=&PLOT,SPACE=(TRK,(5,2)),UNIT=WK10,        00320000
00033 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00330000
00034 : //FT46F001 DD DSN=&OAKP,SPACE=(TRK,(5,2)),UNIT=WK10,        00340000
00035 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00350000
00036 : //FT47F001 DD DSN=&OAK2,SPACE=(TRK,(5,2)),UNIT=WK10,        00360000
00037 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00370000
00038 : //*****                                     00380000
00039 : /* TRAC DATA HANDLING PROGRAM *           00390000
00040 : //*****                                     00400000
00041 : //FT01F001 DD DUMMY                         00410000
00042 : //FT02F001 DD DUMMY                         00420000
00043 : //FT11F001 DD DUMMY                         00430000
00044 : //FT70F001 DD DUMMY                         00440000
00045 : //*****                                     00450000
00046 : /* ENGINEERING MODEL PROGRAM *           00460000
00047 : //*****                                     00470000
00048 : //FT03F001 DD DSN=J3149,XXXXXX,TEMPBC,DATA,DISP=SHR,LBL=(,,,IN) 00480000
00049 : //FT08F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00490000
00050 : //FT21F001 DD DSN=J3149,XXXXXX,ENGMHI,DATA,DISP=(NEW,CATLG,DELETE), 00500000
00051 : //T21F001 DD DSN=J3149,XXXXXX,ENGTHB,DATA,DISP=(NEW,CATLG,DELETE), 00510000
00052 : //T21F001 DD DSN=J3149,XXXXXX,ENGTHR,DATA,DISP=(NEW,CATLG,DELETE), 00520000
00053 :   SPACE=(TRK,(20,10),RLSE),UNIT=TSSWK       00530000
00054 : //*****                                     00540000
00055 : /* KI MESH DIVISION PROGRAM *            00550000
00056 : //*****                                     00560000
00057 : //FT26F001 DD DUMMY                         00570000
00058 : //*****                                     00580000
00059 : /* KI VALUE CALCULATION PROGRAM *         00590000
00060 : //*****                                     00600000
00061 : //FT27F001 DD DSN=J3149,PLESPTS,DATA(OCA18),DISP=SHR,LBL=(,,,IN) 00610000
00062 : //FT31F001 DD DUMMY                         00620000
00063 : //FT32F001 DD DUMMY                         00630000
00064 : //FT37F001 DD DUMMY                         00640000
00065 : //FT38F001 DD DUMMY                         00650000
00066 : //FT50F001 DD DUMMY                         00660000
00067 : //*****                                     00670000
00068 : /* FRACTURE MECHANICS PROGRAM *          00680000
00069 : //*****                                     00690000
00070 : //FT09F001 DD DSN=&FRUOUT,SPACE=(TRK,(20,5),RLSE),UNIT=WK10, 00700000
00071 :   DCB=(RECFM=FB,LRECL=80,BLKSIZE=3200)       00710000
00072 : //FT04F001 DD DSN=J3149,XXXXXX,PRESBC,DATA,DISP=SHR,LBL=(,,,IN) 00720000
00073 : //*****                                     00730000
00074 : /* INPUT DATA FOR PLES/PTS SYSTEM *        00740000
00075 : //*****                                     00750000
00076 : //SYSIN  DD *                            00760000
00077 : -PLESPTS
00078 :   DD DSN=J3149,PLESPTS,DATA(ENGMHI),DISP=SHR,LBL=(,,,IN) 00770000
00079 :   DD DSN=J3149,PLESPTS,DATA(ENGTHB),DISP=SHR,LBL=(,,,IN) 00780000
00080 :   DD DSN=J3149,PLESPTS,DATA(ENGTHR),DISP=SHR,LBL=(,,,IN) 00790000
00081 :   DD DSN=J3149,PLESPTS,DATA(OAKCASE1),DISP=SHR,LBL=(,,,IN) 00800000
00082 :   DD DSN=J3149,PLESPTS,DATA(OAKCASE2),DISP=SHR,LBL=(,,,IN) 00810000
00083 :   DD DSN=J3149,PLESPTS,DATA(OAKCASE3),DISP=SHR,LBL=(,,,IN) 00820000
00084 :   DD DSN=J3149,PLESPTS,DATA(OAKCASE4),DISP=SHR,LBL=(,,,IN) 00830000
00085 :   DD DSN=J3149,PLESPTS,DATA(OAKCASE5),DISP=SHR,LBL=(,,,IN) 00840000
00086 :   DD DSN=J3149,PLESPTS,DATA(OAK2C1),DISP=SHR,LBL=(,,,IN) 00850000
00087 :   DD DSN=J3149,PLESPTS,DATA(OAK2C2),DISP=SHR,LBL=(,,,IN) 00860000
00088 :   DD DSN=J3149,PLESPTS,DATA(OAK2C3),DISP=SHR,LBL=(,,,IN) 00870000
00089 :   DD DSN=J3149,PLESPTS,DATA(OAK2C4),DISP=SHR,LBL=(,,,IN) 00880000
00090 :   DD DSN=J3149,PLESPTS,DATA(OAK2C5),DISP=SHR,LBL=(,,,IN) 00890000
00091 :   DD *
00092 : END
00093 : /*
00094 : ++
00095 : //*
....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8

```

Fig. C.1(a) JCL to execute sample calculation

```

.....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8

00001 : ENGI    1
00002 : TITL
00003 : 2-LOOP SGTR      BOUNDARY=NBASE2S MHI QLMIN=0.04
00004 : FIN
00005 : OPTN   5   2   0   50
00006 : FIN
00007 : SIZE
00008 : &SIZE DCL=0.74,ALCL=5.3,DHPI=0.12741, VADD=0.415,VSYC=28.58892,
00009 : &END
00010 : FIN
00011 : TIME
00012 : &TIME MT=0,DT=20.,NTP=1,TINIT=0.,TEND=3600.,&END
00013 : FIN
00014 : CNST
00015 : &CNST CREF=1.0,NTEMP=31, NSHEAT=31,
00016 :   FTEMP=  0.,   10.,   20.,   30.,   40.,   50.,   60.,
00017 :     70.,   80.,   90.,  100.,  110.,  120.,  130.,
00018 :     140.,  150.,  160.,  170.,  180.,  190.,  200.,
00019 :     210.,  220.,  230.,  240.,  250.,  260.,  270.,
00020 :     280.,  290., 291.41, 170*0.,
00021 :   FDENS=1003.613, 1003.311, 1001.703, 999.101, 995.520, 991.375,
00022 :   986.485, 981.065, 975.039, 968.617, 961.723, 954.381,
00023 :   946.611, 938.438, 929.887, 920.895, 911.494, 901.632,
00024 :   891.345, 880.591, 869.263, 857.486, 845.023, 831.947,
00025 :   818.063, 803.342, 787.650, 770.832, 752.502, 732.386,
00026 :   729.39, 170*0.,
00027 :   FHTEMP=  0.,   10.,   20.,   30.,   40.,   50.,   60.,
00028 :     70.,   80.,   90.,  100.,  110.,  120.,  130.,
00029 :     140.,  150.,  160.,  170.,  180.,  190.,  200.,
00030 :     210.,  220.,  230.,  240.,  250.,  260.,  270.,
00031 :     280.,  290., 291.41, 170*0.,
00032 :   FCREF =1003.613, 1003.311, 1001.703, 999.101, 995.520, 991.375,
00033 :   986.485, 981.065, 975.039, 968.617, 961.723, 954.381,
00034 :   946.611, 938.438, 929.887, 920.895, 911.494, 901.632,
00035 :   891.345, 880.591, 869.263, 857.486, 845.023, 831.947,
00036 :   818.063, 803.342, 787.650, 770.832, 752.502, 732.386,
00037 :   729.39, 170*0., &END
00038 : FIN
00039 : EPSC
00040 : &EPSC EPSIN=1.E-5,EPS2=1.E-5, QLMIN=0.04, &END
00041 : FIN
00042 : TQTD
00043 : &TQTD IRHOPT=1,
00044 : &END
00045 : FIN

```

.....*....1....*....2....*....3....*....4....*....5....*....6....*....7....*....8

Fig. C.1(b) Input data to thermal-mixing calculation with MHI correlation

```

.....*....1.....*....2.....*....3.....*....4.....*....5.....*....6.....*....7.....*....8
00001 : ENGI    1
00002 : TITL
00003 : 2-LOOP SGTR      BOUNDARY=NBASE2S (THEOFANOUS BULK) QLMIN=0.04
00004 : FIN
00005 : OPTN   2   2   0   50
00006 : FIN
00007 : SIZE
00008 : &SIZE DCL=0.74,ALCL=5.3,DHPI=0.12741,VADD=0.415,VSYC=28.58892,
00009 : &END
00010 : FIN
00011 : TIME
00012 : &TIME MT=0,DT=20.,NTP=1,TINIT=0.,TEND=3600.,&END
00013 : FIN
00014 : CNST
00015 : &CNST CREF=1.0,NTEMP=31, NSHEAT=31,
00016 :   FTEMP=  0.,   10.,   20.,   30.,   40.,   50.,   60.,
00017 :     70.,   80.,   90.,   100.,  110.,  120.,  130.,
00018 :     140.,  150.,  160.,  170.,  180.,  190.,  200.,
00019 :     210.,  220.,  230.,  240.,  250.,  260.,  270.,
00020 :     280.,  290., 291.41, 170*0.,
00021 :   FDENS=1003.613, 1003.311, 1001.703, 999.101, 995.520, 991.375,
00022 :     986.485, 981.065, 975.039, 968.617, 961.723, 954.381,
00023 :     946.611, 938.438, 929.887, 920.895, 911.494, 901.632,
00024 :     891.345, 880.591, 869.263, 857.486, 845.023, 831.947,
00025 :     818.063, 803.342, 787.650, 770.832, 752.502, 732.386,
00026 :     729.39, 170*0.,
00027 :   FHTEMP=  0.,   10.,   20.,   30.,   40.,   50.,   60.,
00028 :     70.,   80.,   90.,   100.,  110.,  120.,  130.,
00029 :     140.,  150.,  160.,  170.,  180.,  190.,  200.,
00030 :     210.,  220.,  230.,  240.,  250.,  260.,  270.,
00031 :     280.,  290., 291.41, 170*0.,
00032 :   FCREF =1003.613, 1003.311, 1001.703, 999.101, 995.520, 991.375,
00033 :     986.485, 981.065, 975.039, 968.617, 961.723, 954.381,
00034 :     946.611, 938.438, 929.887, 920.895, 911.494, 901.632,
00035 :     891.345, 880.591, 869.263, 857.486, 845.023, 831.947,
00036 :     818.063, 803.342, 787.650, 770.832, 752.502, 732.386,
00037 :     729.39, 170*0., &END
00038 : FIN
00039 : EPSC
00040 : &EPSC EPSIN=1.E-5,EPS2=1.E-5, QLMIN=0.04, &END
00041 : FIN
00042 : TQTD
00043 : &TQTD IRHOPT=1,
00044 : &END
00045 : FIN
.....*....1.....*....2.....*....3.....*....4.....*....5.....*....6.....*....7.....*....8

```

Fig. C.1(c) Input data to thermal-mixing calculation with Bulk Mixing Model proposed by Theofanous

```

.....*....1.....*....2.....*....3.....*....4.....*....5.....*....6.....*....7.....*....8

00001 : ENGI    1
00002 : TITL
00003 : 2-LOOP SGTR      BOUNDARY=NBASE2S (THEOFANOUS REGIONAL) QLMIN=0.04
00004 : FIN
00005 : OPTN   3   2   0 100
00006 : FIN
00007 : SIZE
00008 : &SIZE DCL=0.74,ALCL=5.3,DHPI=0.12741, VADD=0.415,VSYC=28.58829,
00009 : &END
00010 : FIN
00011 : TIME
00012 : &TIME MT=0,DT=20.,NTP=1,TINIT=0.,TEND=3600.,&END
00013 : FIN
00014 : CNST
00015 : &CNST CREF=1.0,NTEMP=31, NSHEAT=31,
00016 :     FTEMP=  0.,   10.,   20.,   30.,   40.,   50.,   60.,
00017 :           70.,   80.,   90.,  100.,  110.,  120.,  130.,
00018 :           140.,  150.,  160.,  170.,  180.,  190.,  200.,
00019 :           210.,  220.,  230.,  240.,  250.,  260.,  270.,
00020 :           280.,  290., 291.41, 170*0.,
00021 :     FDENS=1003.613, 1003.311, 1001.703, 999.101, 995.520, 991.375,
00022 :           986.485, 981.065, 975.039, 968.617, 961.723, 954.381,
00023 :           946.611, 938.438, 929.887, 920.895, 911.494, 901.632,
00024 :           891.345, 880.591, 869.263, 857.486, 845.023, 831.947,
00025 :           818.063, 803.342, 787.650, 770.832, 752.502, 732.386,
00026 :           729.39, 170*0.,
00027 :     FHTEMP=  0.,   10.,   20.,   30.,   40.,   50.,   60.,
00028 :           70.,   80.,   90.,  100.,  110.,  120.,  130.,
00029 :           140.,  150.,  160.,  170.,  180.,  190.,  200.,
00030 :           210.,  220.,  230.,  240.,  250.,  260.,  270.,
00031 :           280.,  290., 291.41, 170*0.,
00032 :     FCREF =1003.613, 1003.311, 1001.703, 999.101, 995.520, 991.375,
00033 :           986.485, 981.065, 975.039, 968.617, 961.723, 954.381,
00034 :           946.611, 938.438, 929.887, 920.895, 911.494, 901.632,
00035 :           891.345, 880.591, 869.263, 857.486, 845.023, 831.947,
00036 :           818.063, 803.342, 787.650, 770.832, 752.502, 732.386,
00037 :           729.39, 170*0., &END
00038 : FIN
00039 : EPSC
00040 : &EPSC EPSIN=1.E-4,EPS2=1.E-4, QLMIN=0.04, &END
00041 : FIN
00042 : TQTD
00043 : &TQTD IRHOPT=1,
00044 : &END
00045 : FIN

```

.....*....1.....*....2.....*....3.....*....4.....*....5.....*....6.....*....7.....*....8

Fig. C.1(d) Input data to thermal-mixing calculation with Regional Mixing Model proposed by Theofanous

```

.....1.....2.....3.....4.....5.....6.....7.....8

00001 : //JCLG JOB                                     00010000
00002 : //JCLG EXEC JCLG                           00020000
00003 : //SYSIN DD DATA,DLIM='++'                  00030000
00004 : // JUSER 99999999,XX,XXXXXX,8888.77        00040000
00005 :   T,4 C,2 W,2 I,4 SRP GRP                 00050000
00006 :   OOPTP PASSWORD=XXXXXXXXX,NOTIFY=J9999    00060000
00007 : //*****                                         00070000
00008 : //** CONVERT OUTPUT OF ENGINEERING MODEL PROGRAM TO SPL FORMAT & PLOT * 00080000
00009 : //*****                                         00090000
00010 : //---- COMPILE STEP                         00100000
00011 : //FORT771 EXEC PGM=JZKBFOR,REGION=1024K,      00110000
00012 :   PARM='OPT(2),BYNAME,NOPRINT'              00120000
00013 : //SYSUT2 DD SPACE=(TRK,(30,10)),DCB=BLKSIZE=3200,UNIT=WK10 00130000
00014 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00140000
00015 : //SYSTEM DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00150000
00016 : //SYSLIN DD DSN=&OBJ,DISP=(NEW,PASS),UNIT=WK10,          00160000
00017 :   SPACE=(TRK,(30,10),RLSE),DCB=BLKSIZE=3200 00170000
00018 : //SYSIN DD DSN=J3149.PLESPTS.FORT77(ENGSPL),DISP=SHR 00180000
00019 : //FORT772 EXEC PGM=JZKBFOR,REGION=1024K,COND=(4,LT),      00190000
00020 :   PARM='OPT(2),BYNAME,NOPRINT'              00200000
00021 : //SYSUT2 DD SPACE=(TRK,(30,10)),DCB=BLKSIZE=3200,UNIT=WK10 00210000
00022 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00220000
00023 : //SYSTEM DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00230000
00024 : //SYSLIN DD DSN=&OBJ,DISP=(MOD,PASS),UNIT=WK10,          00240000
00025 :   SPACE=(TRK,(30,10),RLSE),DCB=BLKSIZE=3200 00250000
00026 : //SYSIN DD DSN=J3080.WUNTCA.FORT(WUNTCA),DISP=SHR 00260000
00027 : //FORT773 EXEC PGM=JZKBFOR,REGION=1024K,COND=(4,LT),      00270000
00028 :   PARM='ELM(*),OPT(2),BYNAME,NOPRINT'        00280000
00029 : //SYSUT2 DD SPACE=(TRK,(30,10)),DCB=BLKSIZE=3200,UNIT=WK10 00290000
00030 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00300000
00031 : //SYSTEM DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00310000
00032 : //SYSLIN DD DSN=&OBJ,DISP=(MOD,PASS),UNIT=WK10,          00320000
00033 :   SPACE=(TRK,(30,10),RLSE),DCB=BLKSIZE=3200 00330000
00034 : //SYSIN DD DSN=J3080.XSPLEDIT.FORT,DISP=SHR 00340000
00035 : //---- LINK STEP                           00350000
00036 : //LINK EXEC PGM=JQAL,REGION=1024K,COND=(4,LT),PARM='NOMAP,LET' 00360000
00037 : //SYSLIB DD DSN=J2695.1CL1UCL2.LOAD,DISP=SHR 00370000
00038 : //   DD DSN=SYS9.GGS.LOAD,DISP=SHR           00380000
00039 : //   DD DSN=SYS9.PNL.LOAD,DISP=SHR           00390000
00040 : //   DD DSN=SYS9.USSL.LOAD,DISP=SHR          00400000
00041 : //   DD DSN=SYS9.SSL.LOAD,DISP=SHR           00410000
00042 : //   DD DSN=SYS9.SSL2.LOAD,DISP=SHR          00420000
00043 : //   DD DSN=SYS2.FORTLIB,DISP=SHR            00430000
00044 : //SYSPRINT DD SYSOUT=*,DCB=(BLKSIZE=4840)     00440000
00045 : //SYSTEM DD SYSOUT=*,DISP=SHR                00450000
00046 : //SYSUT1 DD UNIT=VIO,SPACE=(TRK,(30,10))     00460000
00047 : //SYSLMOD DD DSN=&LM,DISP=(NEW,PASS),        00470000
00048 : //   SPACE=(TRK,(20,5,1),RLSE),UNIT=WK10       00480000
00049 : //SYSLIN DD DSN=&OBJ,DISP=(OLD,DELETE)        00490000
00050 : //   DD *
00051 : ENTRY MAIN                                00500000
00052 : NAME TEMPNAME                            00510000
00053 : /*
00054 : //RUN EXEC PGM=TEMPNAME,COND=(4,LT)          00520000
00055 : //STEPLIB DD DSN=&LM,DISP=(OLD,DELETE)        00530000
00056 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00540000
00057 : //FT06F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00550000
00058 : //FT10F001 DD DSN=J3149.XXXXX.ENGMHI.DATA,DISP=SHR,LABEL=(,,IN) 00560000
00059 : //FT11F001 DD DSN=J3149.XXXXX.ENGMHI.SPL.DATA,DISP=SHR,LABEL=(,,IN) 00570000
00060 : //   DISP=(NEW,CATLG,DELETE),SPACE=(TRK,(10,5),RLSE),UNIT=D0950 00580000
00061 : //---- SPLPLOT                           00590000
00062 : //SPLPLOT EXEC PGM=TEMPNAME,COND=(4,LT)        00600000
00063 : //STEPLIB DD DSN=J2695.XSPLPLT3.LOAD,DISP=SHR 00610000
00064 : //SYSPRINT DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00620000
00065 : //FT06F001 DD SYSOUT=*,DCB=(RECFM=FBA,LRECL=137,BLKSIZE=19043) 00630000
00066 : //FT01F001 DD SPACE=(TRK,(200,50),RLSE),UNIT=WK10 00640000
00067 : //MPTMST DD DSN=SYS1.KPATNLIB,DISP=SHR        00650000
00068 : //GDFILE DD SYSOUT=G,OUTLIM=0               00660000
00069 : //FT11F001 DD DSN=J3149.XXXXX.ENGMHI.SPL.DATA,DISP=SHR,LABEL=(,,IN) 00670000
00070 : //FT05F001 DD *
00071 : 01MKSC 00011000 50.0   4 12.0   10          00680000
00072 : 
00073 : 
00074 : 
00075 : 
00076 : 03
00077 : 
00078 : TDCC          DC TEMP. (CALCULATED)          00690000
00079 : 
00080 :           DOWNCOMER TEMP.                   00700000
00081 : TDCI          DC TEMP. (RETRAN)             00710000
00082 : 01
00083 : QHPI          HPI FLOW                  00720000
00084 : 
00085 : 0.0 5.0E-2HP INJECTION FLOW             00730000
00086 : /*
00087 : ++
00088 : // 
.....1.....2.....3.....4.....5.....6.....7.....8

```

Fig. C.1(e) JCL to convert to SPL-format data and plot the results

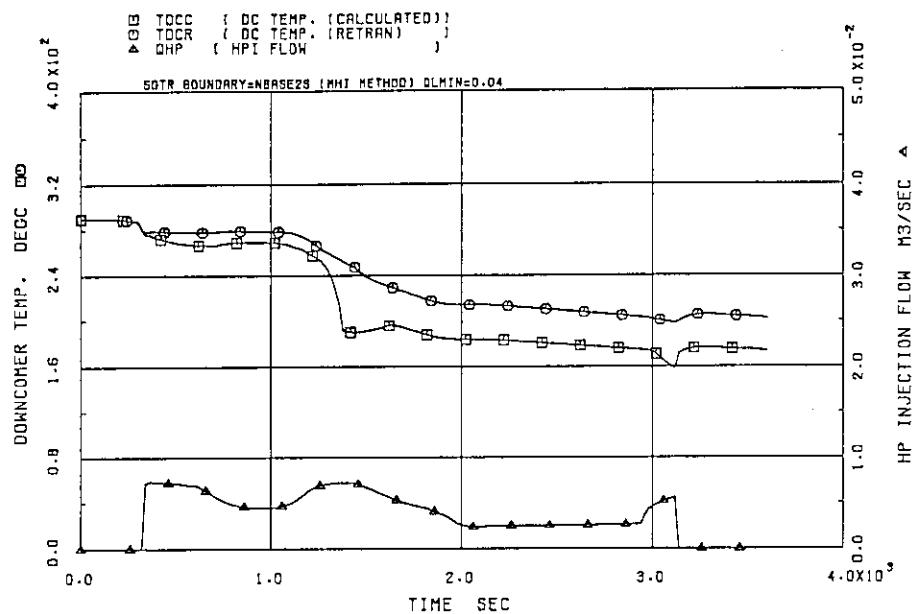


Fig. C.1(f) Results with MHI correlation plotted by SPLPLOT

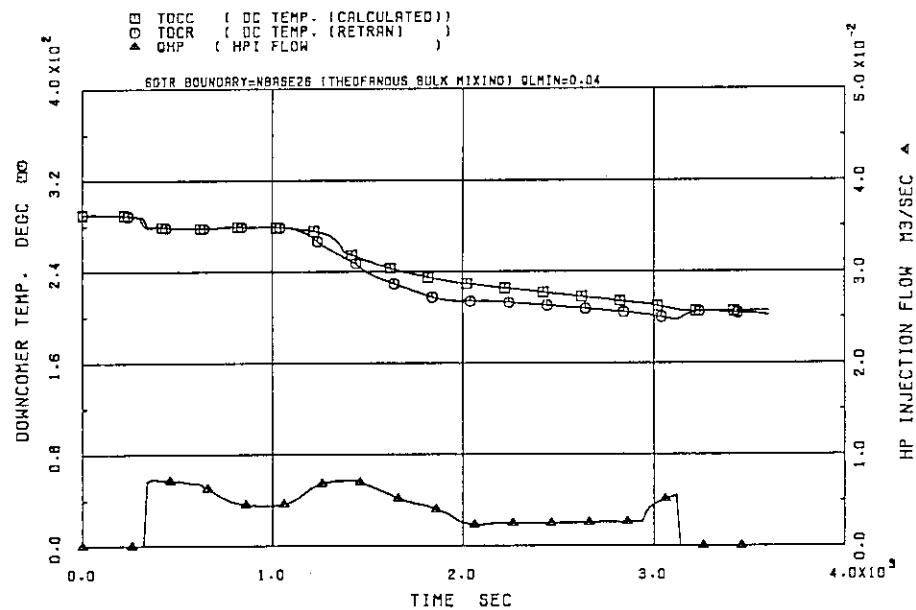


Fig. C.1(g) Results with Bulk Mixing Model proposed by Theofanous plotted by SPLPLOT

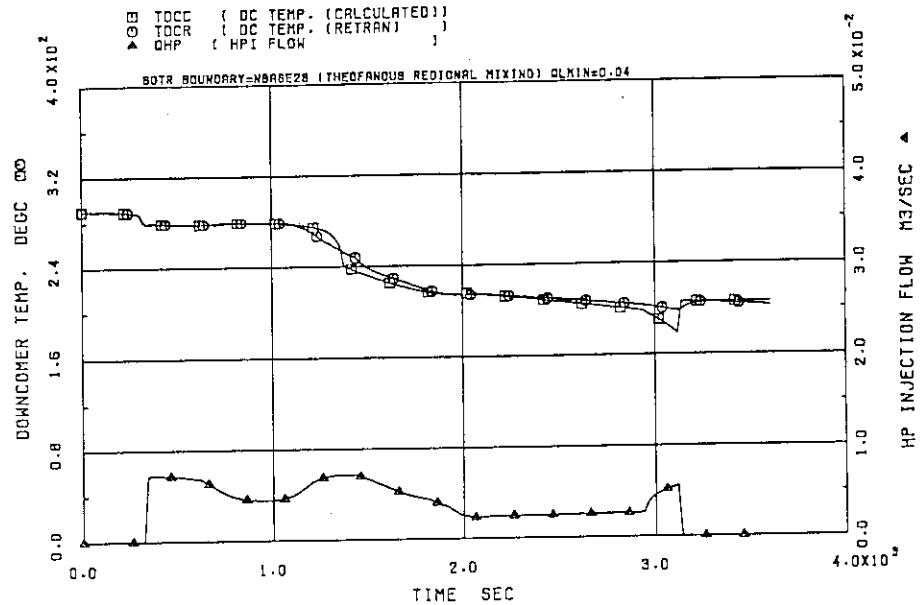


Fig. C.1(h) Results from Regional Mixing Model proposed by Theofanous plotted by SPLPLOT

```

.....*....1.....*....2.....*....3.....*....4.....*....5.....*....6.....*....7.....*....8

00001 : FRAC   1
00002 : KOPT   0   1   0
00003 : TITL M2CASE5 F=2.0E19 C=0.15 P=0.008
00004 : NOD  100
00005 : RATE  1.10000    86.00000   94.50000
00006 : RH01  0.28298    0.12000   0.03330  554.28700
00007 : RH02  0.28298    0.12000   0.03330  554.28700
00008 : RCR   94.50000
00009 : IHT   0 2.37056E-02
00010 : IHF   3   0   0   0
00011 : DTI   0.01000    0.00000   60.0000
00012 : IKV   1   -1
00013 : RTND 2.66000E+01 2.00000E+02 2.00000E+02 2.00000E+19 0.15      0.008
00014 :          2.80000E+04 3.00000E-01 8.03600E-06
00015 : IFP   3   0   0   0
00016 : IKTM  200   1
00017 : IPLO  1   1   1   1   1   1
00018 : XLOG  0.00    0.00
00019 : TMIN  0.00    60.0
00020 : NDAT  0
00021 : JPLO  1   1   1   1   1   1
00022 : ITMX  6
00023 : TIME  10.00   20.00   30.00   40.00   50.00   60.00
00024 : NMAX  0   0
00025 : XYJ1  0.000    0.000    0
00026 : XYJ2  0.000    250.0    0
00027 : XYJ3  0.000    250.0    0
00028 : XYJ4  0.000    0.000    0
00029 : XYJ5  0.000    0.000    0
00030 : XYJ6  0.000    0.000    0
00031 : XYJ7  0.000    0.000    0
00032 : XYI2  0.000    0.000
00033 : ITMX  1   0
00034 : TIME  60.00
00035 : XYI3  0.000    0.000
00036 : ITMX  1   0
00037 : TIME  60.00
00038 : XYI4  0.000    0.000    0.000
00039 : KIPL  1   1   6
00040 : TIME  10.00   20.00   30.00   40.00   50.00   60.00
00041 : XYI5  0.000    0.000    0.000    0.000
00042 : XYI6  0.000    0.000    0.000    0.000
00043 : XYI7  0.000    0.000    0.000    0.000

```

Fig. C.2(a) Input data for stress and fracture mechanics calculations

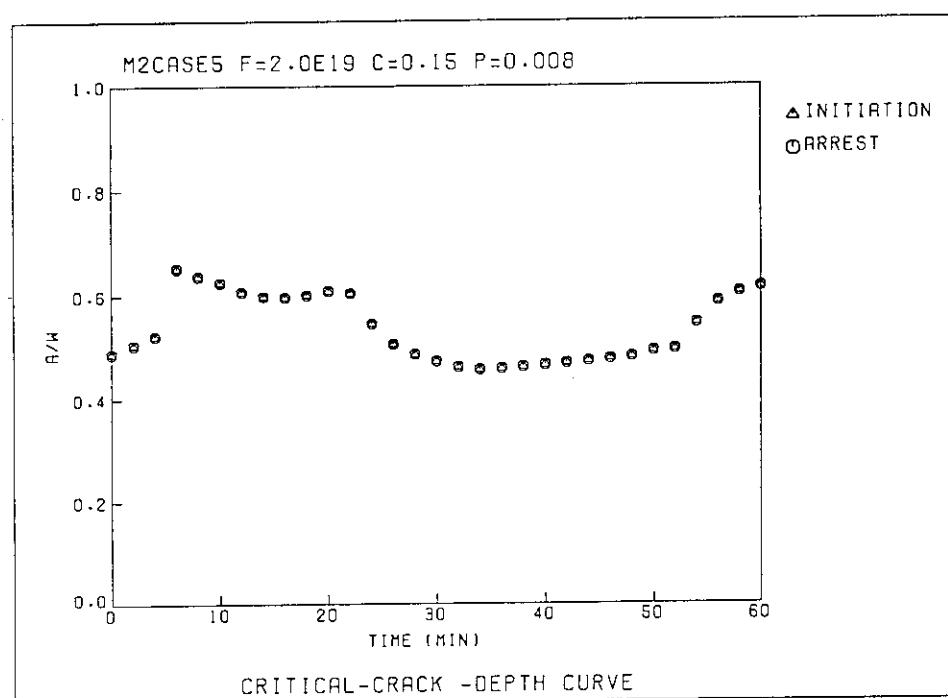


Fig. C.2(b) Plotted results with PLES/PTS (Critical-crack-depth curve)

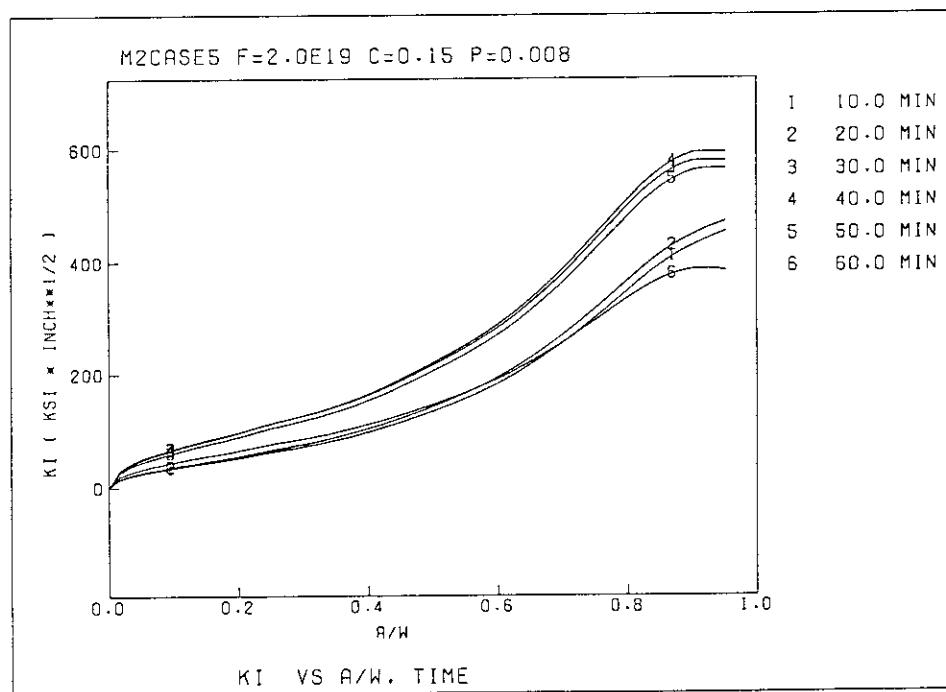


Fig. C.2(c) Plotted results with PLES/PTS (Distribution of k_I within vessel wall)

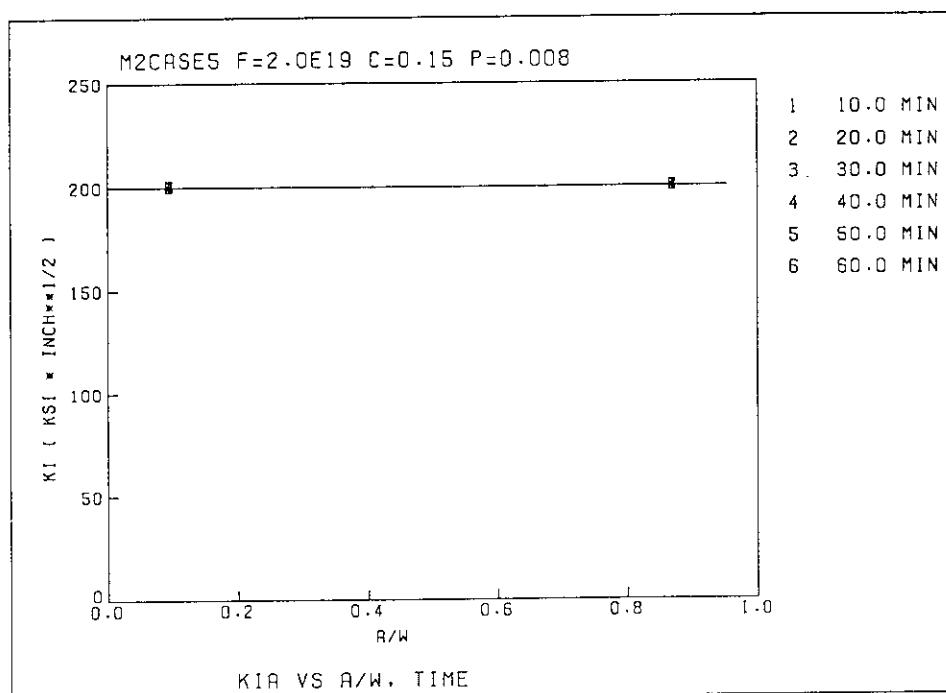


Fig. C.2(d) Plotted results with PLES/PTS (Distribution of k_{Ia} within vessel wall)

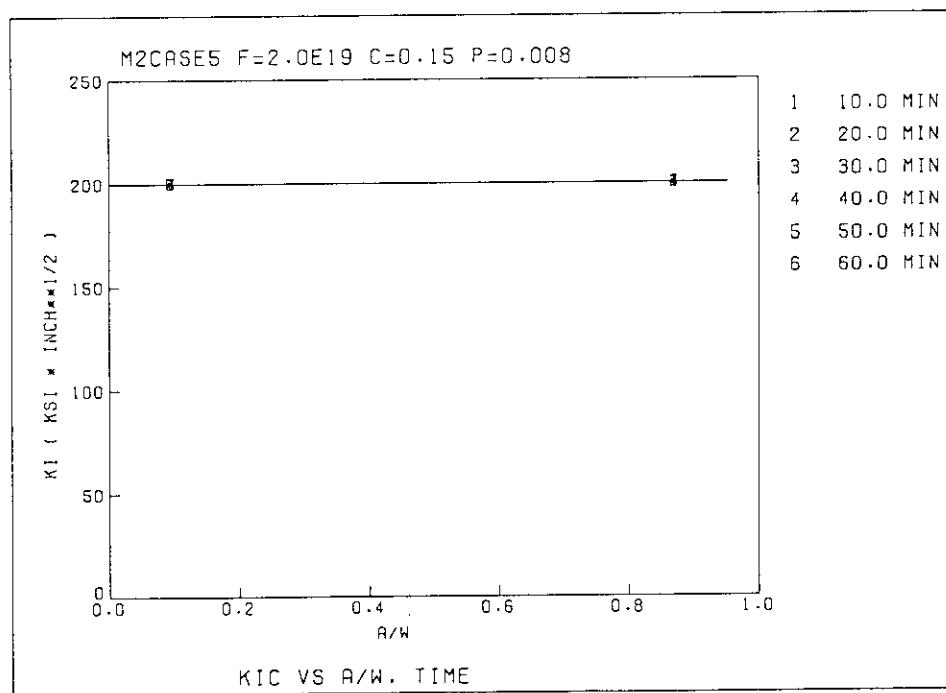


Fig. C.2(e) Plotted results with PLES/PTS (Distribution of k_{Ic} within vessel wall)

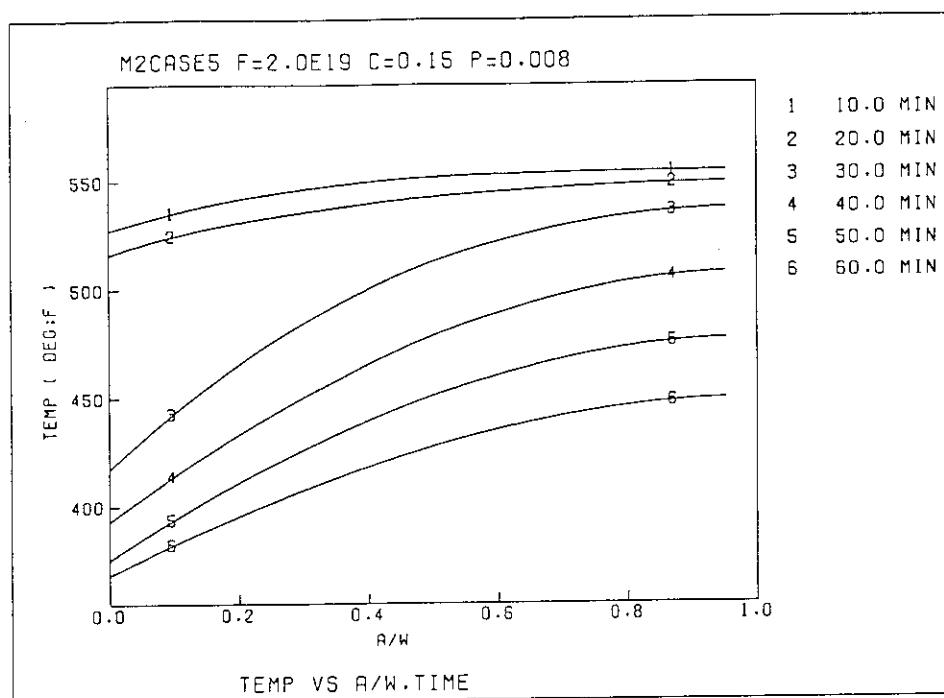


Fig. C.2(f) Plotted results with PLES/PTS (Temperature distribution within vessel wall)

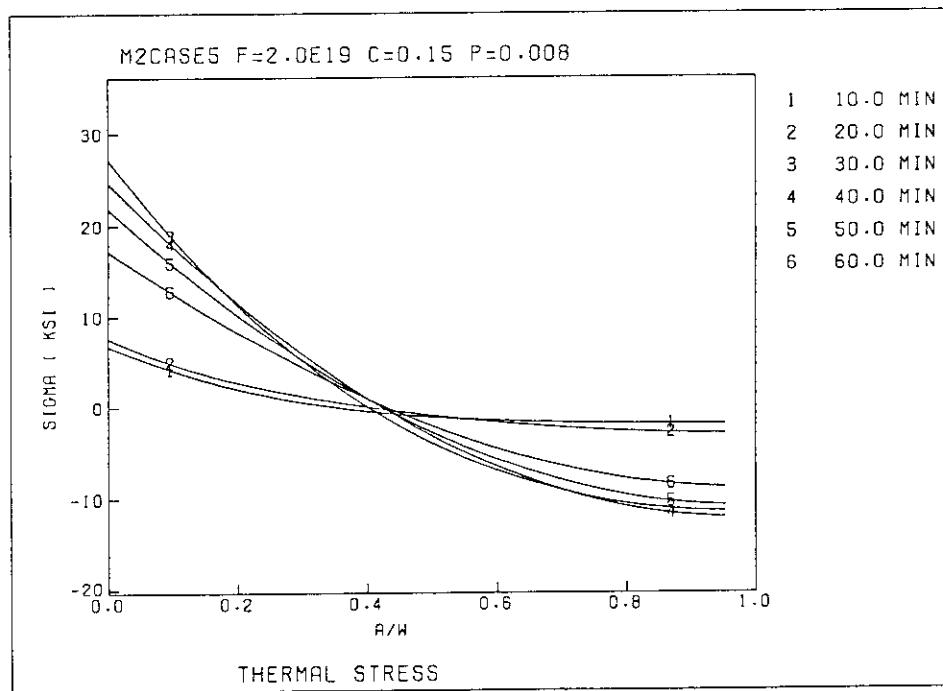


Fig. C.2(g) Plotted results with PLES/PTS (Distribution of thermal stress within vessel wall)

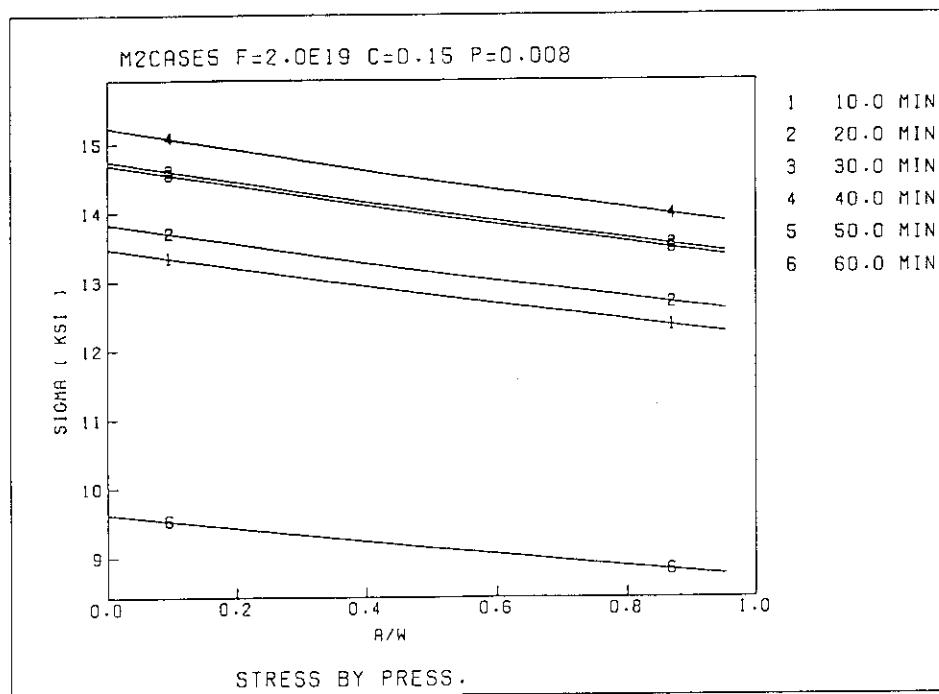


Fig. C.2(h) Plotted results with PLES/PTS (Distribution of stress due to internal pressure within vessel wall)

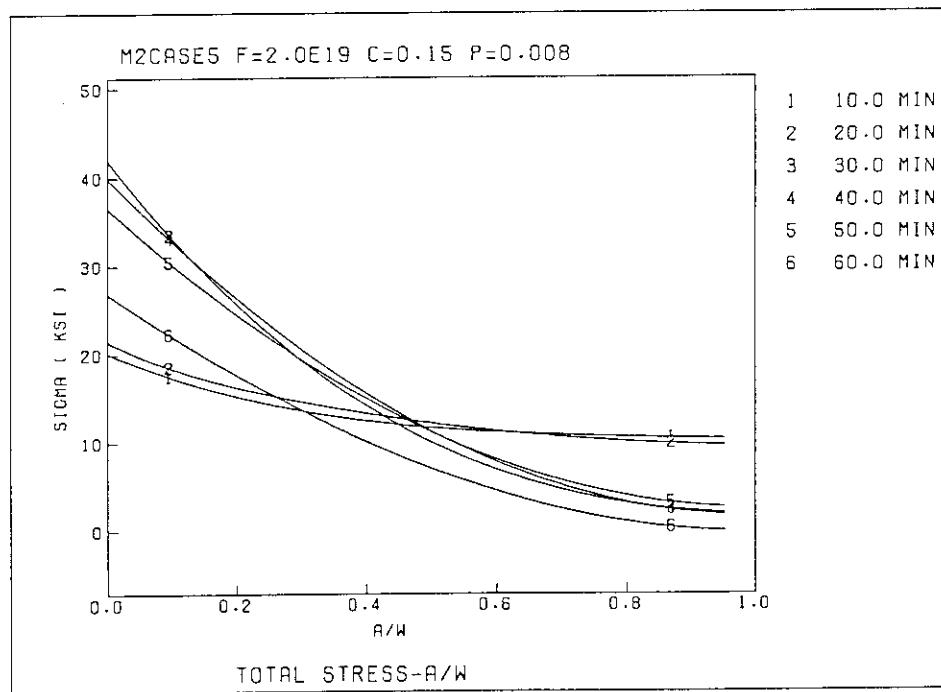


Fig. C.2(i) Plotted results with PLES/PTS (Distribution of total stress within vessel wall)

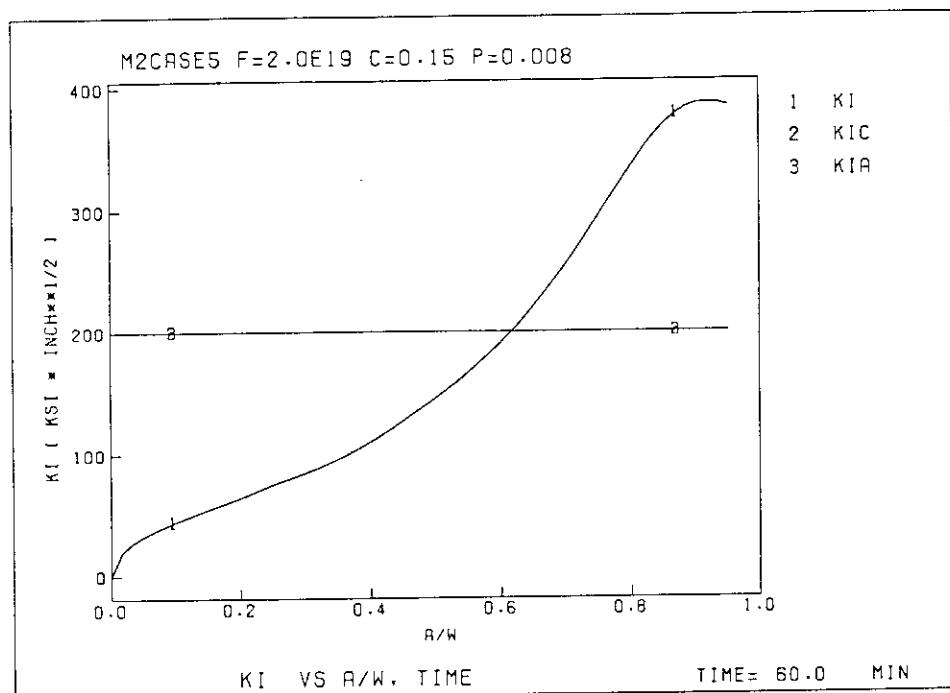


Fig. C.2(j) Plotted results with PLES/PTS (Transient of k_I distribution within vessel wall)

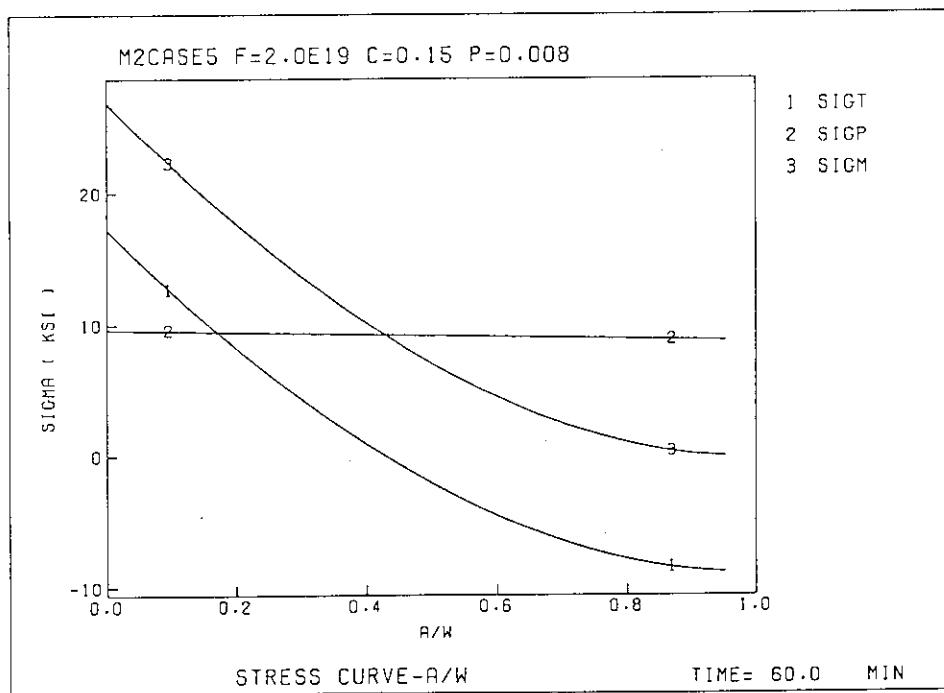


Fig. C.2(k) Plotted results with PLES/PTS (Transient of total stress distribution within vessel wall)

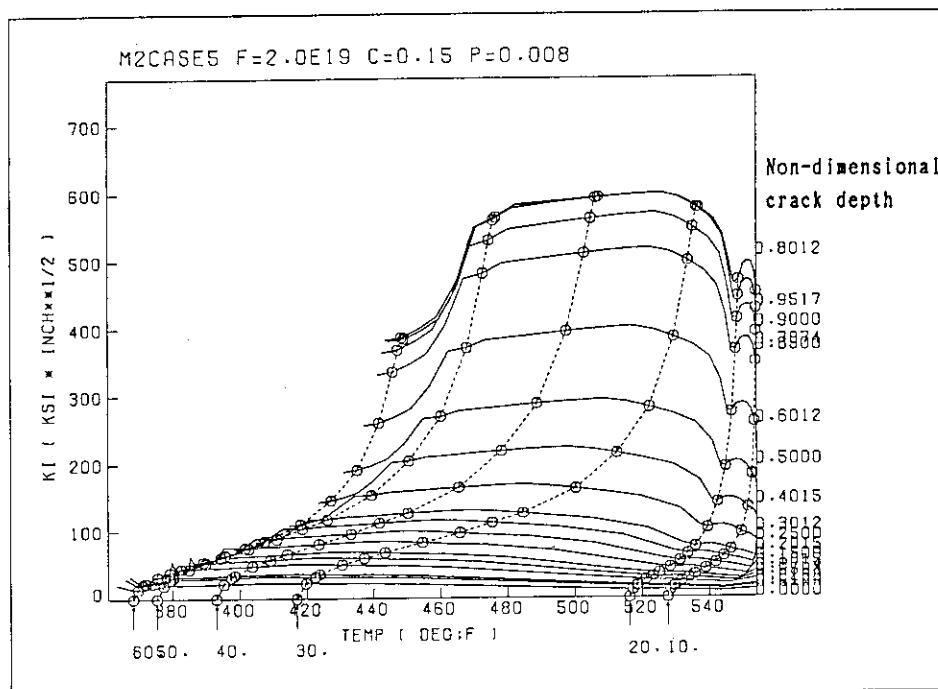


Fig. C.2(1) Plotted results with PLES/PTS (k_I for various initial crack depths as a function of temperature at the crest of crack)

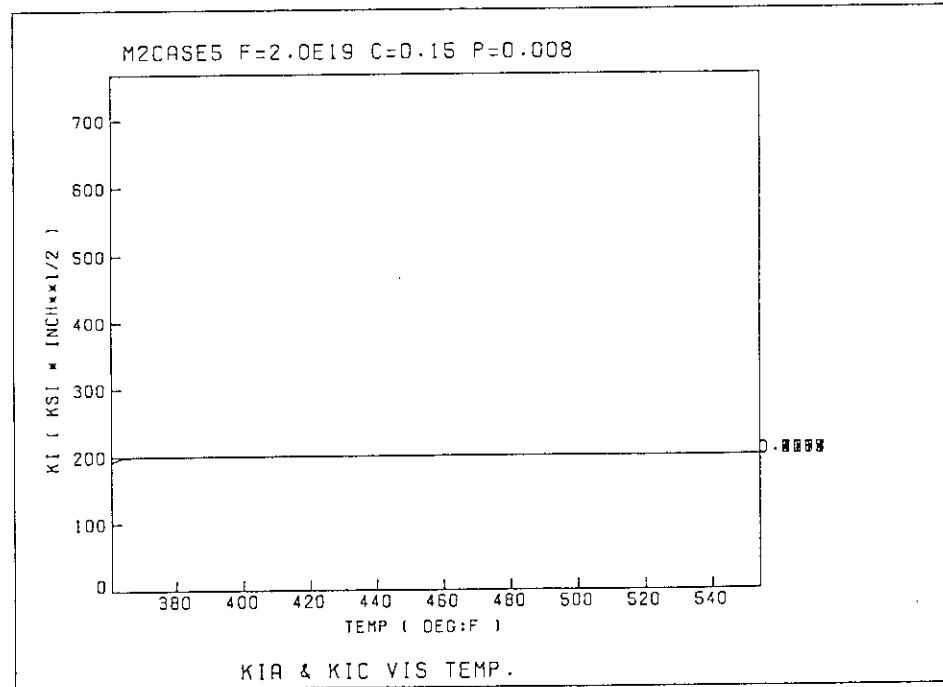


Fig. C.2(m) Plotted results with PLES/PTS (k_{Ia} and k_{Ic} as a function of temperature at crack crest of crack)

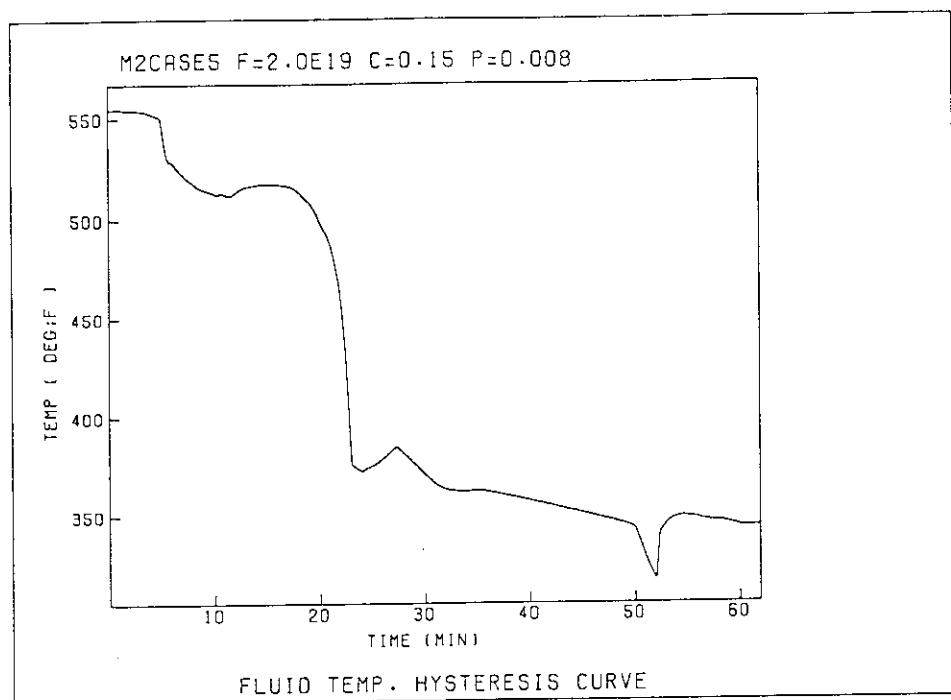


Fig. C.2(n) Plotted results with PLES/PTS (Coolant temperature used in stress calculation)

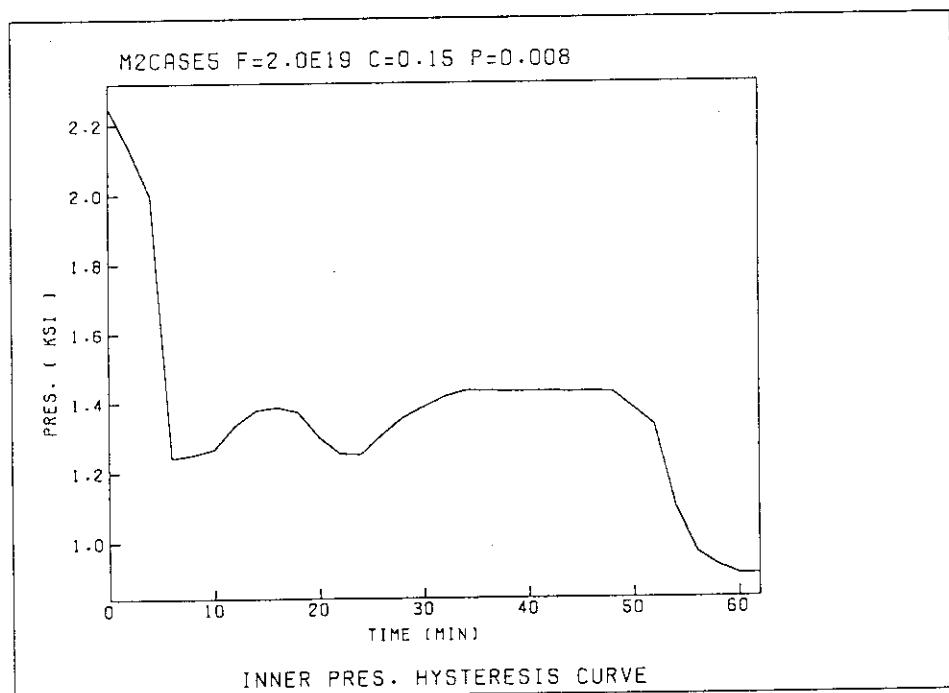


Fig. C.2(o) Plotted results with PLES/PTS (Internal pressure used in stress calculation)

```

.....*....1.....*....2.....*....3.....*....4.....*....5

00001 : OAK2    1
00002 : TITL M2CASE5 F=2.0E19,CU=0.15,P=0.008,D=32
00003 : PDMM 32.000
00004 : CASE   1
00005 : IF9     9   0
00006 : YMIN    0.0   240.0     0.0   280.0
00007 : KIPL   1   3   0 999

.....*....1.....*....2.....*....3.....*....4.....*....5

```

Fig. C.3(a) Input data to generate Okamura's plot for specific initial crack depth

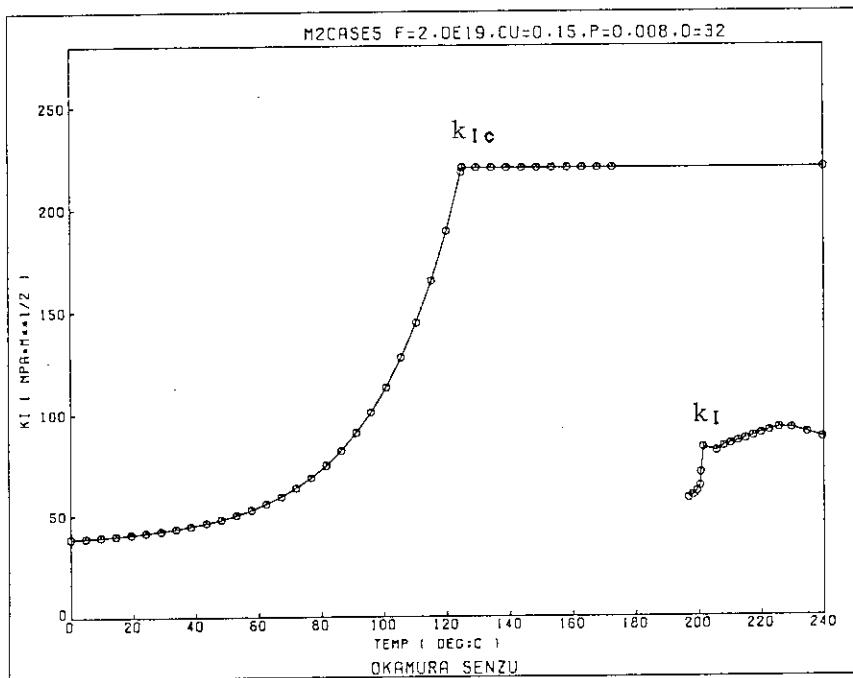


Fig. C.3(b) Plotted results with PLES/PTS (Okamura's plot for specific initial crack depth : k_{Ic} and k_I for a specific initial crack depth as a function of temperature at crest of crack)