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METHODS FOR THE ANALYSIS OF
BOILING WATER REACTORS
TRANSIENT THERMAL MARGIN ANALYSIS CODE
(MAYU04-YAEC)

Prepared By	Kevin J. Burns K. J. Burns	12/29/80 (Date)
Reviewed By	Bruce C. Slifer B. C. Slifer	12/29/80 (Date)
Approved By	Joe C. Turnage J. C. Turnage	12/30/80 (Date)

Yankee Atomic Electric Company
Nuclear Services Division
1671 Worcester Road
Framingham, Massachusetts 01701

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ABSTRACT

A modified version of the MAYU04 computer code has been developed for the evaluation of fuel transient thermal margins. The Critical Power Ratio (CPR) approach is used to describe the conditions at which a boiling transition from nucleate to film boiling occurs. Comparisons to transient boiling transition data are presented, and specific application to the Vermont Yankee Nuclear Power Plant is provided.

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1.0 INTRODUCTION

1.1 Purpose

A modified version of the MAYU04 computer code, hereafter referred to as MAYU04-YAEC, will be used to calculate hot channel thermal margins under transient conditions. The modifications made to the original MAYU04 code [1] include the addition of both the EPRI void model [2] and the GEXL* critical quality versus boiling length correlation [3]. This report describes the modifications, the qualification of MAYU04-YAEC, and the application of MAYU04-YAEC to a typical reactor transient.

1.2 Brief Description

MAYU04-YAEC is a one-dimensional computer code which computes the transient thermal-hydraulic conditions of a single channel. The conservation equations, heat transfer and pressure drop correlations, and numerical solution scheme utilized by the code are described in detail in Reference [1]. Briefly, the vapor continuity, mixture continuity and mixture energy equations are solved by the method of characteristics to determine the channel transient thermal-hydraulics. The axial pressure gradient is neglected in the solution, hence the mixture momentum equation is solved for the channel pressure drop only as an edit calculation. The governing equations are expressed in terms of a drift flux formulation in order to account for nonuniform phase velocities and radial distributions, although

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*GEXL is a General Electric Company proprietary critical quality vs. boiling length correlation.

thermodynamic equilibrium is assumed between phases. The drift flux parameters C_o and V_{gj} are evaluated according to the EPRI void model [2], and the void/equilibrium quality relationship implied by this model is utilized. Finally, thermal margins are measured in terms of the Critical Power Ratio (CPR), and evaluated via the GEXL critical quality versus boiling length correlation [3] using the local instantaneous thermal-hydraulic conditions.

1.3 Model Qualification

MAYU04-YAEC is used to predict 4x4 rod bundle transient boiling transition data. Although the GEXL correlation is not utilized in these predictions, a similar steady state critical quality versus boiling length correlation (based on steady state boiling transition data obtained from the 4x4 rod bundle test section) is used in conjunction with MAYU04-YAEC to predict the time and axial location of boiling transition. The predictions of transient boiling transition were found to be generally satisfactory.

1.4 Model Application to a Typical Transient

Typical inlet mass flux, inlet enthalpy, neutron power and channel pressure as functions of time for a Turbine Trip Without Bypass (TTWOB) transient are input to MAYU04-YAEC (along with suitable channel geometry and power peaking factors), and the transient thermal-hydraulic conditions are evaluated. These results are then used with the GEXL correlation to predict the occurrence of boiling transition, and a CPR is calculated at each time step. The CPR for the transient is defined simply as the initial steady state CPR minus the minimum value of CPR during the transient.

2.0 DESCRIPTION

2.1 Thermal-Hydraulics

As stated in Reference [1], the following assumptions are made in the derivation of the conservation equations:

(1) The liquid and vapor phases are in thermodynamic equilibrium.

(2) Subcooled boiling can be neglected.

(3) The kinetic and potential energy contributions to the mixture energy can be neglected.

(4) The fluid flow is one-dimensional.

(5) The vapor phase flows only in the upward direction.

(6) Axial variations in pressure with respect to the system reference pressure are small.

(7) The vapor and liquid phases can be coupled by a drift flux model.

(8) The flow area is constant in space and time.

The resulting mixture continuity, vapor continuity and mixture energy equations are used to calculate the transient (cross sectional average) thermal-hydraulic conditions of the channel. Assumption (6) allows the momentum equation to be decoupled from the continuity and energy equations, hence the mixture momentum equation is solved only for editing purposes. The time dependent boundary conditions required as input to the code consist of the bundle inlet mass flux, system pressure, bundle power and bundle inlet enthalpy. Finally, a one-dimensional radial heat conduction model [1] is used to calculate the time varying fuel rod surface heat flux.

2.2 Physical Correlations

2.2.1 Heat Transfer and Pressure Drop Correlations

The heat transfer coefficients required for solution of the radial heat conduction problem are calculated from the Dittus-Boelter relation for single-phase liquid flow, from the Thom correlation for two-phase nucleate boiling, and from the Dougall-Rohsenow correlation for co-current two-phase film boiling. Single-phase friction factors are given by a fit to the Moody curves. Two-phase friction factors are obtained by multiplying the equivalent single-phase friction factor by a two-phase friction multiplier, obtained from the Jones fit to the Martinelli-Nelson correlation [1].

2.2.2 Void Model

The governing equations are expressed in terms of a drift flux formulation. The original MAYU04 ramp void model [1] gives the drift flux parameters C_o and V_{gj} as functions of void fraction (α). This model is replaced by the EPRI void model [2], which also expresses the drift flux parameters C_o and V_{gj} as functions of α. The EPRI void model's drift flux parameters are based on void/equilibrium quality data obtained from 6x6 rod arrays at typical BWR conditions.

2.2.3 Critical Quality Correlations

The solution of the governing equations yields the time varying thermal-hydraulic conditions of the channel at each axial node. At every time step, the critical quality is evaluated from a critical quality versus boiling length correlation, using the local instantaneous thermal hydraulic conditions. For a given bundle, such a correlation gives the critical quality as a function of boiling length, pressure and mass flux. It has been observed [3] that this form of correlation satisfactorily correlates BWR boiling transition data for all axial power profiles of interest. That is, the critical quality versus boiling length type of correlation implicitly accounts for the effects of nonuniform axial heat flux on boiling transition. Boiling transition is predicted whenever the local quality calculated by MAYU04-YAEC equals or exceeds the critical quality given by the correlation.

The correlation used in the qualification of MAYU04-YAEC (Section 3.2) is based on steady state boiling transition data for the specific test section of interest. In the application of the code to an actual reactor transient (Section 4.1), however, the GEXL correlation [3] is utilized. This correlation is based on steady-state boiling transition data obtained from a multitude of electrically heated test sections, including simulated full size BWR bundles.

2.3 Thermal Margins

As stated earlier, the figure of merit used to quantify thermal margin is Critical Power Ratio (CPR). CPR is defined as the ratio of the power necessary to obtain the critical quality at some elevation (for given hydraulic conditions of mass flux and pressure), to the actual operating power. The original version of MAYU04 calculates an approximate CPR according to the following formula:

$$CPR = [CPR(Z)]_{min.} = \frac{X_c\ (LB,P,G) + \frac{\Delta h_{sub}}{h_{fg}}}{\left[X(Z) + \frac{\Delta h_{sub}}{h_{fg}}\right]_{min.}} \qquad (1)$$

where:

Z = elevation (ft)

LB = boiling length (ft)

P = pressure (psia)

G = mass flux ($lbm/hr\text{-}ft^2$)

Δh_{sub} = inlet subcooling (Btu/lbm)

h_{fg} = latent heat of vaporization (Btu/lbm)

X = local quality

X_c = critical quality, evaluated from the correlation as a function of LB, P and G.

Equation (1) is an exact expression for CPR under steady-state conditions, provided that the boiling length (LB) corresponds to the critical power.

However, CPR $\geq$ 1.0 (i.e., LB $\leq LB_c$) for cases of interest here, and since X_c increases with increasing LB, it follows that the approximation given by Equation (1) yields a value for CPR which is less than the exact value. Thus, the exact CPR can be calculated in an iterative fashion as follows:

(1) Calculate an initial estimate for CPR using Equation (1).

(2) For the instantaneous hydraulic conditions, calculate a new enthalpy distribution corresponding to a power level which is a factor of CPR higher than the original power level,

$$h'(Z) = CPR \ (h(Z) - h_{in}) + h_{in}$$

where:

$h'(Z)$ = revised enthalpy at elevation Z (Btu/lbm)

h_{in} = inlet enthalpy (Btu/lbm)

$h(Z)$ = original enthalpy at elevation Z (Btu/lbm)

(3) Compute a revised boiling boundary bas . on the revised enthalpy distribution, and calculate a revised critical quality at each elevation based on the revised boiling lengths (using the same local instantaneous values for the hydraulic parameters P and G).

(4) Use the values of X_c calculated in Step (3) to calculate CPR' (the approximate CPR at the increased power level) from Equation (1).

(5) If the value of CPR' is 1.0 (within the required convergence criterion), then the value of CPR which was used in Step (2) was correct. Otherwise, increase CPR by the additive factor (CPR'-1.0) and proceed to Step (2).

(6) Repeat Steps (2) - (5) until the iteration converges in Step (5).

A subroutine which utilizes the above iterative procedure for calculating transient CPR was incorporated into MAYU04-YAEC. Although the CPR concept is not well defined under transient conditions, CPR values calculated according to the above procedure are exact under steady conditions (and for CPR=1.0), and provide a convenient measure of thermal margin during transients.

3.0 QUALIFICATION

3.1 Analytical Comparisons

Reference [1] provides a comparison of MAYU04 to an exact solution for an exponential flow decay transient assuming constant drift flux parameters, C_o and V_{gj}. As seen from the results presented [1], MAYU04 closely approximates the exact solution, especially for large boiling lengths representative of those at which the thermal margin usually reaches its minimum value.

3.2 Comparisons to Rod Bundle Transient Boiling Transition Data

Reference [4] provides both steady-state and transient boiling transition data for single-rod, 9-rod and 16-rod electrically heated test sections. The 16-rod assembly data was chosen for use in the qualification of MAYU04-YAEC, since this geometry most closely approximates full size BWR assembly geometries. The axial heat flux profile for this 16-rod assembly was that of a chopped cosine, and the nominal radial peaking factor was uniform. Steady-state boiling transition data were used in Reference [4] to develop a critical quality versus boiling length correlation for the test section.

A total of nine flow decay transients were analyzed using MAYU04-YAEC. Boiling transition was predicted whenever the local instantaneous quality equaled or exceeded the critical quality, as calculated from the correlation using the local instantaneous thermal-hydraulic conditions predicted by MAYU04-YAEC. These flow decay transients conservatively simulate a pump seizure accident, since the flow is quickly reduced to about half of its initial value, while the power level remains essentially constant. The inlet enthalpy, inlet mass flux, channel pressure and channel power data for each case were taken from Reference [4] and used to prepare input decks for MAYU04-YAEC.

Table 3.1 compares the MAYU04-YAEC predicted results and the experimental results for boiling transition (BT), where experimental BT was indicated by rod thermocouple temperature excursions. Both the time to initial BT and the spacer locations of initial and subsequent BT are shown. A boiling transition was experimentally observed for all nine cases, and was also predicted by MAYU04-YAEC for those nine cases. Furthermore, the time to initial BT was predicted within ± 0.35 sec. for seven out of nine cases, and was predicted conservatively in time for the remaining two cases. Finally, the locations of both the initial BT and its subsequent penetration were predicted within one spacer location of the experimentally observed location in all nine cases.

The above results support the quasi-steady state use of a critical quality versus boiling length correlation (along with local instantaneous thermal-hydraulic parameters) for the prediction of transient BT. In addition, these results reflect the adequacy of the MAYU04-YAEC solution technique, as well as the applicability of its various constitutive models, including the EPRI void model.

3.3 Verification of the Fuel Rod Conduction Model

The one-dimensional radial heat conduction model contained in MAYU04-YAEC was not utilized in Section 3.2, since the power input to the electrical heaters appeared directly in the clad, and since the power was held constant for these flow decay transients. In order to apply MAYU04-YAEC to actual reactor transients, however, it is necessary to utilize the fuel rod conduction model in order to calculate the correct time varying surface heat flux. Thus, it is desirable to check this model against some standard. The RETRAN code was chosen as the standard for two reasons. First, RETRAN has undergone extensive verification and qualification studies [5]. Secondly, it is necessary to show that the RETRAN and MAYU04-YAEC conduction solutions are consistent, since RETRAN will provide the transient thermal hydraulic input conditions for MAYU04-YAEC in licensing calculations.

A RETRAN run was made for the power versus time history shown in Figure 3.1. The fuel rod was modeled with 6 radial conduction nodes in the fuel region and 4 nodes in the clad region. A constant gap conductance of 1000 Btu/hr-ft^2-^{o}F was assumed. A uniform axial power profile was utilized, and all of the heat transferred out of the fuel was assumed to appear as a heat flux at the clad surface. The fuel and clad material properties as functions of temperature were obtained from Reference [6].

The heat flux at a particular axial node as a function of time for the RETRAN run was then compared to the time varying heat flux predicted by MAYU04-YAEC. MAYU04-YAEC was run utilizing the same geometry, radial conduction nodalization, gap conductance, axial power peaking factors, material properties and channel power as a function of time as used in the RETRAN run. Furthermore, the channel pressure, inlet mass flux and inlet enthalpy as functions of time required as input to MAYU04-YAEC were obtained from the RETRAN results. Table 3.2 compares the RETRAN and MAYU04-YAEC predicted results for surface heat flux for selected time steps at an elevation of 6.5 feet from the bundle inlet (the transient pressure versus time at this elevation was used as the channel average pressure in the MAYU04-YAEC run). As seen from this table, the percentage difference between the RETRAN and MAYU04-YAEC predicted heat flux is on the order of 1-2%, with the highest percentage difference occurring near the time at which the heat flux reaches its peak value. Although these results do not rigorously qualify the MAYU04-YAEC conduction model, they do serve to support both the validity of the model and the consistency between the RETRAN and MAYU04-YAEC conduction models.

TABLE 3.1

Comparison of Measured and Predicted
Time and Locations of Boiling Transition

Run No.	Time of First BT (sec.)		(Time BT Measured- Time BT Predicted)	Spacer Location of BT	
	Measured	Predicted		Measured	Predicted
102	2.8	3.05	-0.25	3	2
105	3.5	3.19	0.31	3,4	2,3
106	3.0	2.75	0.25	3,2	2,3
108	4.0	3.78	0.22	3,4,2	2,3
110	5.2	4.32	0.88	3,2	2,3,4
111	3.5	3.80	-0.30	3,4,2	2,3,4
112	6.2	4.07	2.13	3	2,3
113	5.2	5.53	-0.33	3,2	2
114	4.5	4.61	-0.11	3,4,2	2.3

TABLE 3.2

Comparison of Predicted Heat Flux
at the 6.5 Foot Elevation for RETRAN and MAYU04-YAEC

Time (sec)	Heat Flux (Btu/hr-ft^2-^{o}F) MAYU04-YAEC	RETRAN	Percentage Difference
0.0	80457	80454.8	0.0027
0.10	81182	80417.7	0.9504
0.20	81176	80396.0	0.9702
0.30	81207	80414.3	0.9858
0.40	81158	80404.6	0.9370
0.50	80577	79808.0	0.9636
0.60	81104	80099.0	1.2547
0.70	85769	84711.6	1.2482
0.80	95977	94508.5	1.5538
0.90	109646	107722	1.7861
1.00	117456	115154	1.9991
1.10	117070	114449	2.2901
1.20	113766	111702	1.8478
1.30	110954	109063	1.7339
1.40	108412	106756	1.5512
1.50	105937	104545	1.3315

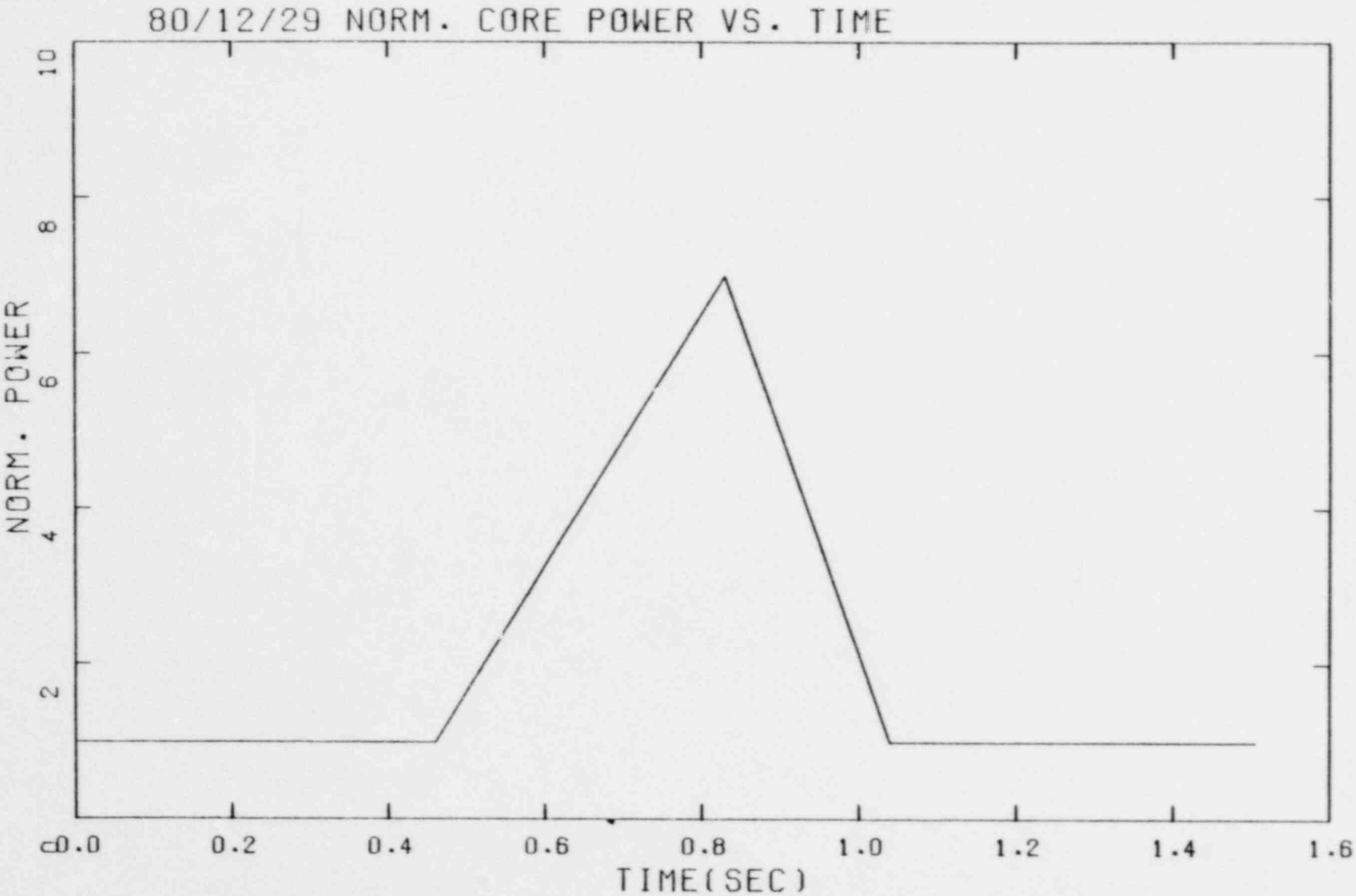

FIGURE 3.1
Normalized Power Versus Time
for RETRAN and MAYU04-YAEC
Conduction Model Comparison

4.0 APPLICATION

4.1 Abnormal Operational Transients

In order to demonstrate the application of MAYU04-YAEC to a typical reactor transient, the code was run for the case of a Turbine Trip Without Bypass (TTWOB) transient. An outlet peaked axial heat flux distribution and geometric characteristics for an 8x8 fuel assembly were used, along with representative local rod peaking factors. The axial power shape remained constant during the transient, as required by the code. Transient values of channel power, channel pressure, inlet mass flux and inlet enthalpy were obtained from the results of a RETRAN [5] code run for a TTWOB. For the fuel rod conduction model, temperature dependent material specific heat and material conductivity for both the fuel and the clad were obtained from Reference [6], and a fuel-to-clad gap conductance of 1000 Btu/hr-ft^2-^{o}F was assumed.

A plot of the transient CPR as a function of time calculated by MAYU04-YAEC is presented in Figure 4.1. CPR was calculated in the manner described in Section 2.3. The CPR, defined as the initial CPR minus the minimum CPR during the transient, was calculated to be 0.14.

4.2 Range of Applicability

As stated in Reference [1], with the proper set of correlations MAYU04-YAEC is capable of analyzing the following types of transients:

(1) Pressure, power and flow transients, including LOCA up to core spray initiation time.

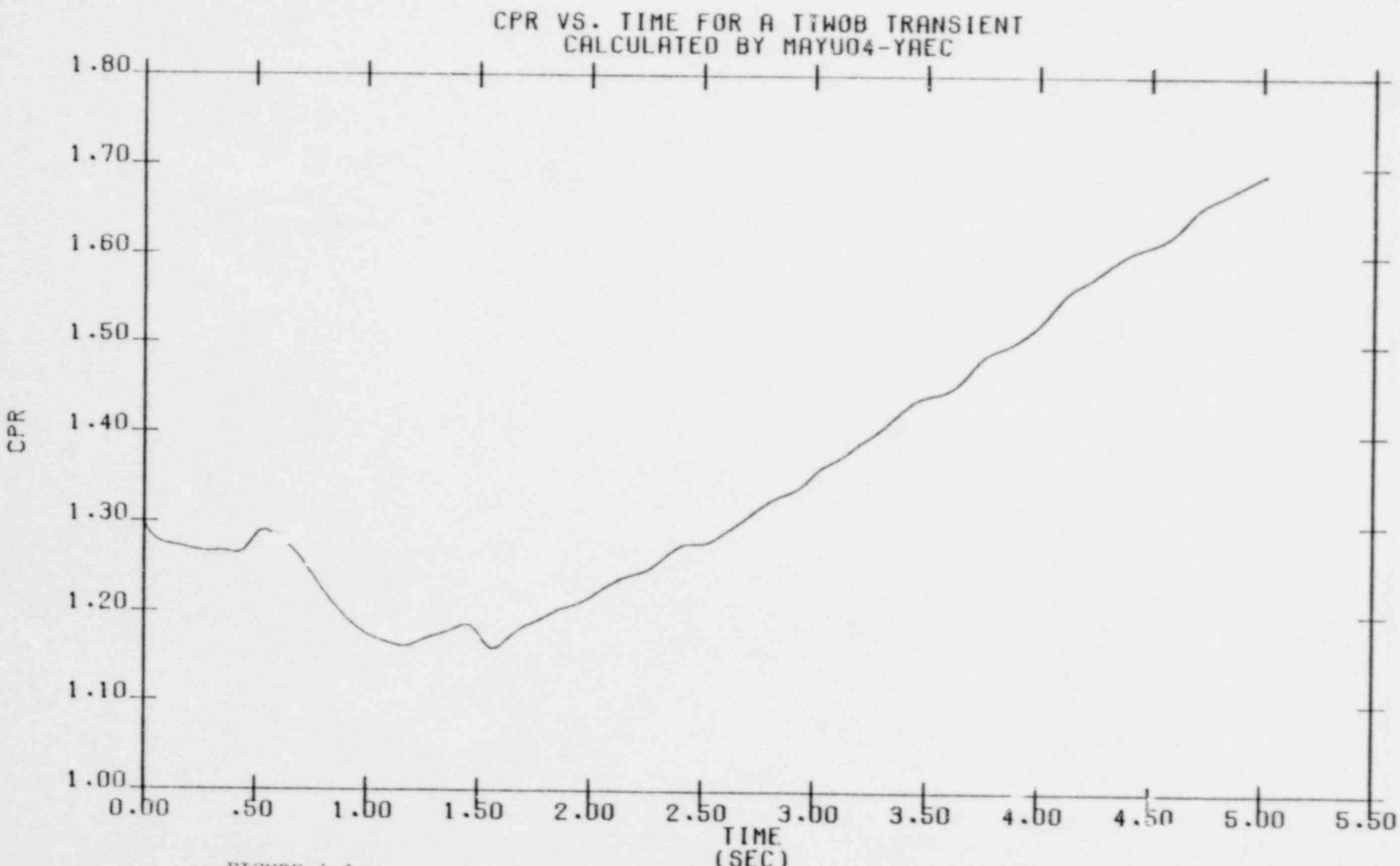

FIGURE 4.1
CPR Versus Time for a TTWOB Transient

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5.0 REFERENCES

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