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AUSTRALIAN ATOMIC ENERGY COMMISSION
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A SENSITIVITY STUDY OF THE HEAT TRANSFER PROCESSES INVOLVED IN A HOT-LEG RUPTURE IN A PRESSURISED WATER-COOLED SYSTEM

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W.J. GREEN

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ABSTRACT

A series of computer experiments was performed, using the reactor thermal analysis code THETA1-B, to ascertain the significance and relative importance of the various heat transfer processes in relation to the prediction of maximum surface temperatures for:

(i) the fuel cladding during the blowdown phase of a loss of coolant accident (LOCA) for a hot-leg rupture in a pressurised water reactor system; and

(ii) an electrically heated tube of a simple water-cooled test assembly, subjected to a corresponding hot-leg blowdown, for which experimental results have been published.

The significance of several factors was considered, including the choice of heat transfer correlation for a particular heat transfer regime, and inlet coolant flow conditions.

For both cases the predicted maximum surface temperature was sensitive to a number of factors, including choice of heat transfer correlations for (i) critical heat flux, (ii) flow boiling transition region and, in particular, (iii) stable film boiling.

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COMPUTER CALCULATIONS; HEAT TRANSFER; BLOWDOWN; PWR TYPE REACTORS; LOSS OF COOLANT; RUPTURES; FUEL ELEMENTS

CONTENTS

(continued)

CONTENTS (Continued)

1. INTRODUCTION

The complete analysis of a loss of coolant accident (LOCA) in a water-cooled reactor (WCR) is extremely complex and, to enable fluid and thermal responses of the system to be calculated accurately, detailed knowledge is required of the coolant dynamics and the heat transfer processes. Furthermore, to enable the thermal response of the fuel rods to be determined, the complete set of conservation equations must be solved in detail throughout the system.

There have been many analytical and computational attempts to rationalise and solve this LOCA analysis problem, and much experimental work to provide data on the wide range of heat transfer processes involved. However, current computer codes necessarily make arbitrary assumptions and use steady state correlations to describe transient fluid and heat transfer processes. Furthermore, the steady state correlations used are often different for each code and there are no universally accepted and proven means of delineating the boundaries between thermal hydraulic regimes.

The blowdown phase of a LOCA arising from a hot-leg rupture is considered here, and the effects are examined of various options or parameters, such as choice of correlation, magnitude of heat transfer coefficent, and inlet coolant flow conditions, on the thermal response of

- a typical pressurised water reactor (PWR) fuel pin, and
- a water-cooled, heated tube test assembly for which experimental data are available [Hicken *et al.* 1972].

The transient thermal hydraulic digital computer code THETA1-B (Thermal Energy Transport Analyser, version 1-B)* [Hocevar & Wineinger 1972] was chosen for this investigation because of its versatility, having several correlation options already available within the code, and because of its ability to identify the heat transfer processes involved in the analysis.

THETA1-B was written specifically to solve equations that describe the thermal energy transfer processes that would occur if a WCR fuel pin were subjected to a LOCA. It solves the two-dimensional thermal diffusion equation for a single fuel pin and the one-dimensional conservation of

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* Note that British imperial units are used because the output from the THETA1-B code is in these units.

energy equation for the associated coolant channel. The two solutions are linked at the fuel pin/fluid interface by the boundary conditions of surface temperature and heat flux.

2. HEAT TRANSFER REGIMES INVOLVED IN A LOSS OF COOLANT ACCIDENT

Brief descriptions have previously been given by Green and Lawther [1976] of the terms used to refer to the heat transfer regimes occurring in a water-cooled reactor LOCA. The same terminology is used here but the following descriptions are given to emphasise particular features of certain regimes.

2.1 Flow Boiling

Flow boiling is the term used to describe the boiling process when the fluid is flowing along a channel. It can be one of two types:

> *Transition boiling* which refers to the phenomenon of intermittent drying and wetting of the heated surface and which may occur immediately following the onset of dryout. With flow boiling, this mode occurs usually for a very short time during a transient [Hocevar & Wineinger 1972; Tong 1966] and may be observed as either a fast rise in heated surface temperature or as a gradual rise with or without rapid temperature fluctuations.
>
> *Stable film boiling* which occurs when a vapour film covers the heated surface. For high quality liquid deficient flows, the liquid may be carried in a dispersed flow of entrained droplets in the central core. Stable film boiling can also occur in low quality or even subcooled fluid conditions.

2.2 Pool Boiling

Pool boiling is the term used to describe the boiling process for a heating surface submerged in a large volume of stagnant liquid, but in the THETA1-B code, pool boiling correlations may be applied for coolant water mass fluxes below 60 lb/s ft^2.

3. CALCULATION OF THERMAL RESPONSES USING THETA1-B

Input data for the THETA1-B code can be classified broadly into two main areas, one relating to the fuel pin and the other to the coolant. The fuel pin may be modelled using both axial (< 20) and radial (< 50) nodes, whereas the fluid channel is modelled by axial regions corresponding to those used in the fuel pin.

The heat transfer model incorporates the following heat transfer regimes: forced convection in subcooled liquid and superheated vapour;

nucleate boiling; forced convection vaporisation; transition boiling; and stable film boiling. More than one option of heat transfer correlation exists for several of the heat transfer regimes.

3.1 Data Input for a PWR Loss of Coolant Accident

The fuel pin data were made the same as those given in the sample problem of Hocevar and Wineinger [1972] which related to a typical PWR fuel pin. The fuel pin power density decay rate was also retained as that given by Hocevar and Wineinger [1972] (Figure 1).

When specifying the inlet coolant flow conditions, data given by Zane [1975] on the core transient flow rate experimentally obtained for a hot-leg LOCA in a semiscale reactor model, have been simplified to eliminate second order perturbations, and scaled in magnitude to represent flow in a full-size PWR. The resulting flow transient is shown in Figure 2a. Shown on Figure 2b is the hypothetical inlet mass flow response used when the effect is being considered of different mass flow reponses on thermal performance. As input data for these investigations, it has been assumed that the pressure decay transient data of Hocevar and Wineinger [1972] are reasonably applicable and that the inlet enthalpy can be assumed constant during the period considered. These input conditions are shown on Figures 1 and 2 respectively.

3.2 Data Input for a Water-cooled, Thin-wall, Heated Tube

In order to simulate a thin-wall heated tube internally cooled by water and suddenly subjected to a LOCA, the model described in THETA1-B was modified by submitting data such that the fuel pin was divided into two regions: (1) a thin annular region whose thickness and thermal properties, apart from density, represented the uniformly heated thin-wall tube described by Hicken *et al.* [1972]; and (2) a central core whose thermal properties were the same as the annular region except for density which was taken arbitrarily as one hundredth of the annular region value. The material density for the model was obtained by maintaining the thermal mass of the model the same as that of the experimental tube.

Simulation of the fluid channel for the model was achieved by specifying the flow area and equivalent hydraulic diameter to be the same as in the experimental assembly.

Initially, the inlet coolant conditions were taken as (i) the mass flow and pressure transient responses as given by Hicken *et al.* [1972], and (ii) a constant inlet enthalpy. The mass flow and pressure responses referred to have been reproduced in Figures 3 and 4. In later investigations hypothetical inlet mass flow responses were considered (see Figure 5).

4. RESULTS AND DISCUSSION

4.1 Maximum Fuel Cladding Temperatures for the Blowdown Phase of a Hot-leg LOCA in a PWR System

4.1.1 Optional choices within THETA1-B

Since dryout is predicted to occur within 10-80 ms (Table 1), it was considered that the predryout regimes would be of such short duration that choice of correlations for these regimes would not have any real significance in terms of the resulting maximum fuel cladding temperature.

TABLE 1

EFFECT OF CHOICE OF CHF CORRELATION ON MAXIMUM CLADDING TEMPERATURE AND TIME TO DRYOUT

Flow Film Boiling Correlation: Groeneveld*

CHF Correlation		Max. Clad. Temperature (^oF)	Time to First Dryout (s)
THETA1-B Option No.	Correlation*		
1	W3	663	~0.04
2	GE design limit	1279	~0.01
3	Combination of W3 and GE	1278	~0.03
4	Macbeth	1292	~0.02
5	Barnett	1301	~0.02
6	Becker	1419	~0.01
7	Combination of W3 and Barnett	1137	~0.04
8	B & W2	1160	~0.08
9	Modified Barnett	1301	~0.02
10	Combination of B & W2, Barnett, and Modified Barnett	1172	~0.08

* *All these correlations are detailed and referenced in the THETA1-B report [Hocevar & Wineinger 1972].*

CHF Options For the simplified mass flow response deduced from data presented by Zane [1975], choice of critical heat flux (CHF) correlation from the options available can have a significant effect on predicted maximum surface temperature as can be seen in Figure 6. Before, however, considering in more detail some of the particular effects produced by each option, it should be pointed out that, apart from those using option 1 (the W3 correlation), all predictions indicated that, for much the greater part of the transient period being considered, stable film boiling was the most significant regime with respect to maximum surface temperature. Considering now the individual effects of each optional CHF choice, it was found that:

- Use of the W3 correlation (option 1) indicated that, in the exit region of the channel, mass fractions exceeded 0.15 during the periods ~ 0.1 to ~ 4.5 s and ~ 6 to ~ 15 s, and that, at the axial position of maximum heat flux, mass fractions were greater than 0.15 during the period of ~ 0.7 to ~ 2.0 s. Since the W3 correlation gives rise to excessively high values of predicted CHF for mass fractions greater than 0.15, it is not valid for much of the transient in the exit regions of the channel and also at the position of maximum heat flux during an important period in the transient. The correlation also indicated that the transition regime was predicted as being just present (i.e. the CHF was marginally exceeded) over a very limited surface area for 0.04 to ~ 0.3 s and thereafter nucleate boiling applied.
- The GE design limit (option 2) indicated the onset of transition boiling as occurring at ~ 0.01 s after the initiation of the break, with stable film boiling occurring after ~ 0.7 s had elapsed. During the period 0.01 to 0.7 s the maximum cladding temperature initially increased but soon decreased before (at a time of 0.1 s) again rising rapidly. This behaviour is considered to be a result of the sensitivity of the GE design limit to the significant variation in flowrate occurring in the initial 0.2 s.
- Option 3 (a combination of the W3 correlation and GE design limit) indicated a very similar result to that observed using option 2 alone, except for the period from initiation to ~ 0.1 s. For this period the W3 correlation was evidently selected as appropriate.

- The Macbeth correlation (option 4) indicated the onset of transition boiling at ~ 0.02 s and the onset of stable film boiling at ~ 0.7 s. During the period 0.02 to 0.7 s the surface area over which transition boiling appeared to be present varied considerably. For most of this period, between 30 and 40 per cent of the fuel pin surface appeared to be in the transition boiling regime, but at ~ 0.3 s, this was reduced to ~ 5 per cent. As a result the maximum surface temperature, after initially rising quite rapidly during the first 0.1 s, decreased slightly to a minimum at ~ 0.3 s before again rising rapidly.
- The Barnett correlation (option 5) and the modified Barnett correlation (option 9) produced very similar temperature responses to those of the Macbeth correlation with the exceptions that (i) during the transition boiling period the surface area, over which it appeared to be operative, did not contract in size before film boiling, and (ii) stable film boiling appeared to be present after ~ 0.5 s.
- Use of the Becker correlation (option 6) caused the maximum cladding surface temperature to (i) rise more rapidly from 0.0 to 1.0 s of the transient than any other option, and (ii) reach a maximum value which was ~ 150-200°F higher than those predicted by other options. Transition boiling commenced at ~ 0.01 s and was axially extensive. Stable film boiling appeared to be present after ~ 0.5 s.
- Option 7, which is a combination of the W3 and Barnett correlations, indicated that whilst the W3 correlation was used from 0.0 to 1.0 s of the transient, thereafter the Barnett correlation was used to predict the CHF. The net result on the maximum cladding surface temperature was that a significant rise was delayed until ~ 1 s had elapsed and subsequent temperatures were ~ 200°F less than those indicated by option 5.
- Use of options 8 and 10 produced almost identical results. This was to be expected since the Babcock and Wilcox (B&W2) correlation which is used alone in option 8, is also the chosen correlation in option 10 for system pressures greater than 1500 psia, i.e. up to ~ 1 s. The B & W2 correlation indicated that transition boiling appeared very briefly between

0.08 and 0.09 s but that, apart from this, nucleate boiling applied until ~ 0.5 s had elapsed. Transition boiling then applied, followed at 0.9 s by stable film boiling.

Examination of the effect of choice of the independent CHF correlations (i.e. options 1, 2, 4, 5, 6 and 8), on predicted maximum surface cladding temperature, showed that significant variations in response occur during the first 4 s of the transient and that there is a wide range in the predicted values of maximum surface temperature. If the W3 correlation is ignored as invalid, then the maximum surface temperature ranged between ~ 1420°F and ~ 1100°F, a difference which represents nearly 50 per cent of the total maximum temperature rise.

Flow Film Boiling Options As has already been mentioned, for the inlet coolant conditions being considered, the flow film boiling regime appeared to be the most significant regime during the blowdown phase of a hot-leg LOCA in a PWR system. The calculations indicate that at the axial position corresponding to the maximum cladding surface temperature, the flow film boiling regime applied for more than 14 of the first 15 s, i.e. after the initiation of dryout and the subsequent transition boiling, flow film boiling became established and, apart from predictions using the W3 CHF correlation, continued for the next 14 s.

It would therefore be expected that differences among flow film boiling correlations would have a significant effect on the maximum cladding surface temperature response. As Figure 7 shows, this was, in fact, the case. However, whilst the Dougall-Rohsenow correlation (option 1) predicted temperatures ~ 300°F less than those predicted by the Miropolskii correlation (option 2), the predictions of options 2 and 3 (the Groeneveld correlation) were similar.

4.1.2 Coolant inlet mass flux

A limited investigation of the effect of inlet mass flux variation on maximum cladding temperatures indicated that changing the mass flux variation from that shown in Figure 2a to that shown in Figure 2b increased maximum cladding temperatures by ~ 200°F (see Figure 8). From this observation it would appear that, if stable film boiling conditions become established early in the transient (i.e. at ~ 0.5 s) and superheated steam conditions do not prevail (as could occur with reversed flow or effectively zero flow conditions) the mass flux response, although affecting the maximum cladding temperatures to some extent, must be varied quite markedly to have a significant effect.

4.2 Maximum Tube Temperatures in a Blowdown Experiment using a Water-cooled Heated Tube

The work reported by Hicken *et al.* [1972] has been chosen as an example of an experiment aimed at investigating the heat transfer processes occurring during blowdown by using a uniformly heated, thin-wall tube test section. The information reported is limited but appears to be adequate for an initial sensitivity analysis. In addition to dimensional details on which a model can be based to investigate the sensitivity of predicted values of maximum tube temperature to various heat transfer correlations and regimes, the work by Hicken *et al.* provides enough experimental details to enable comparisons between predicted and experimental values of maximum tube temperature.

4.2.1 Optional choices within THETA1-B

CHF Options The inlet flow conditions of Figures 3 and 4, which correspond to the experimental blowdown conditions, show that the choice of CHF correlation from the options included in THETA1-B can have a significant effect on predicted maximum tube temperature; this can be seen from Figure 9. However, before the details of the temperature responses shown on Figure 9 are discussed, it should be noted that not all of the options available in THETA1-B are independent for the experimental conditions being considered. For example, option 3 gave the same results as option 2 since mass exit qualities were greater than 0.15 at the time when dryout was predicted. (This option chooses the smaller of the W3 and GE values for qualities $\leqslant 0.15$ and the GE design limit for qualities > 0.15.) In the case of option 7, since the pressure was always less than 1500 psia, the Barnett correlation (option 5) was selected instead of the W3. Similarly, for option 10 because the pressures were always within the range 1300 psia to 725 psia, it gave the same results as option 9. Options 3, 7 and 10 therefore need not be considered any further since they gave results identical to those of options 2, 5 and 9 respectively.

Figure 9 shows that substantially different temperature transients were predicted for the various correlations. In brief, the results can be summarised as follows.

For options 4, 5 and 9 (i.e. the Macbeth, Barnett, and modified Barnett correlations respectively) transition boiling was predicted at ~ 1.2 s, which was immediately followed by stable film boiling. The differences among the predicted maximum tube temperatures which did arise when these correlations were used resulted from the correlations' prediction of stable film boiling conditions at different locations and at different times in the transient. Figure 9 shows for the three options, the differences were ⩽ ~ 60°F, which is within ~ 10 per cent of the rise in the maximum tube temperature occurring in the transient.

For options 1, 2, 6 and 8, forced convection vaporisation conditions were established at ~ 1.3 s.

The W3 correlation (option 1) predicted high CHF values and dryout conditions were not reached. However, the coolant was predicted to have exit mass fractions > 0.15 during much of the transient, so this was not a valid application of this correlation.

Use of the GE design limit (option 2) indicated that dryout occurred at ~ 1.6 s and the results indicated that after 3 s progressive rewetting was taking place.

Use of the Becker correlation (option 6) indicated that the transition boiling regime was reached only briefly (between 1.8 and 2 s), followed by rewetting.

Use of the B & W2 correlation (option 8) indicated that dryout occurred at ~ 2 s followed by stable film boiling conditions except for brief changes to transition boiling at ~ 3, ~ 5 and ~ 6 s.

All of the CHF correlations included in THETA1-B are intended to apply to rod bundles or annuli. However, the basic form of each of these correlations had been obtained from a corresponding round tube CHF correlation and their use here has only been to establish whether choice of CHF correlation influenced the predicted maximum surface temperature response.

In an attempt to investigate the different temperature responses produced by choice of CHF correlation, the BACE code [Chapman 1977] was used to determine, at appropriate coolant and geometrical conditions, the relationship between predicted CHF and mass flux for four of the options investigated. As can be seen on Figure 10, this showed that there were significant differences among the predictions from the four correlations considered. However, it must be emphasised that these differences are only valid for the fluid and geometrical conditions stated on Figure 10 and that at, say, a different coolant pressure the relationship among the four correlations could be quite different.

Flow Film Boiling Options As has already been discussed, the choice of CHF option in THETA1-B can have a significant influence on predicted maximum tube temperature response and on the stability of post dryout conditions. For the flow conditions given in Figures 3 and 4, the experimental data of Hicken *et al.* [1972] indicate that after ~ 1.1 s post dryout conditions applied. Consequently the Barnett CHF correlation (option 5) was chosen when the effect of choice of flow film boiling correlation on maximum tube temperatures was being assessed, although, as Figure 9 shows, CHF options 4 and 9 would have been equally suitable.

Results shown in Figure 11 indicate that the calculated surface temperature response is sensitive to choice of flow film boiling correlation. This is because the flow film boiling regime is predicted as being present at the position of maximum surface temperature almost immediately after the onset of dryout and, thereafter, until the end of the test period (~ 10 s). Maximum surface temperatures are thus a direct indication of differences in these correlations.

Also shown in Figure 11 are comparisons of theoretical predictions with interpolated experimental data. Here, for the conditions and correlations used, good agreement occurs between measured and predicted temperature responses in the early part of the transient, but as time progresses a widening disagreement appears, with predicted values significantly below measured values.

4.2.2 Transition boiling

Using the Barnett CHF correlation, the Miropolskii film boiling correlation, and the inlet flow conditions shown in Figures 3 and 4, a limited investigation was made to examine the effect on tube temperature response of varying the method of application of the McDonough *et al.* correlation for transition flow boiling. As one variation, the pressure dependent constant in the correlation was increased by an arbitrary factor of 10 thereby shortening the duration of the regime. As another variation in mathematically modelling the transition boiling regime, the McDonough *et al.* correlation was replaced by an equation stating that the heat flux during transition boiling was equal to the CHF, which increased the period during which transition boiling would apply. These investigations showed that, although increasing the pressure dependent factor had little influence on the temperature response, equating the transition heat flux to that of the CHF did considerably reduce maximum tube temperatures during the period 1.1 to 2.5 s, and thereafter predicted a return to nucleate boiling conditions. Maximum tube temperatures were predicted to rise to a maximum value of ~ 650°F at 2 s and then return to a fairly constant value of ~ 550°F.

It appears therefore that the influence of transition boiling on maximum tube temperature can be very significant if the stable film boiling regime does not become established.

4.2.3 Coolant inlet mass flux

The influence of coolant inlet mass flux on maximum tube temperatures was investigated by using the mass flux variation shown on Figure 4 and considering flow regime correlations which predicted a maximum tube temperature response in reasonable agreement with experimental data, and then changing the inlet mass flux behaviour to the hypothetical cases (1) and (2) on Figure 5.

As expected these hypothetical mass fluxes caused higher values of maximum tube temperature to be predicted, as Figure 12 shows. From this figure it can be deduced that if an accurate comparison is to be made between a theoretically predicted maximum tube temperature response and experimental data, the variation of inlet mass flux with time is important information. However, note that the temperature changes shown on Figure 12 resulted from quite radical changes in mass flux.

5. CONCLUSIONS

5.1 Prediction of Maximum Fuel Cladding Temperature for the Blowdown Phase of a LOCA in a PWR System

Investigations to determine the sensitivity of fuel pin temperature responses to various correlation options, in a LOCA involving the double-ended rupture of an outlet pipe of a PWR, indicate that determination of critical heat flux and heat transfer coefficients for flow transition boiling and flow film boiling regimes are the most important factors. Pool boiling regimes or superheated steam conditions were not relevant at any time during the transient period studied.

In brief, the conclusions were that:

- if the results predicted by the W3 correlation are ignored (since application of this correlation is invalid for important periods during the transient), choice of CHF correlation produces a variation in predicted maximum surface temperatures which represents ~ 50 per cent of the total maximum surface temperature rise;

- choice of flow film boiling correlation indicated that, although the Miropolskii and Groeneveld correlations predict similar maximum surface temperatures, the Dougall-Rohsenow correlation predicts maximum temperatures of up to ~ 300°F less than those predicted by the other two correlations, a difference representing ~ 40 per cent of the total maximum cladding surface temperature rise; and
- different coolant inlet mass flux variations significantly affect the predicted surface temperatures.

5.2 Prediction of Maximum Tube Temperatures in a Blowdown Experiment with a Water-cooled Tube

To complement the above investigation, a similar study for a water-cooled, electrically heated tube was conducted and showed:

(1) choice of CHF correlation can significantly affect the calculated maximum temperature response and cause re-establishment of predryout coolant conditions to be predicted in the later part of the transient. (Note however, that all of the CHF correlations included in THETA1-B relate to rod bundles or annuli and not to single tubes. Furthermore, in the case of the W3 correlation, use of the correlation was invalid since the predicted mass fractions were greater than 0.15 for much of the period of the transient, and the correlation is not recommended for such conditions.);

(2) choice of flow film boiling correlation has a significant influence on calculated values of maximum tube temperature, resulting from the fact that during the greater part of the transient, flow film boiling coolant conditions obtain with the consequence that differences in predicted temperatures were closely related to variations in correlations. (For the correlations and conditions considered, the maximum variation in maximum tube temperature was ~ 150°F, i.e. ~ 25 per cent of the total rise in maximum tube temperature for the transient period considered.);

(3) as with some CHF correlations, the mathematical expression used to describe transition boiling can produce a marked variation in predicted thermal performance by indicating the re-establishment of predryout conditions after the onset of dryout; and

(4) coolant inlet mass flux, as expected, significantly influences predicted tube temperatures. (For the conditions investigated, variations in maximum tube temperature of ~ 150°F were obtained.)

Consequently it may be concluded that, when comparisons are being made between predicted and measured temperature responses for an experimental configuration of the type described by Hicken *et al.* [1972],

- reliable information on coolant mass flux variation is required to enable a reasonably accurate maximum surface temperature response to be predicted, and
- choices of steady state CHF correlation, flow film boiling correlation and model (or correlation) to describe transition boiling can have significant effects on predicted temperatures.

5.3 Comparison of the Thermal Responses of a PWR Fuel Pin and a Uniformly Heated Thin-wall Tube Subjected to a Hot-leg LOCA

With a PWR fuel pin the power generated within the fuel is non-uniform and the thermal capacity of the fuel pin is not insignificant. Nevertheless, it has been found that the heat transfer regimes which are most significant when predicting maximum surface temperatures during a hot-leg LOCA involving a double-ended rupture of an outlet pipe, are the same as those for an experimental hot-leg LOCA involving a thin-wall, uniformly heated tube, i.e. transition flow boiling and flow film boiling, together with the prediction of CHF conditions.

A comparison of the maximum surface temperature responses of the two systems shows, however, that with the experimental assembly the CHF was not reached until 1.2 s had elapsed, whereas in the reactor case it was attained in milliseconds. Further consideration of the transient responses also shows that the maximum cladding temperature of the fuel pin was predicted as occurring between 1 and 3 s after initiation of the break, whereas in the experimental configuration surface temperatures appeared to be still rising after 10 s. This difference in temperature responses cannot be attributed simply to differences in mass flux variations since (i) in the reactor case, for both the mass flux variations investigated, the maximum surface temperature remained generally constant over the period 5 to 11 s with only small oscillations in its magnitude (corresponding to the variations in mass flux shown in Figure 2a); and (ii) in the experimental case the mass flux was essentially constant at ~ 20 per cent full flow between 6 and 10 s but the surface temperature steadily increased with time. Neither can the difference be attributed to differences in power generation since in both cases, after ~ 2 s, this parameter was constant at ~ 10 per cent full power. It may be inferred therefore that, although the thermal capacity of the fuel pin, and its non-uniform heat generation are substantially different from those of the heated tube, they do not change the significance of the heat transfer regimes in each system, but influence the actual magnitude and shape of the temperature responses predicted.

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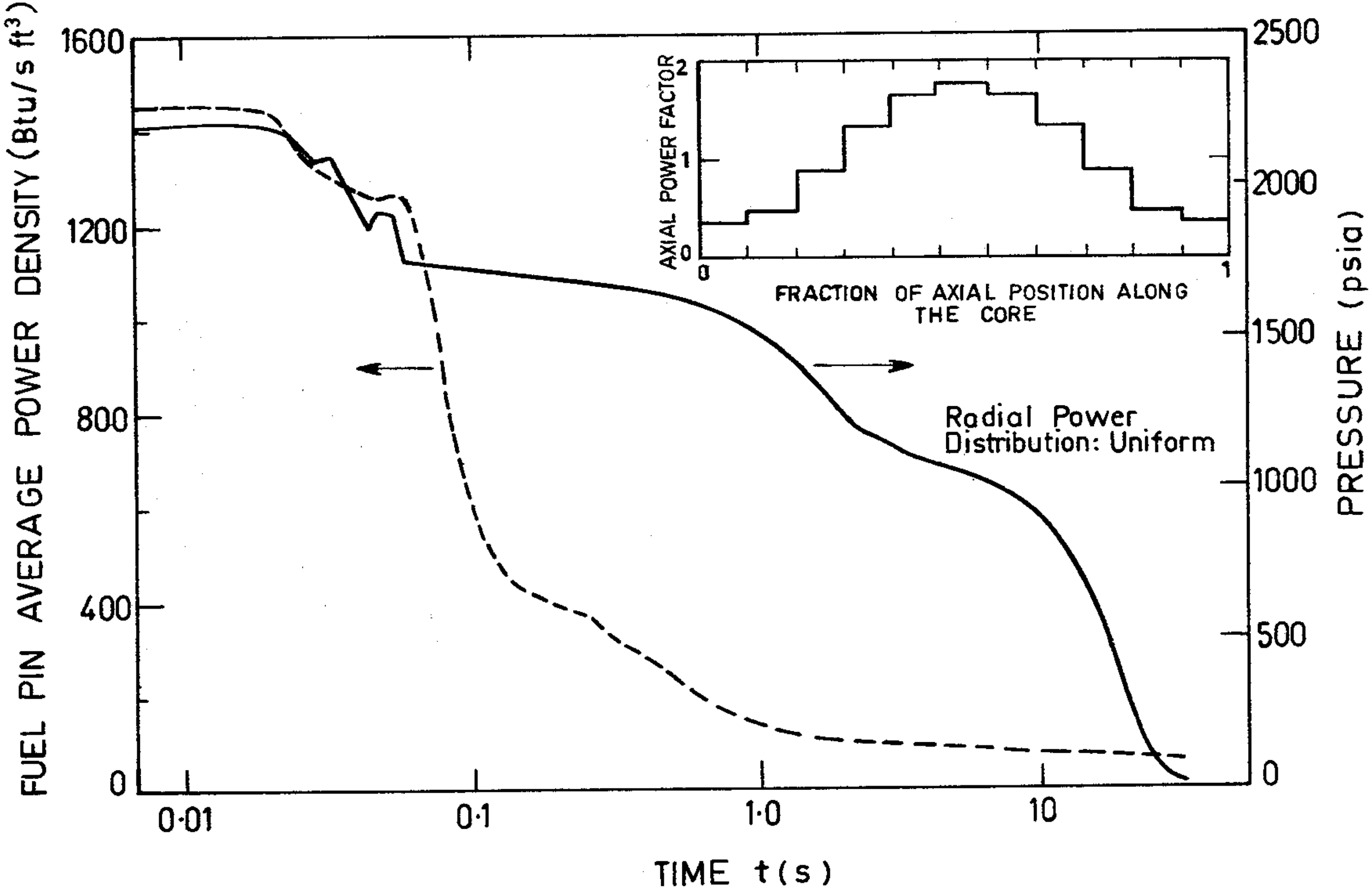


FIGURE 1. TYPICAL PWR CORE CONDITIONS DURING A LOCA

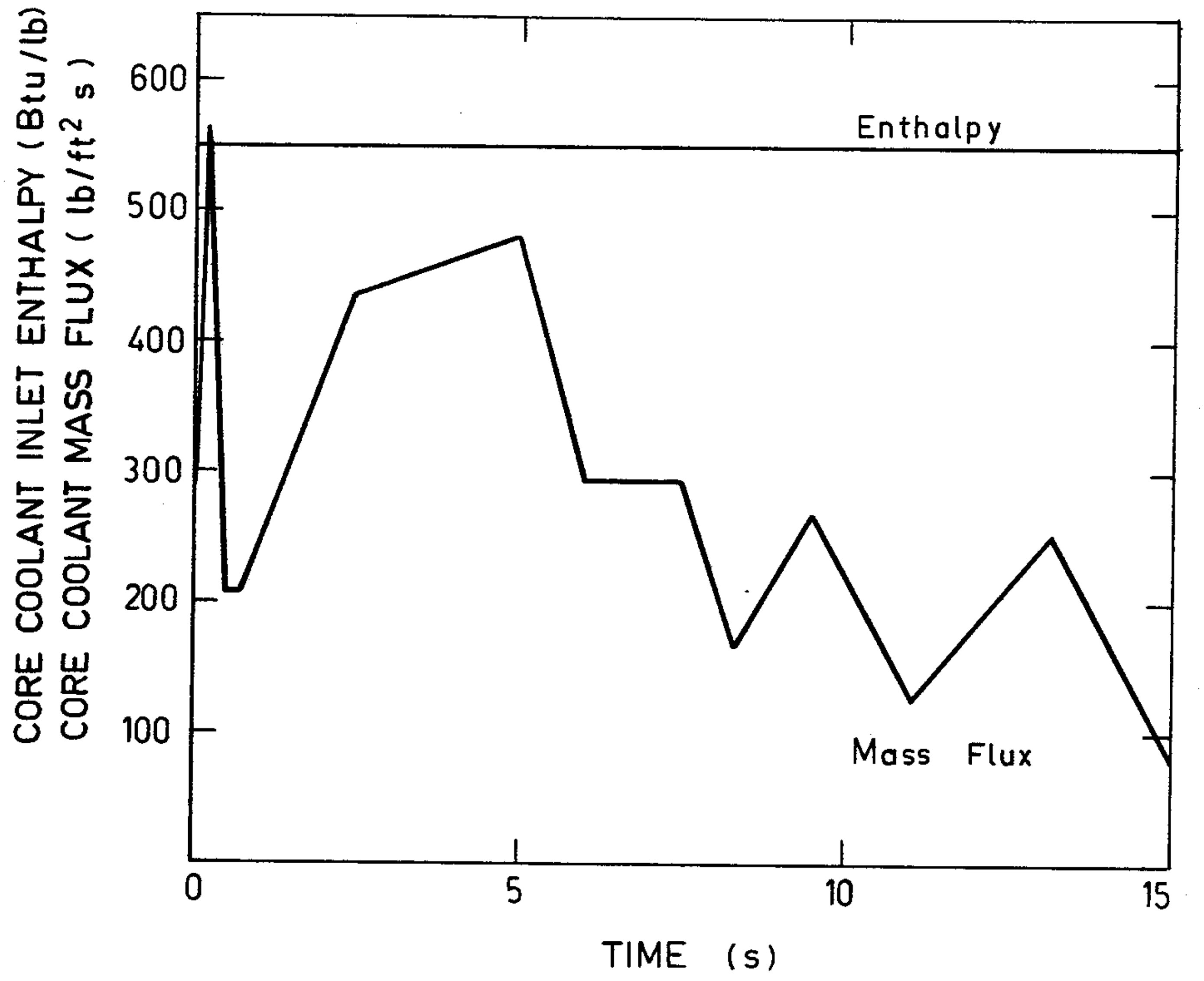


FIGURE 2a. CORE COOLANT FLOW CONDITIONS IN A PWR SUBJECTED TO A HOT-LEG LOCA (ADAPTED FROM ZANE 1975)

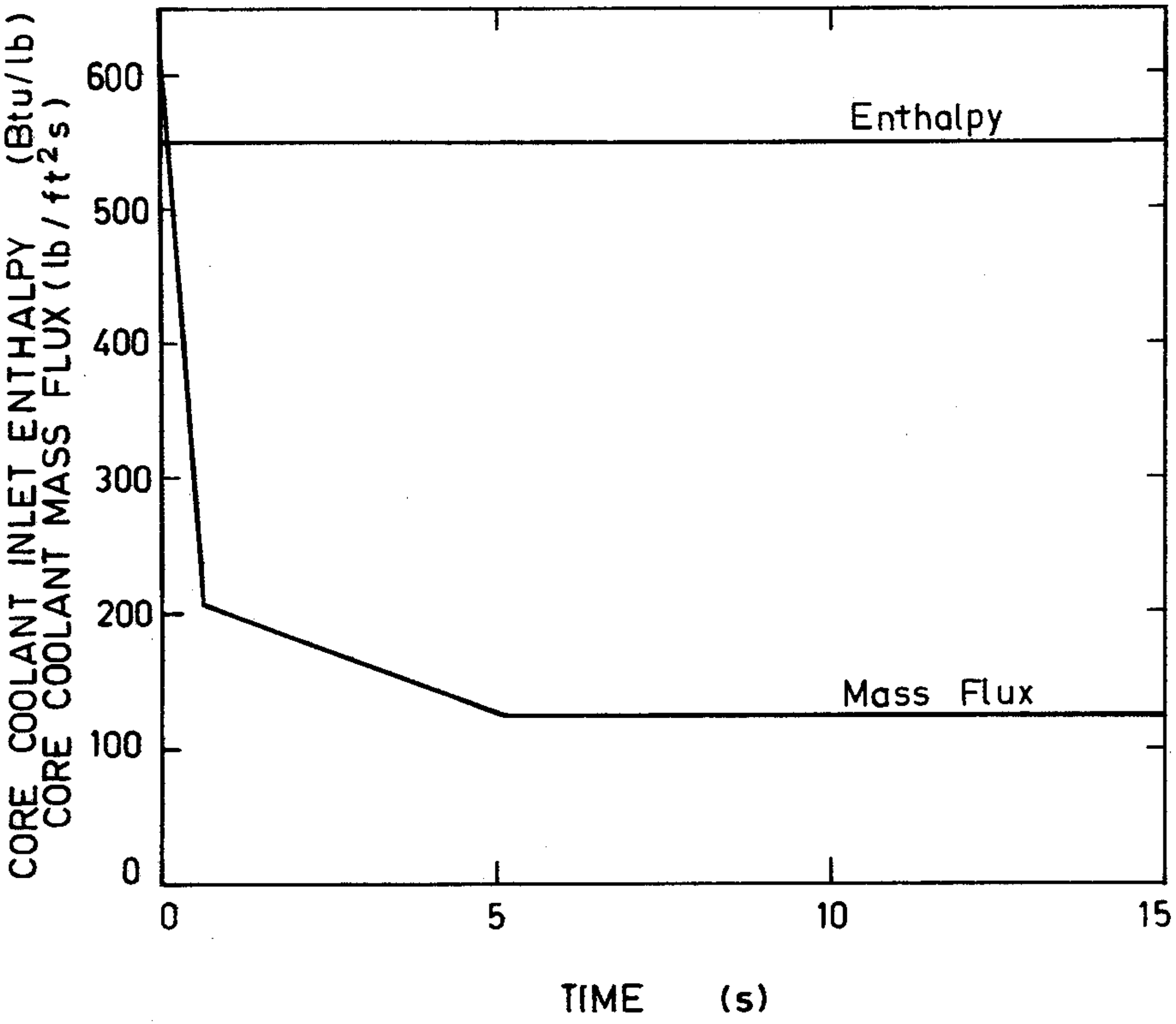


FIGURE 2b. HYPOTHETICAL CORE COOLANT FLOW CONDITIONS IN A PWR SUBJECTED TO A HOT-LEG LOCA

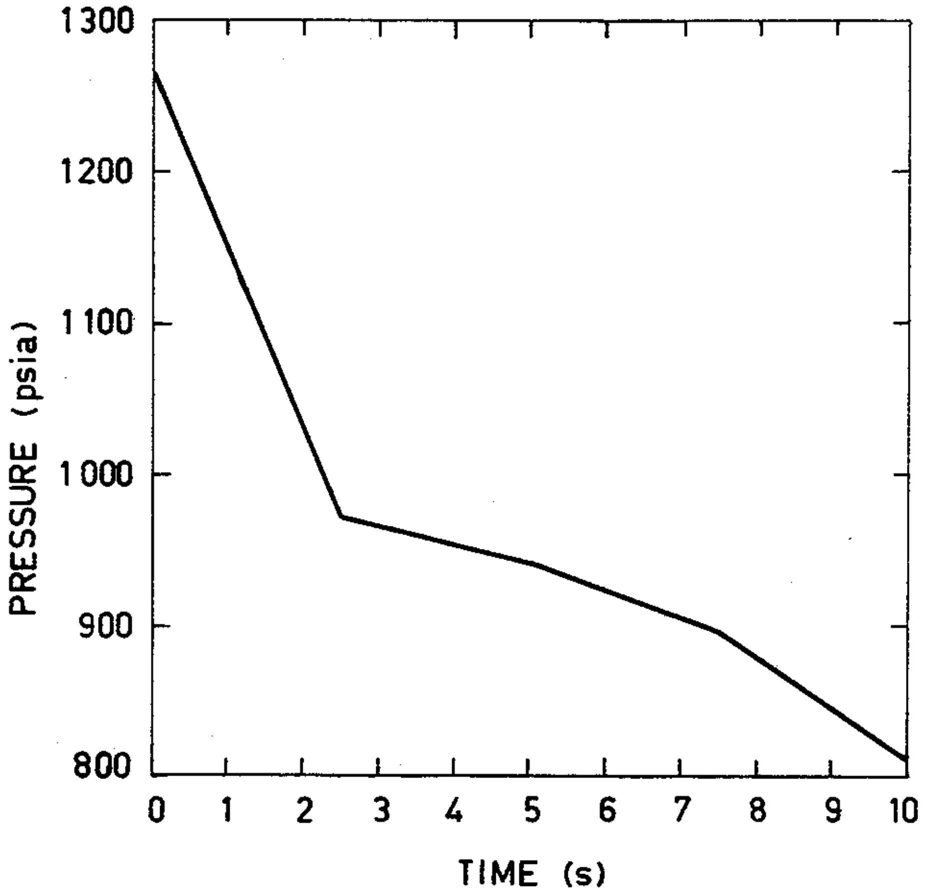


FIGURE 3. PRESSURE RESPONSE DURING A HOT-LEG BREAK BLOWDOWN EXPERIMENT USING A THIN-WALL TUBE

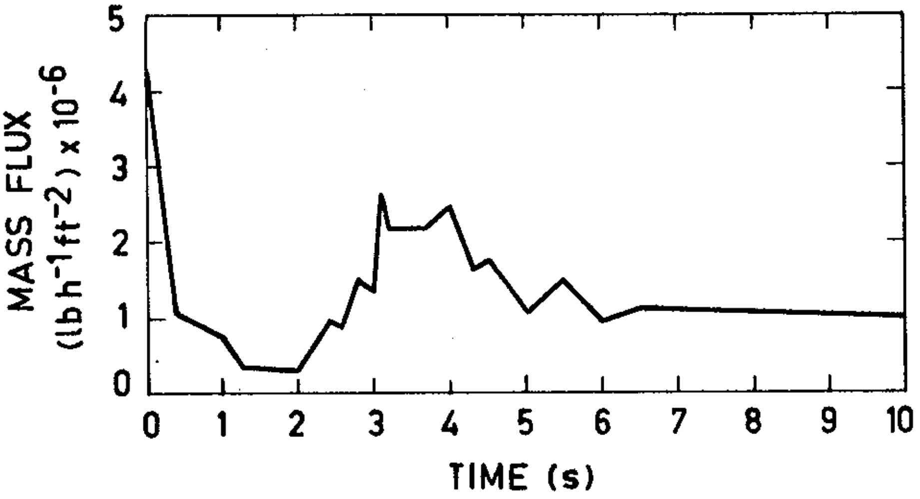


FIGURE 4. ESTIMATED MASS FLUX RESPONSE DURING A HOT-LEG BREAK BLOWDOWN EXPERIMENT USING A THIN WALL TUBE

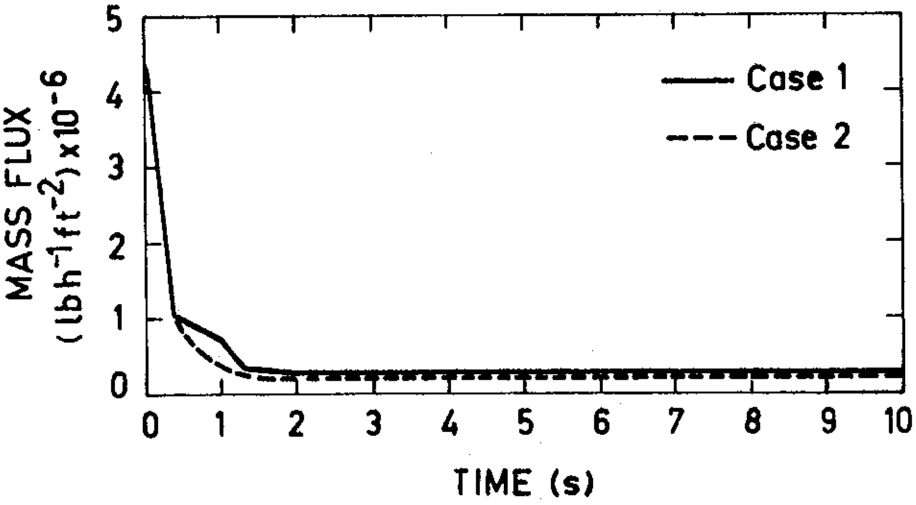
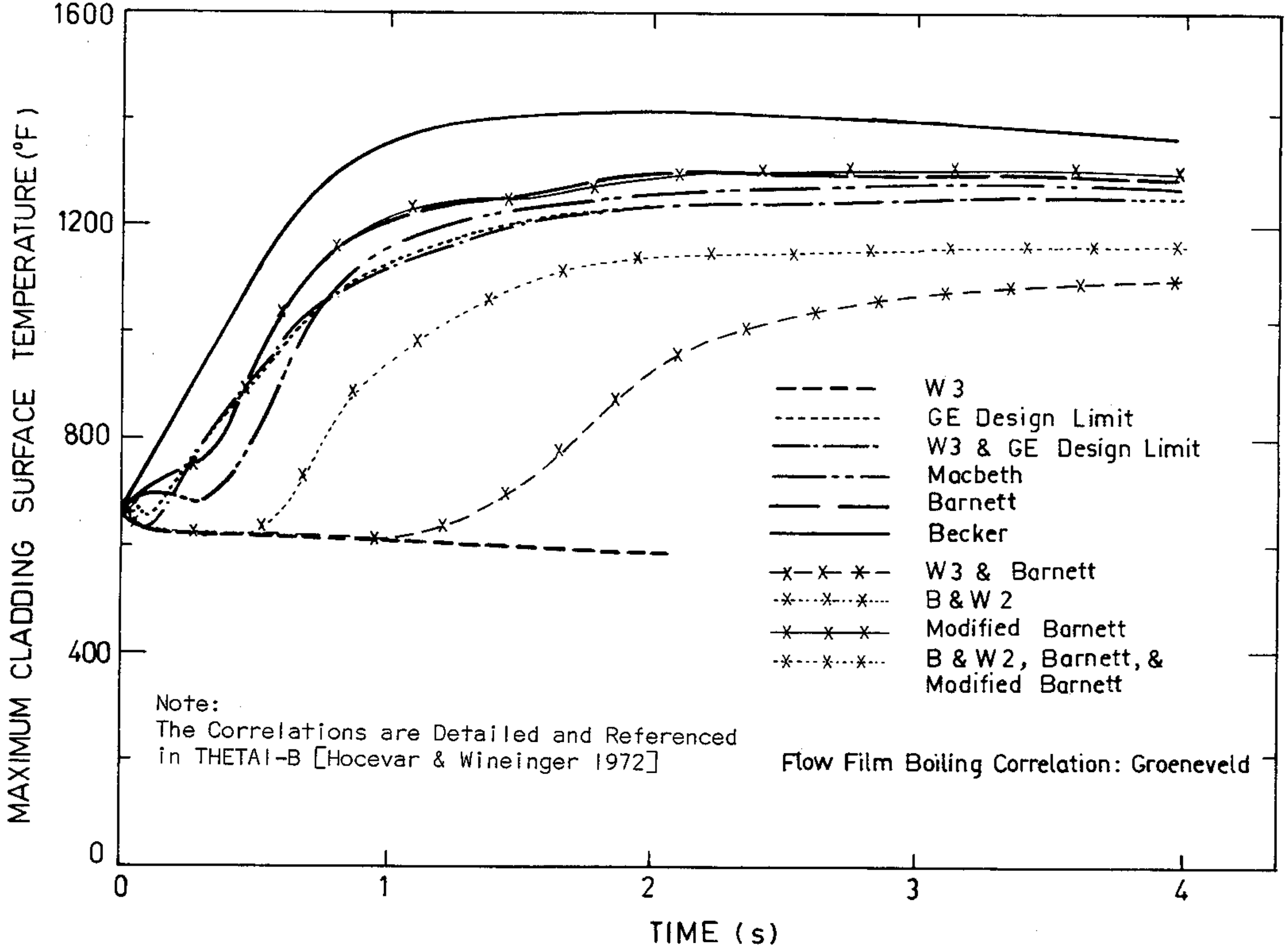


FIGURE 5. HYPOTHETICAL MASS FLUX RESPONSES DURING AN EXPERIMENTAL BLOWDOWN



Note:
The Correlations are Detailed and Referenced in THETA1-B [Hocevar & Wineinger 1972]

Flow Film Boiling Correlation: Groeneveld

FIGURE 6. EFFECT OF CHOICE OF CHF CORRELATION ON MAXIMUM CLADDING SURFACE TEMPERATURE

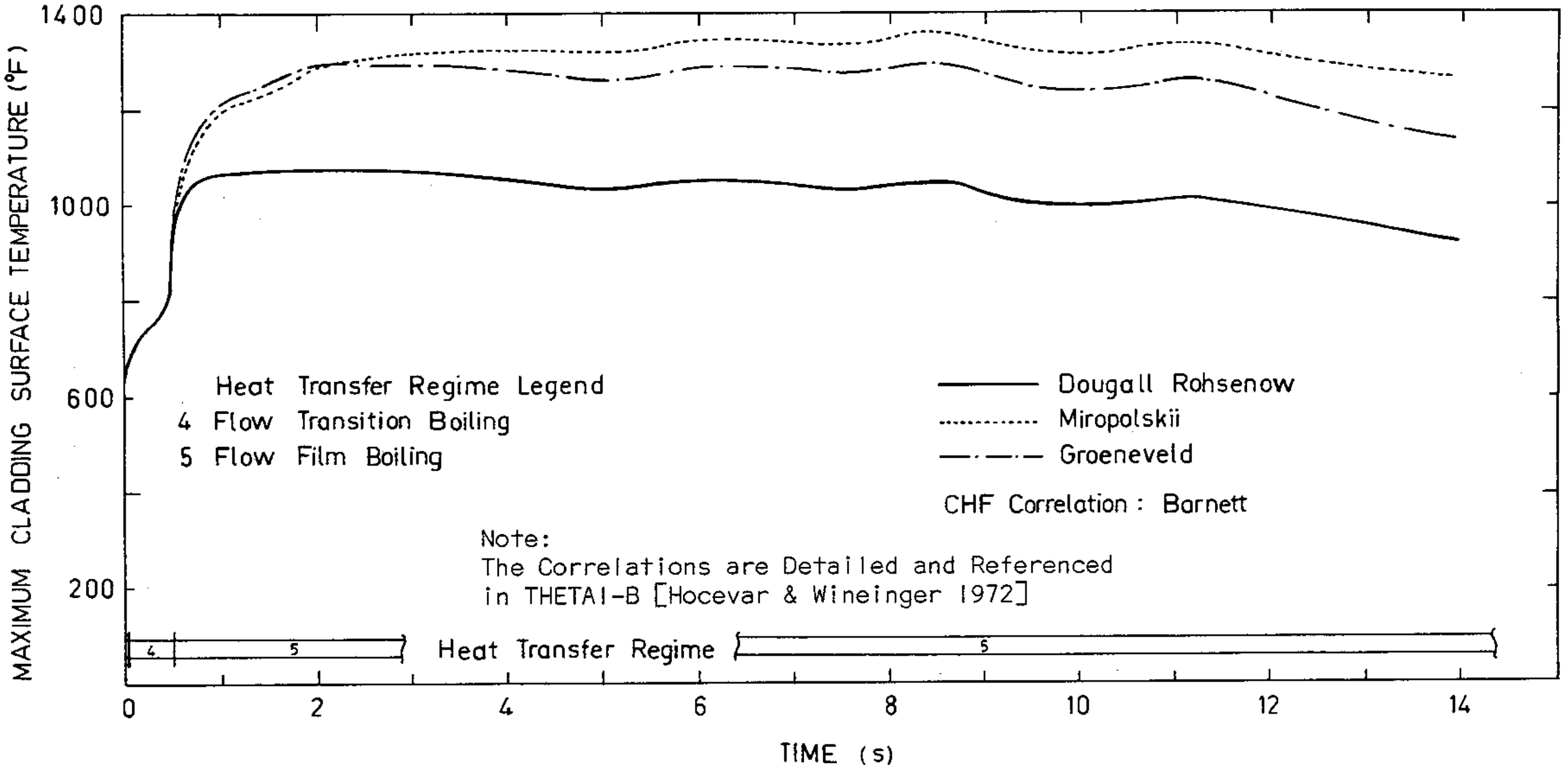


FIGURE 7. EFFECT OF CHOICE OF FILM BOILING CORRELATION ON MAXIMUM CLADDING SURFACE TEMPERATURE

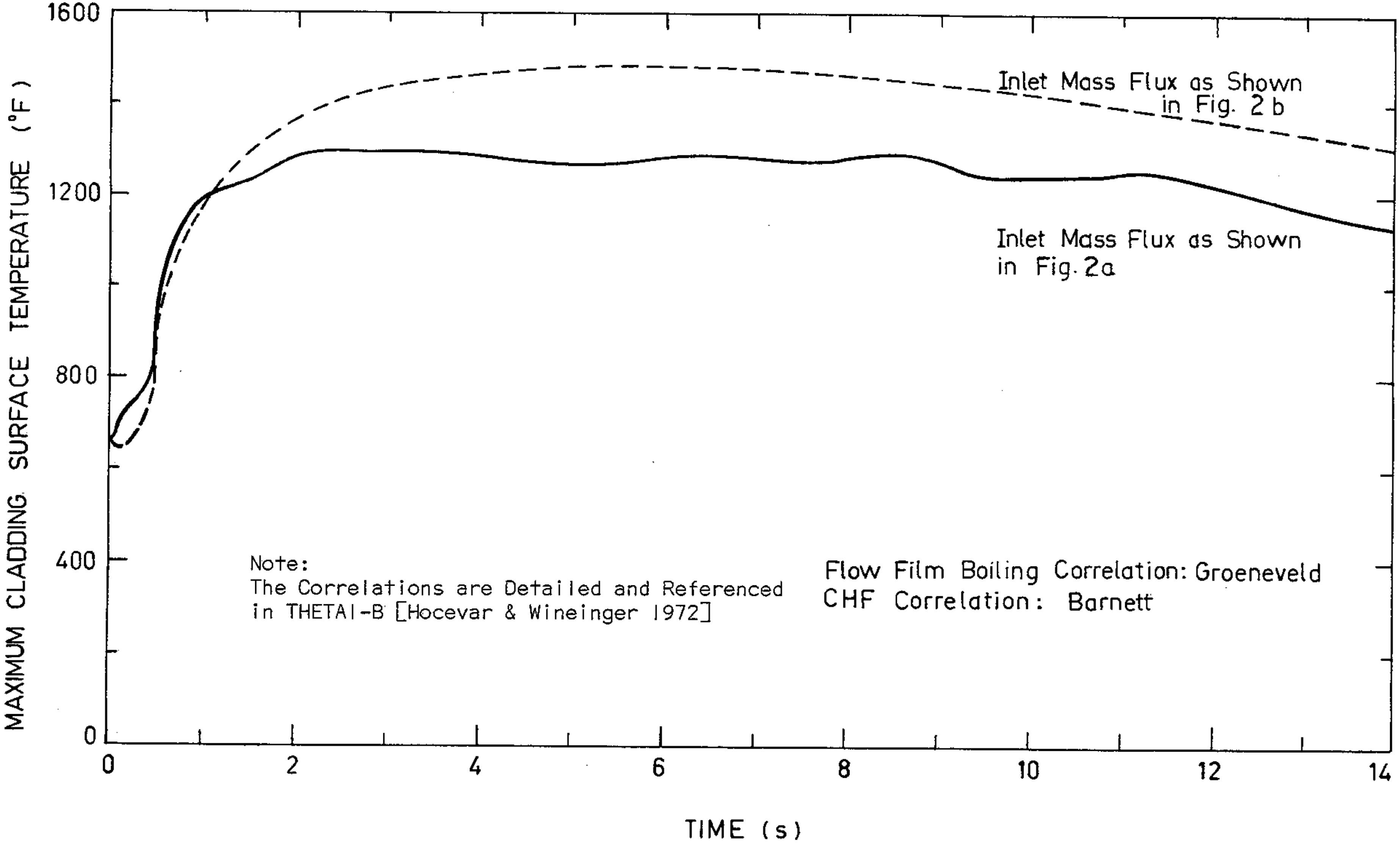


FIGURE 8. EFFECT OF MASS FLUX RESPONSE ON MAXIMUM CLADDING SURFACE TEMPERATURE

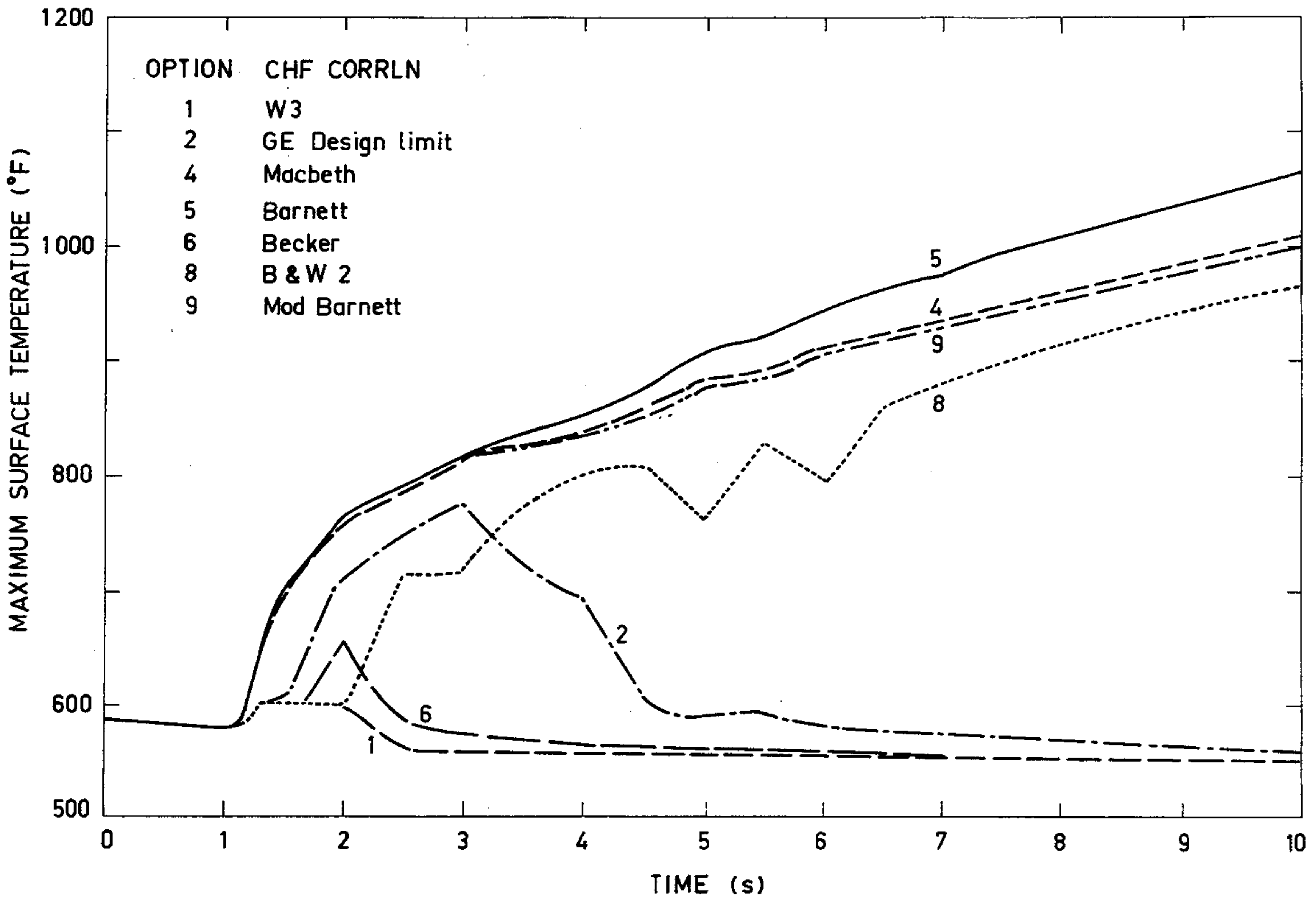


FIGURE 9. EFFECT OF CHOICE OF CHF CORRELATION ON MAXIMUM SURFACE TEMPERATURE OF AN ELECTRICALLY HEATED TUBE

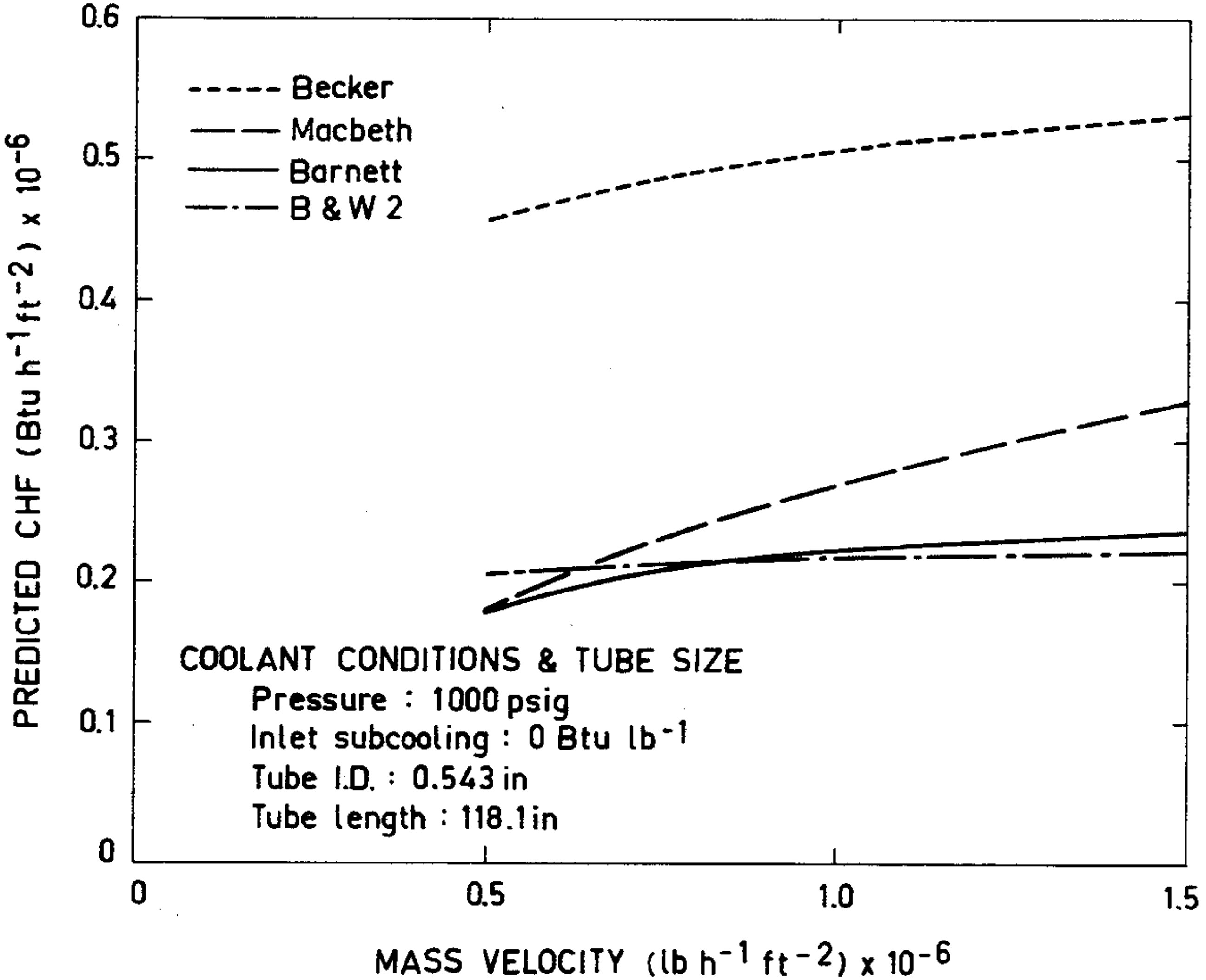


FIGURE 10. RELATIONSHIP BETWEEN MASS VELOCITY AND CHF PREDICTED BY CORRELATIONS INCLUDED IN THETA1-B FOR A UNIFORMLY HEATED TUBE

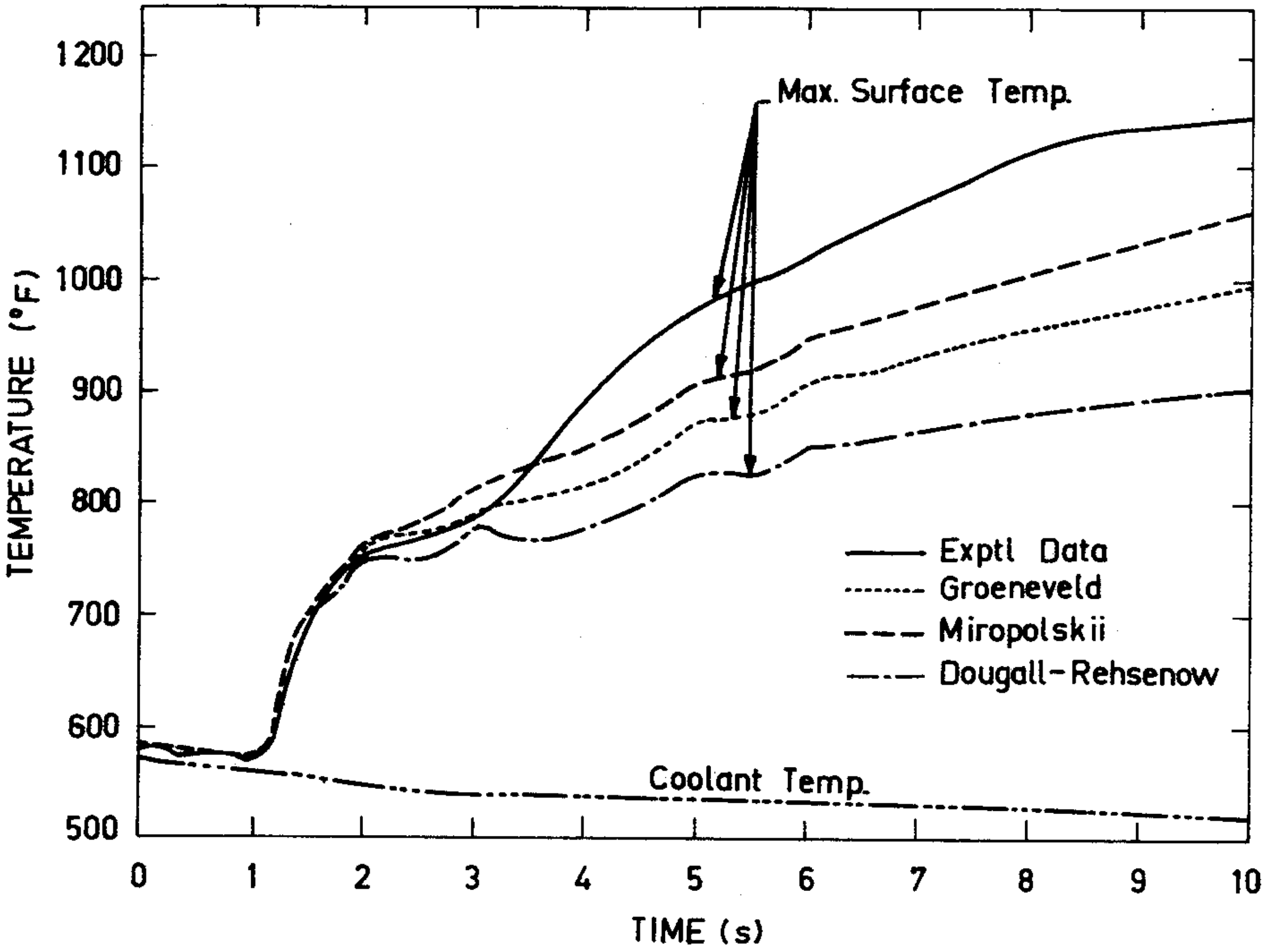


FIGURE 11. EFFECT OF CHOICE OF FILM BOILING CORRELATION ON MAXIMUM SURFACE TEMPERATURE OF AN ELECTRICALLY HEATED TUBE

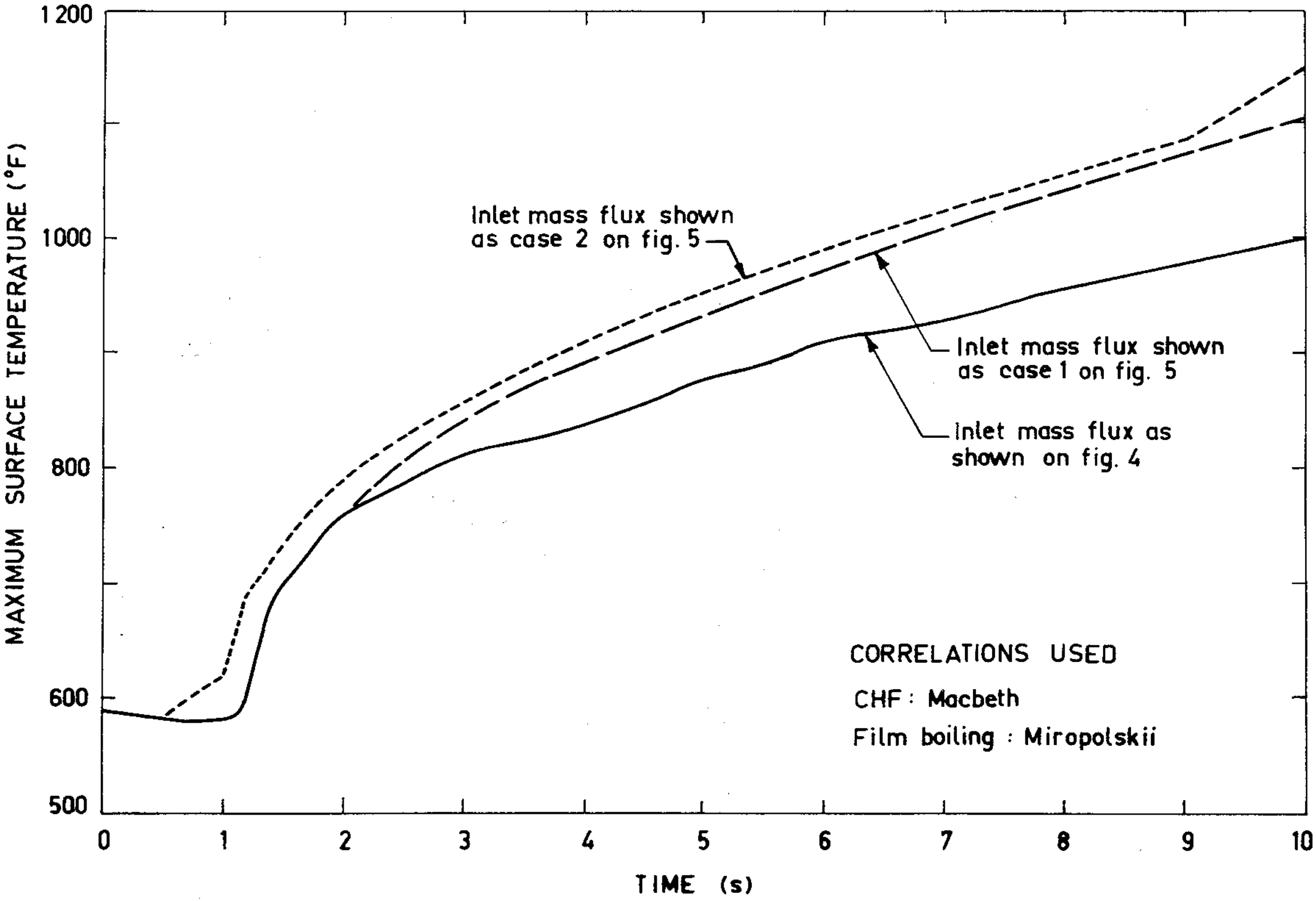


FIGURE 12. EFFECT OF INLET MASS FLUX ON MAXIMUM SURFACE TEMPERATURE OF AN ELECTRICALLY HEATED TUBE