ANALYSIS OF EFFECTS OF CALANDRIA TUBE UNCOVERY UNDER SEVERE ACCIDENT CONDITIONS IN CANDU REACTORS

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INTRODUCTION

A study is being undertaken for the Atomic Energy Control Board to assess the thermal and hydraulic behavior of CANDU reactor cores under accident conditions more severe than those normally considered in the licensing process (1,2). The objective of the study is to provide AECB with increased knowledge on the safety of CANDU reactors, in particular on the possible consequences of severe accident sequences so as to assist in establishing more comprehensive assessments of risk to the public and to facilitate examination of licensing submissions.

At the time of writing, the study has not been completed, but some significant results have been obtained and considerable insight into severe accident sequences has been gained. In this paper, we consider the effects on a coolant channel of the uncovery of a calandria tube by moderator boil-off following a LOCA in a Bruce reactor unit in which emergency cooling is ineffective and the moderator heat sink is impaired by the failure of the moderator cooling system. Calandria tube uncovery and its immediate consequences, as described here, constitute only one part of the entire accident sequence. Other aspects of this sequence as well as results of the analysis of the other accident sequences studied will be described in the final report on the project and in later papers.

Of course, it must be recognized that the behavior of core components under the extreme conditions considered in this study is in general quite speculative since little experimental information on core component behavior under these conditions is available. However, the approach used has been to model physical behavior of the core components and moderator on a fundamentally-sound basis and to provide flexibility in the computer programs. This flexibility will enable the sensitivity of the core behavior to various assumptions to be established and will permit improvements in the analysis as more experimental information becomes available. Obviously, the analyses at this stage have considerable uncertainties associated with them so that the results must be treated with some caution.

METHOD OF APPROACH

In the initial stages of the project, considerable thought was devoted to the approach and methods to be used. Comprehensive studies of severe accident sequences in light water reactors, the Reactor Safety Study (Rasmussen Study) (3) in the USA and the German Risk Study (4) were used as guides in establishing the basic approach in the present investigation. However, this investigation was not intended to be a comprehensive study such as these; only a single type of accident was selected for study: a large Loss-of-Coolant Accident (LOCA). The study is confined to physical processes with no estimates of probabilities of event sequences being included.

An event tree, as shown in Figure 1, was developed to identify potential event sequences following the LOCA. The code used to identify events is defined in the Nomenclature. In Figure 1, the upper branch for an event or function indicates success, the lower branch, failure. In this event tree, the unique safety feature of CANDU reactors, the moderator heat sink (MHS) and cooling system (MCS), is recognized. Studies of severe accident conditions in CANDU reactors show that there will be no fuel melting even for a large LOCA combined with loss of emergency core-cooling (LOECC) provided that the moderator heat sink and the moderator cooling system are effective (5,6,7).

Accident sequence S1 in Figure 1 represents the conventional large LOCA single-failure (SF) accident, as analyzed in the Canadian licensing process, in which all special safety systems function as designed. In this sequence, MHS and MCS are not generally needed and therefore no options are shown for these systems.*

The dual failures considered in the licensing process analysis of LOCA plus containment impairment (CI) and LOCA plus LOECC are shown in accident sequences S2 and S9 respectively.

Failure of the moderator heat sink (e.g., by moderator coolant pipe rupture) makes the operation of the moderator cooling system irrelevant, so that no option is shown in Figure 1 for this event in the cases where MHS fails.

Two accident sequences shown in Figure 1 were selected for study: S11, loss of moderator cooling system (LOMCS) and S13, loss of moderator heat sink (LOMHS). In addition, a brief assessment was to be made of accident sequence S15, failure to shut down.

The study has been undertaken using a Bruce reactor unit to represent a typical CANDU reactor.

To investigate an accident sequence, a detailed and comprehensive analytical flow chart has been developed which identifies the various

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* In certain cases of LOCA's with early stagnation during blowdown, pressure tube ballooning may occur, which could require the moderator heat sink and cooling system to assist the emergency cooling system in providing adequate cooling of the fuel (5). This accident sequence has not been considered in the present study.

analytical steps required and relates them to each other. Such a chart is too long to be shown in its entirety in this paper, but the initial portion of the chart for accident sequence S11 is illustrated in Figure 2. The complete flow chart for accident sequence S11 is given in reference 2, together with a discussion of the various analytical steps. In all, there are 55 boxes representing separate analytical steps in the entire chart.

In this paper, as stated in the Introduction, we consider a key element in accident sequence S11, the effects on a coolant channel of the uncovery of a calandria tube by moderator boil-off caused by heat flow from the coolant channels to the uncooled moderator. The analytical methods used to characterize calandria tube uncovery in accident sequence S11 are also applicable to the same aspect of accident sequence S13. The major difference between calandria tube uncovery in the two cases is that uncovery will occur sooner, in general, in sequence 13 than in sequence 11.

DESCRIPTION OF ACCIDENT SEQUENCE

In the accident sequence considered here, it is assumed that the LOCA results in late stagnation during primary coolant blowdown with the result that, with failure of the emergency cooling function, the pressure tubes sag onto the calandria tubes (5,6). Contact between the tubes provides an effective heat flow path to the moderator heat sink which prevents fuel melting provided that the moderator cooling system functions properly (5,6,7). In the present case, it is assumed that the moderator cooling system also fails so that the moderator heats up and the calandria pressure increases until the rupture disks on the four calandria relief ducts break. The calandria pressure drops to that of the reactor building with no flashing of the moderator, as shown by the analysis. Continued heating of the moderator eventually causes it to begin boiling. As boiling continues, moderator is lost through the relief ducts in the form of vapor and as liquid entrained in two-phase flow through the ducts. Eventually, as the void fraction near the top of the calandria increases, the top row of calandria tubes will become uncovered, resulting in a rapid temperature rise of these tubes, now cooled mainly by convection and radiation to the steam generated by boiling of the moderator. Pressure tube and fuel temperatures, in consequence, will also increase. The temperature increase of the calandria tubes will be sufficient to initiate an exothermic chemical reaction between the Zircaloy tubes and the steam flowing over them.* This reaction will cause a further increase of calandria tube, pressure tube and fuel temperatures. Eventually, other rows of tubes will be uncovered and similar subsequent behavior will occur. In the study, the temperature histories of the components of fuel channels at various locations within the core under these conditions have been determined so as to establish the likelihood of calandria tube and pressure tube melting, or disintegration by other mechanisms, and the likelihood of fuel melting.

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* Results of the study show that Zircaloy-water reactions between steam flow in the fuel channel and the fuel sheaths and the pressure tube will have been completed by the time of calandria tube uncovery, even for the top row of tubes.

ANALYTICAL METHODS

The total heat source to the moderator in this accident sequence was determined by grouping fuel channels according to average powers into four groups and applying the IMPECC program (6,7,8) to each group to establish heat flows to the moderator as a function of time, for the case of pressure tubes sagging onto calandria tubes at a pressure tube temperature of 1000°C (1,2). Allowance was made for the heat generated within the channels by the exothermic Zircaloy-water reaction resulting from steam flow through the channels using information from Whiteshell Nuclear Research Establishment (9). Figure 3 shows the heat source resulting from this reaction for a steam flow rate of 12 gm/sec per channel, which results in the maximum temperature rises of the fuel sheaths and the pressure tube because of the Zircaloy-water reaction.

A computer program, MODBOIL, has been developed to analyze the thermal-hydraulic behavior of the moderator under these conditions. In MODBOIL, the moderator is divided into 24 horizontal slices, one for each row of calandria tubes. Transient heat balances are written for each slice for both sub-cooled and boiling conditions. The program calculates the pressure over the moderator at any time, the time of breakage of the rupture disks, the initiation and development of moderator boiling, the void fractions in each slice, the pressure distribution through the calandria, allowing for two-phase flow pressure losses in the relief ducts and from row to row and the rate of moderator expulsion from the calandria. MODBOIL also determines the time of effective uncovery for each row of calandria tubes. The criterion used for tube uncovery is the transition from churn-turbulent flow to mist flow in a volume-heated pool, as established by Ginsberg, et al. (10). As a tube row is uncovered, the heat source from that row to the boiling moderator is reduced to zero in MODBOIL. In addition, MODBOIL allows for heat source re-distribution from any channel row to the moderator in the bottom slice in the calandria. This feature models channel disintegration or melting after calandria tube uncovery. Because the mechanisms and extent of channel disintegration are not established, several options are available to enable the sensitivity of moderator thermal-hydraulic behavior to various assumptions and parameters to be established. Channel disintegration can be assumed to occur at an arbitrary time after calandria tube uncovery or can be assumed to take place when the maximum calandria tube temperature reaches approximately 1750°C, the melting point of Zircaloy.* The program also permits the fraction of disintegrated channel material in each row to be varied from 0 to 1, and permits a specified fraction of the disintegrated Zircaloy fraction to be molten at the moment of disintegration.** The program allows for the stored heat of the disintegrated material as well as the decay heat to be released into the moderator in the bottom slice, allowing for film boiling (and radiation) or nucleate boiling depending on the heat transfer conditions.

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* This disintegration condition is specified in the MODBOIL program using an empirical relationship deduced from a series of runs with IMPECC-UCZ for various uncovery times, steam flow rates and fuel element power ratings.

** The fuel material is assumed to remain solid, since, as we will see, its melting temperature is not reached in any of the cases considered.

Since the Zircaloy material in uncovered calandria tubes will be rapidly oxidized, and thus embrittled, another option in MODBOIL allows for the simultaneous disintegration of all uncovered rows should a row above them disintegrate. That is, uncovered rows can be assumed to disintegrate under the impact of disintegrating rows above them.

Finally, since there will be sudden surges of steam flow with entrained liquid flow through the relief ducts as disintegrated channels fall into the bottom slice, MODBOIL allows for two-phase choked flow from the relief ducts, and the resulting pressure surge in the calandria, as dictated by the flow conditions.

The thermal behavior of uncovered calandria tubes is established by using a modification of the IMPECC program, IMPECC-UCZ. In this modification, analysis for a given row of fuel channels proceeds in the normal fashion in IMPECC until the specified uncovery time, which is established from MODBOIL for the given row. From this time on, the calandria tube is assumed to be cooled only by convection and radiation to steam flowing over the tube, generated from the moderator surrounding the lower fuel channels.* In IMPECC-UCZ, the steam flow rate is assumed to be constant. Of course, actual steam flow rates will not be constant; MODBOIL results show that there is a general decrease of steam flow rate with time, but that sudden surges occur as uncovered channels disintegrate. Thus, a range of steam flow rates, established from MODBOIL runs, has been used in the study to determine the sensitivity of predicted results to steam flow rate. In IMPECC-UCZ, the steam temperature is also assumed to be constant. Again, the sensitivity of predicted results to a range of steam temperatures has been investigated.

IMPECC-UCZ incorporates equations to predict the heat generated by the Zircaloy-steam reaction as the temperature of an uncovered calandria tube rises rapidly. The reaction rate is controlled by either solid-state diffusion of oxygen through the Zircaloy or mass transfer of oxygen from the steam flow, whichever is slower. For solid-state diffusion, the rate equations of Urbanic and Heidrick (11) are used. For mass transfer from the steam, the analogy between heat and mass transfer together with Grimison's empirical equation for turbulent-flow heat transfer across a bank of cylindrical tubes arranged on an in-line pattern (e.g., 12) have been used in the program.

The Zircaloy-water reaction on the calandria tube is assumed to be complete when the complete tube thickness has been oxidized.

RESULTS

Heat Source to Moderator

Figure 4 shows the total heat flow rate to the moderator as a function of time established using IMPECC applied to the four groups of channels, as

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* Results obtained with MODBOIL show that the sudden surges of steam generated by disintegrated channels in the bottom slice of moderator result in considerable entrainment of liquid flow into the upper slices. In effect, the upper tube rows are re-covered with liquid for a short time. However, it is assumed that the calandria tubes are not rewetted under these conditions, since their temperatures are very high at these times.

discussed in the previous section. The peaks shown in the curve during the time that the heat source is increasing represent the rapid discharges of stored energy from the pressure tubes as those in each group sag onto the calandria tubes. Only three peaks are evident, instead of the four expected, because the first peak, being relatively small, was obscured in the computer plot. Figure 4 shows that the peak power to the moderator reaches about 88 MW some 18 minutes after the initial pipe rupture occurs. The power to the moderator drops to about 46 MW after 40 minutes. In MODBOIL, this total heat source is distributed amongst the channel rows, with the fission product decay heat contribution proportional to the average power in a given row.

Results for No Channel Disintegration

To study the behavior of the core under conditions considered here requires the re-iterative use of the programs MODBOIL and IMPECC-UCZ. Initial runs were made with MODBOIL, ignoring any channel disintegration, to establish ranges of uncovery times and steam flow rates to use in IMPECC-UCZ. These runs showed that steam flow rates gradually decreased with time after tube uncovery, as shown in Figure 5, for the case of no channel disintegration.

Initial runs were then made with IMPECC-UCZ, which assumes a fixed steam flow rate, for the top row of channels (row 1) for the uncovery time predicted from MODBOIL and for two steam flow rates, one the value at the moment of uncovery and one a lower value at a later time. Results are shown in Figure 6 for the maximum calandria tube temperature as a function of time. Figure 6 shows that higher peak temperatures of the calandria tube are predicted for the higher steam flow rate. It is apparent that, for these conditions, the Zircaloy-steam reaction rate must be controlled by mass transfer and that the heating effect resulting from the higher mass-transfer rate with the higher steam flow rate dominates the cooling effect resulting from the higher heat transfer rate under these conditions.* Later runs with IMPECC-UCZ have confirmed this behavior, as we will see.

Using the uncovery times predicted by MODBOIL with no channel disintegration, and the highest steam flow rates (at the moment of calandria tube uncovery) for each case, which will be conservative, IMPECC-UCZ runs were made for rows 4 and 12. These rows contain channels with the highest channel powers in the core, and the analysis has been done for the highest axial fuel element power rating (FEPR) in these rows under full-power pre-accident conditions, 40 W/cm.

Figure 7 shows that the predicted calandria tube temperatures in each row exceed for several minutes the Zircaloy melting temperature of about 1750°C, as is also the case for row 1 as shown in Figure 6. However, the situation is not as clear-cut as it appears. Calculations of the energy per unit mass of tube above the melting point in each case and comparisons with the latent heat of fusion of Zircaloy show that there is insufficient energy for complete melting of the calandria tubes. Also, the temperature transient oxidizes the tubes to ZrO_2. The melting point of ZrO_2 (~ 2700°C) is considerably higher than the calculated peak temperatures reached in the transient. The results

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* It is evident that the peak temperatures of the calandria tube reached in these transients are governed by the Zircaloy-steam reaction, since in runs with the Zircaloy-steam reaction rates set to zero, peak calandria tube temperatures follow approximately the lower dashed curve in Figure 6.

of the IMPECC-UCZ runs show that there will be considerable oxidation of the calandria tubes before their temperatures reach 1750°C in each case. Therefore, while some damage and partial melting of the calandria tubes in the higher power regions of a row is to be expected, it is not likely that there would be complete disintegration of all the channels in a row, particularly since the pressure tubes, which reach maximum predicted temperatures within a few degrees of those of the calandria tubes, will have already been oxidized by the internal steam flow before calandria tube uncovery.

Figure 8 shows the temperature histories of the hottest fuel elements in rows 1, 4 and 12 during the accident sequence for the same conditions* as those used to predict the calandria tube temperatures in Figures 6 and 7. In all cases, both the initial peaks, resulting from normal cooling by the moderator, and the second peaks, resulting from calandria tube uncovery, are well below the UO_2 melting temperature of about 2800°C. Therefore, for these conditions, no fuel melting would be expected if there is no fuel channel disintegration.

To explore further the sensitivity of the peak calandria tube and fuel temperatures to steam flow rate, several additional runs were made with IMPECC-UCZ for row 12. The results, shown in Figure 9, confirm that the predicted peak calandria tube temperatures increase with increasing steam flow rates up to steam flow rates of about 10^6 lb_M/hr. Figure 9 also shows that the peak fuel element temperature is very insensitive to steam flow rate and is well below the melting point of UO_2 over the entire range of steam flow rates investigated.

The sensitivity of the peak calandria tube and fuel temperatures to initial fuel element power rating and to steam temperature was also examined for a fixed steam flow rate. The results are again shown in Figure 9. The predicted peak calandria tube temperature is reduced by less than 100°C for an initial FEPR of 12 W/cm, the lowest value expected, in an outer bundle, for this row. Such an insensitivity to FEPR is to be expected since the peak calandria tube temperatures are governed mainly by the Zircaloy-steam reaction. The predicted peak calandria tube temperature is increased only about 150°C for an increase in steam temperature from 100°C to 300°C, so that peak calandria tube temperatures are also relatively insensitive to the assumed steam temperature. Thus, temperature rises of steam flowing over lower uncovered calandria tubes, which are estimated to be of the order to 200°C for typical conditions, will not significantly affect the predicted calandria tube temperatures in the upper rows.

Figure 9 also shows that the predicted peak fuel temperature is very insensitive to steam temperature, as expected. However, as would be expected, the peak fuel temperature is much more sensitive to initial FEPR, being about 1700°C for FEPR of 12 W/cm compared to about 2150°C for FEPR of 40 W/cm.

Results for Significant Channel Disintegration

The foregoing results, as noted earlier, have been obtained under the assumption that there is no disintegration of fuel channels after calandria tube uncovery.

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* The maximum steam flow rate of 322,000 lb_M/hr was used for row 1.

As mentioned earlier, results from these and other runs with IMPECC-UCZ were used to establish an empirical equation for disintegration delay times which was then incorporated into MODBOIL. In addition, MODBOIL also incorporates an option for arbitrary disintegration delay times, as noted in the previous section of this paper. Analyses using MODBOIL have been completed using each of these criteria for channel disintegration. With channel disintegration, there are sudden surges of steam generation and liquid entrainment as disintegrated channels are quenched in the bottom slice of moderator. This behavior is illustrated in Figure 5, for the case of complete disintegration of each row as the calandria tube temperature reaches 1750°C, with all Zircaloy assumed to be molten at the instant of disintegration and with any uncovered channels assumed to disintegrate if struck by higher disintegrating channels. This situation represents the most severe situation for channel disintegration. Figure 5 shows that the surges of steam flow rate in this case are superimposed on a gradually decreasing mean steam flow rate, similar to that for no channel disintegration, also shown in Figure 5, although the mean rates at any time are significantly higher than those for the case of no channel disintegration. Obviously, with channel disintegration moderator will be expelled from the calandria more rapidly than with no channel disintegration, as is illustrated in Figure 10, for the same conditions as in Figure 5.

Runs with IMPECC-UCZ for conditions representative of those expected with severe channel disintegration have not been completed yet, but various conclusions can be drawn from existing knowledge. The major effects of channel disintegration on the behavior of fuel channels will be earlier row uncovery and higher average steam flow rates.

Although most rows will uncover earlier, the uncovery times of the top three or four rows obviously cannot be affected significantly by subsequent channel disintegration. Because of the insensitivity of peak fuel temperatures to steam flow rates, as shown in Figure 9, we would not expect any significant changes in peak fuel temperatures for these rows in spite of the higher average steam flow rates after uncovery. Therefore, we would still not expect any fuel melting in these cases, for the period before channel disintegration occurs, even for row 4, which contains a maximum power channel.

Since the uncovery time for lower rows will occur earlier, we expect that peak fuel temperatures would be higher for cases of channel disintegration than for cases of no channel disintegration (Again, the higher average steam flow rates in the former cases would not be expected to affect peak fuel temperatures greatly, as indicated in Figure 9). The effect of earlier uncovery time on the peak fuel temperature in a given row can be deduced from a comparison of the results for rows 4 and 12 in Figure 8, in which FEPR is the same, 40 W/cm, the highest value in the core. Because of the insensitivity to steam flow rate, the difference in peak fuel temperatures for rows 4 and 12 shown in Figure 8 can be attributed mainly to earlier uncovery time for channel 4 compared to channel 12. This temperature increase, for the maximum FEPR in the core and for an uncovery time as premature as can reasonably be expected, is only about 250°C, and the resulting peak fuel temperature is still obviously well below the melting point. We may thus conclude that earlier uncovery times for lower channels, under the conditions expected in this accident sequence, will still not result in fuel melting, for the period before channel disintegration occurs. However, this conclusion is tentative, pending runs with IMPECC-UCZ which are representative of the conditions expected with channel disintegration.

For conditions following fuel channel disintegration in any of these cases, fuel melting is even less likely since fuel pellets and debris in such a case will be directly exposed to boiling moderator and will be rapidly quenched from the temperatures just prior to disintegration, which we have concluded will probably be well below the melting point. Runs of MODBOIL with the severe disintegration considered earlier show that fuel debris will be quenched to temperatures close to the moderator saturation temperature within 60 to 90 seconds of the time of disintegration.

Finally, Figure 10 shows that, under the most severe disintegration conditions, the moderator will not be completely expelled from the calandria until about 40 minutes after the beginning of the accident sequence. The fuel debris will remain quenched until a minute or so before this time. (In the case of no channel disintegration, a significant amount of moderator remains in the calandria an hour after accident initiation.) Thus, even in the worst case, the reactor operators would have time to take remedial action by providing an alternative heat sink should an accident sequence such as that considered here occur.

CONCLUSIONS

The analyses completed so far indicate that while there will probably be some serious damage to, and some disintegration of, calandria tubes and pressure tubes, no fuel melting is probable in this severe accident sequence, at least until all the moderator has been expelled from the calandria. This conclusion is tentative, pending completion of the study, but the basis for this conclusion is reasonably good. Other analyses, done as part of this overall study will provide information on fuel debris behavior and possible melting following complete moderator expulsion from the calandria.

The Rasmussen and other safety studies (3,4) demonstrate that serious hazards to the public result only from gross fuel meltings with the consequent complete release of gaseous and volatile fission products. Therefore, we can conclude that this very severe and highly improbable accident sequence, to the extent analyzed so far, is not likely to cause serious hazards to members of the public in the vicinity of a CANDU reactor power plant.

Of course, as pointed out in the Introduction, little experimental information is now available on core components under the extreme conditions considered in this study. Therefore, results obtained have many uncertainties associated with them and present conclusions must be treated with caution. Nevertheless, the analytical methods described here should provide a basis for more firmly-based analyses in the future as more experimental results are developed in programs such as that at WNRE on severe fuel damage (e.g., 13).

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NOMENCLATURE

CI - Containment impairment

CON - Containment

DF - Dual failure

ECI - Emergency coolant injection

ECLT - Emergency cooling - long term

FEPR - Fuel element power rating, W/cm.

FRCMAS - Fraction of mass of uncovered, disintegrated channels which falls to bottom of calandria

FRMELT - Fraction of Zircaloy in mass of fallen channels which is molten

LOCA - Loss-of-coolant accident

LOECC - Loss of emergency core-cooling

MCS - Moderator cooling system

MHS - Moderator heat sink

SD - Shut down (special safety system)

SF - Single failure

TCT - Calandria tube temperature

TFl - Fuel temperature

TRS - Steam temperature

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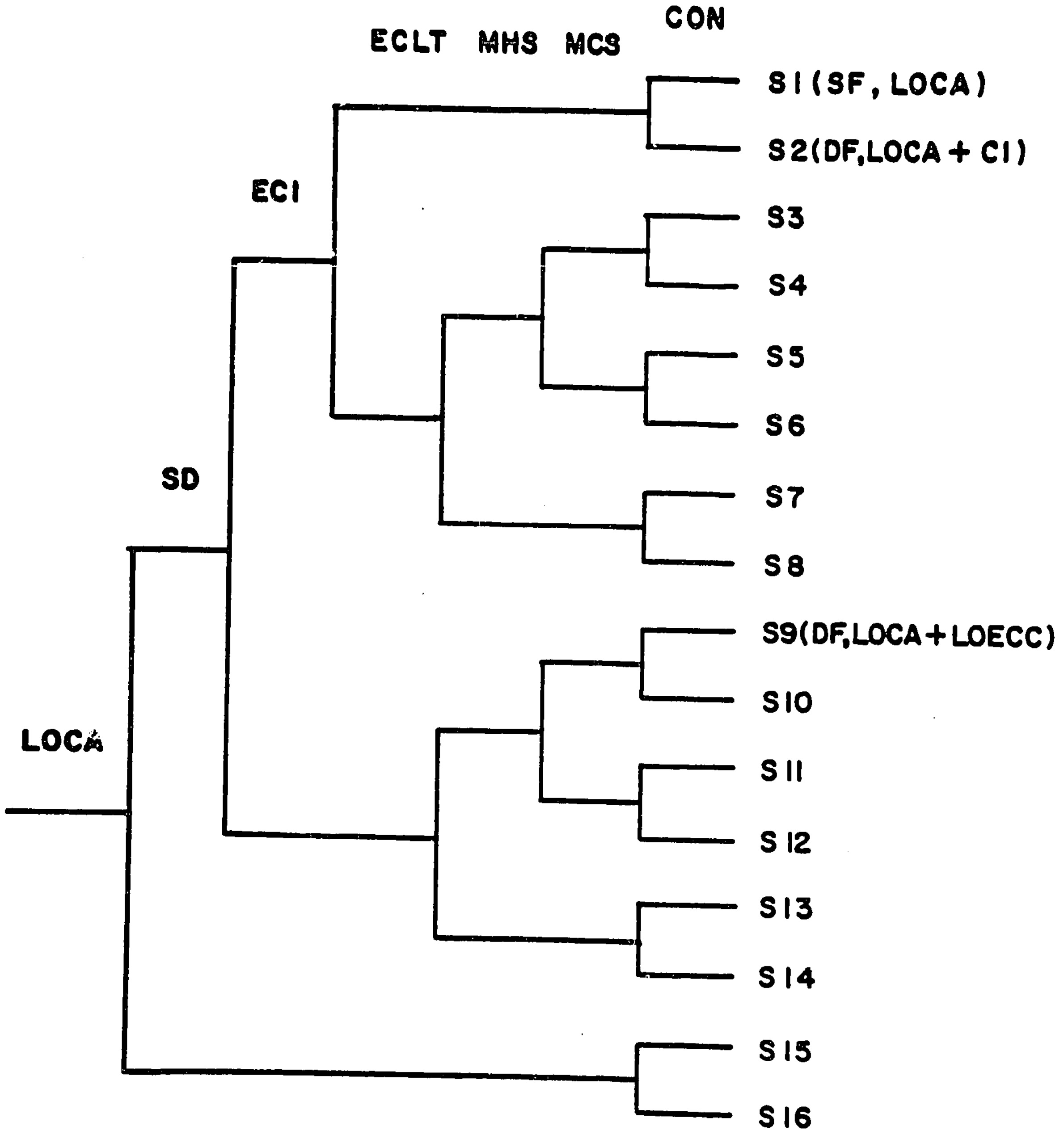


CANDU LOCA FUNCTIONAL EVENT TREE.
ACCIDENT SEQUENCES

Fig. 1

CANDU MELTDOWN STUDY
ACCIDENT SEQUENCE Sii

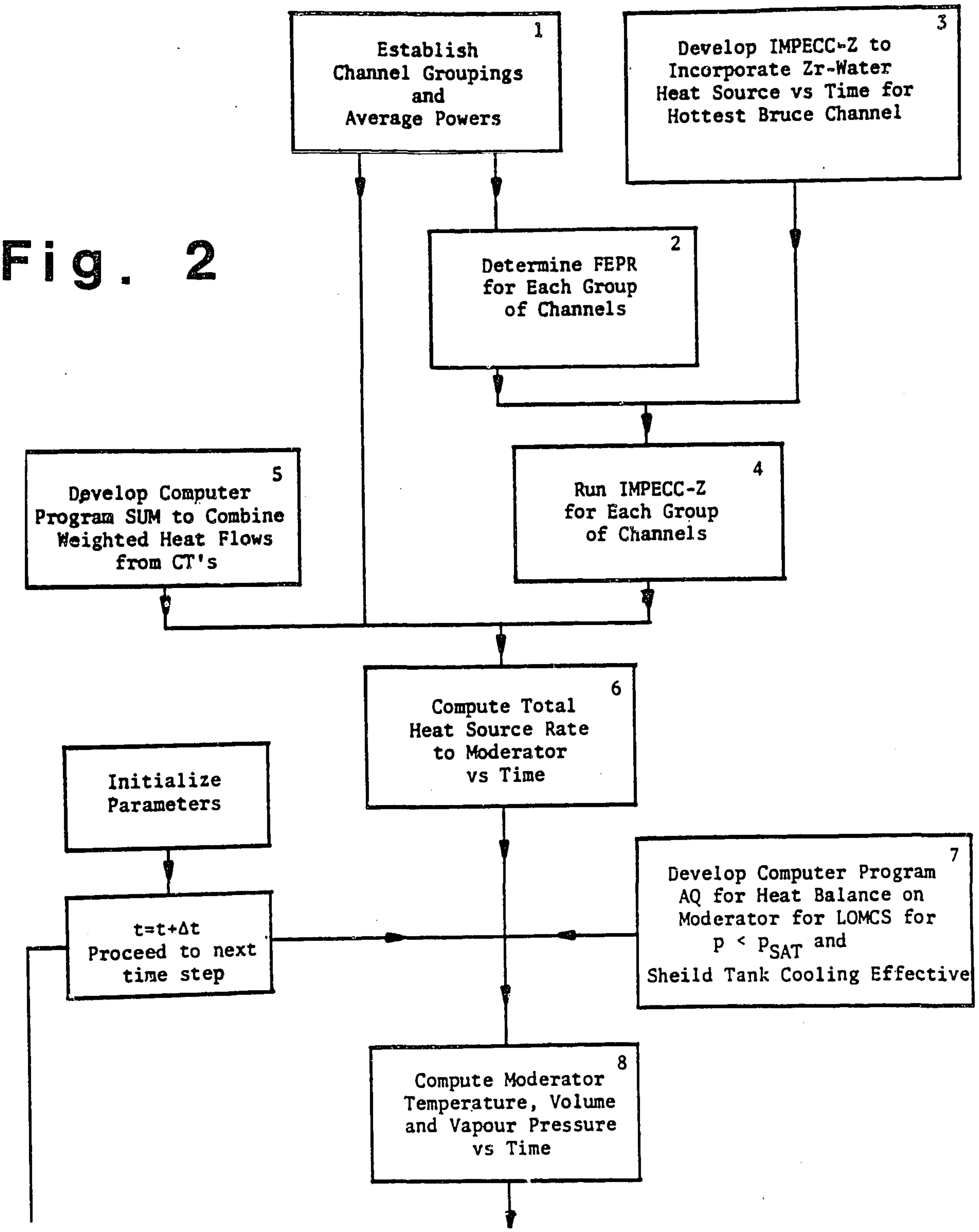
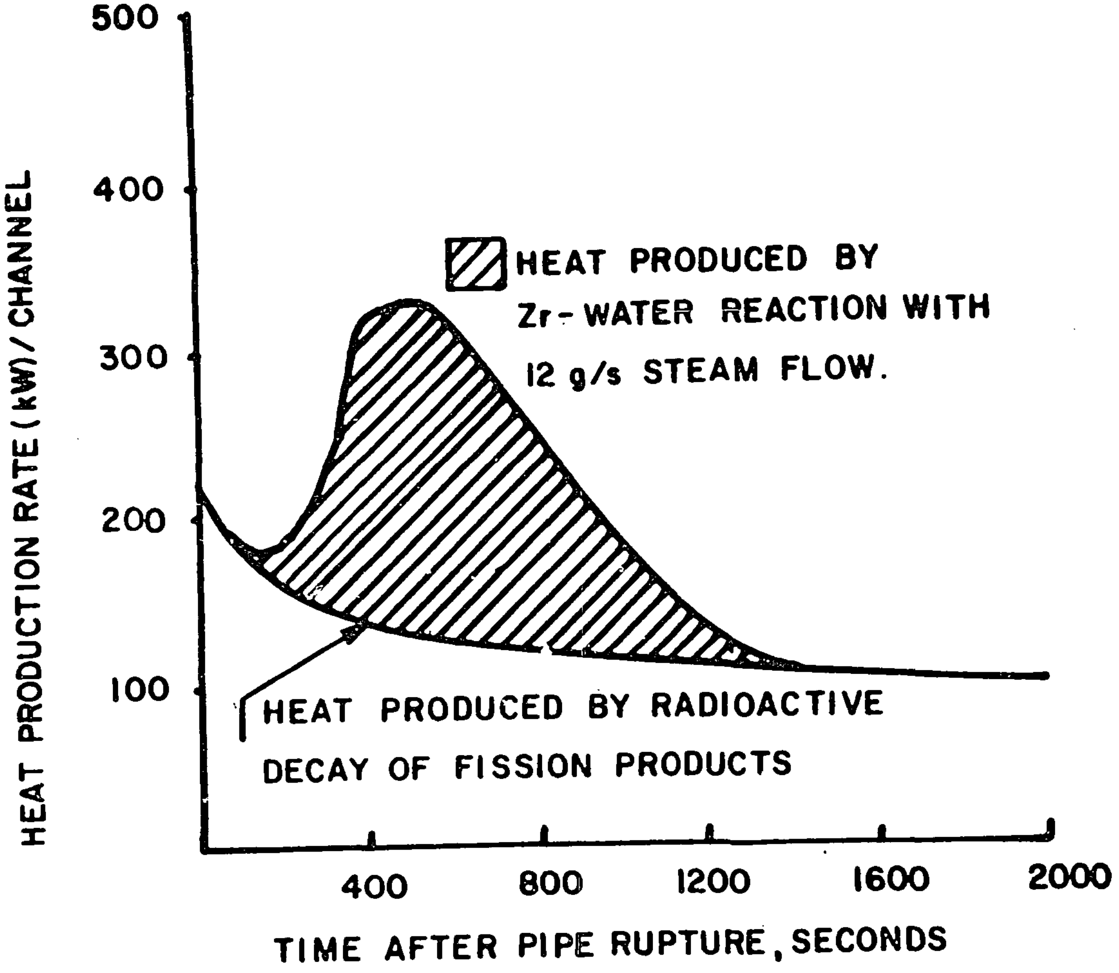


Fig. 2

Fig. 3



HEAT PRODUCTION RATE BY ZIRCALOY-WATER REACTION.
BRUCE MAXIMUM POWER CHANNEL CONDITIONS

Fig. 4

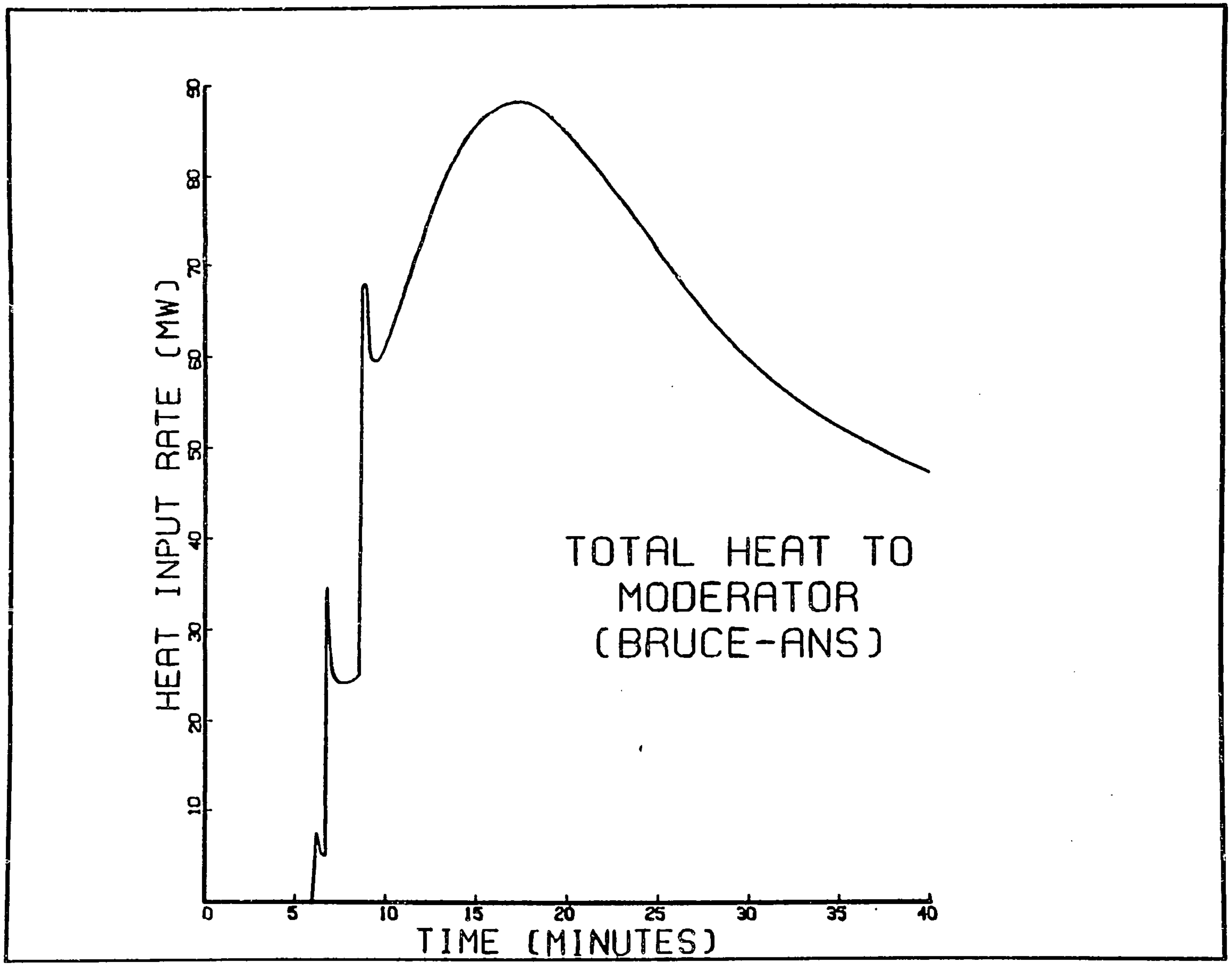

TOTAL HEAT TO
MODERATOR
(BRUCE-ANS)
HEAT INPUT RATE (MW)
10
20
30
40
50
60
70
80
90
0
5
10
15
20
25
30
35
40
TIME (MINUTES)

FIG. 5

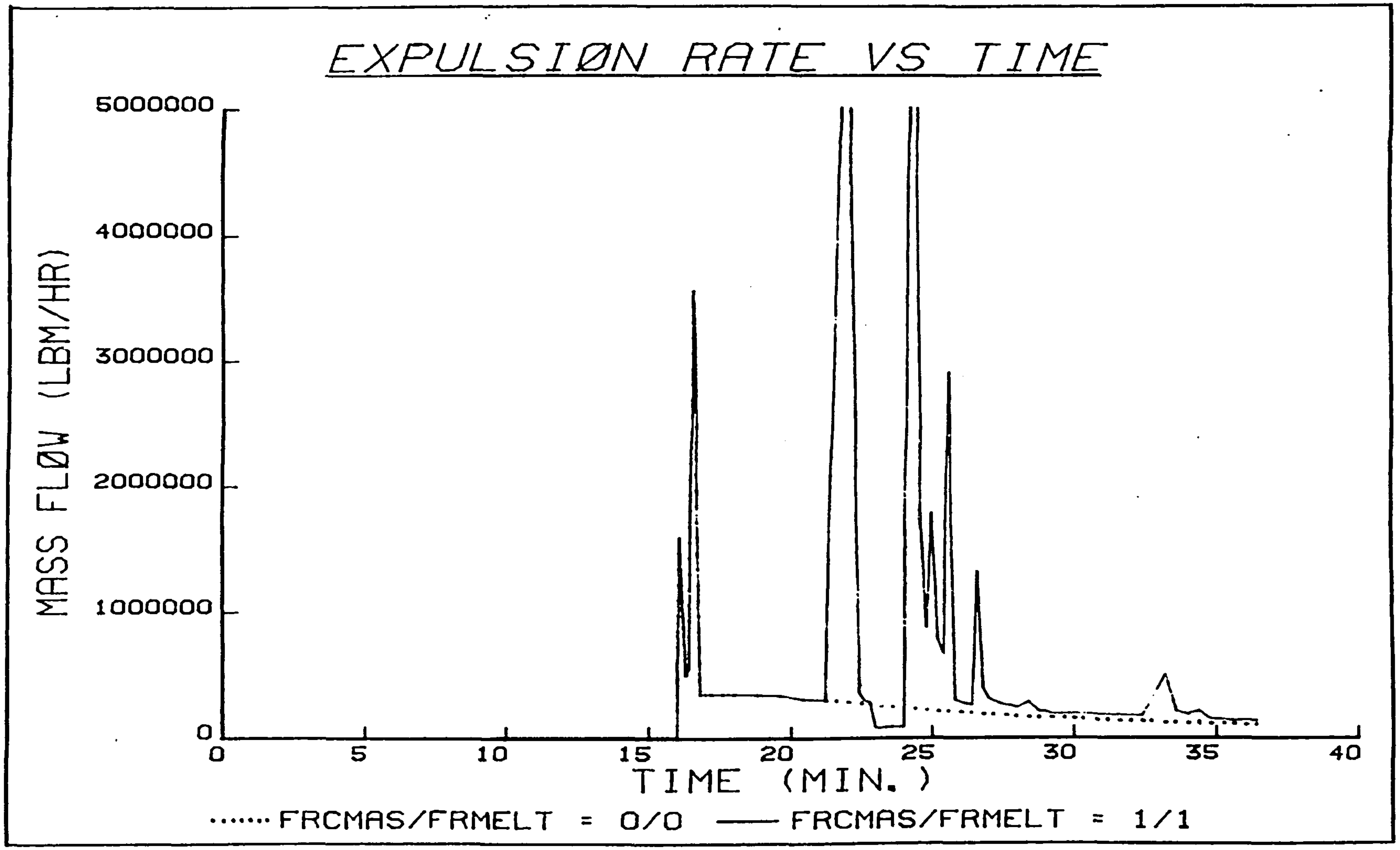
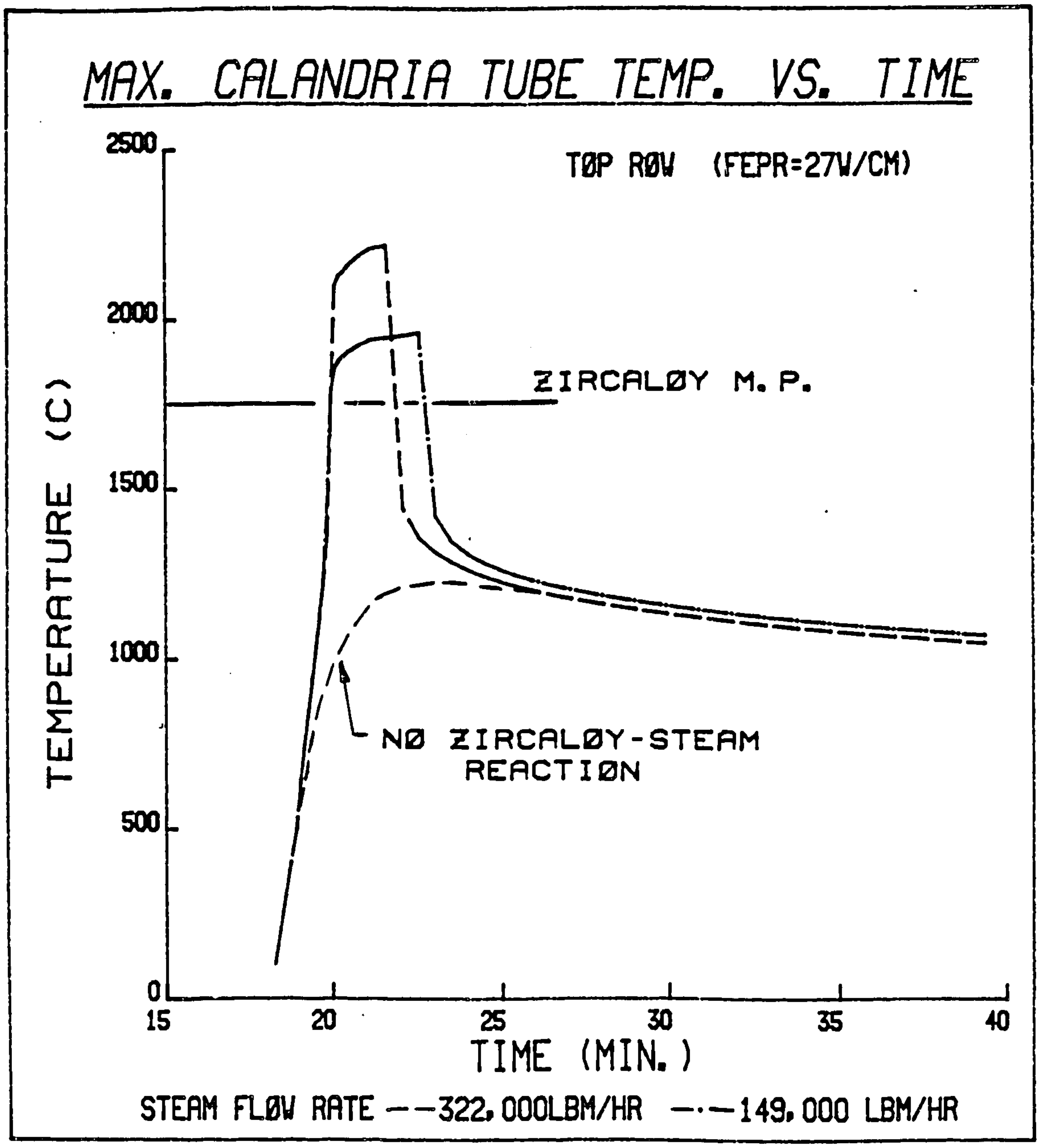

EXPULSIØN RATE VS TIME
MASS FLØW (LBM/HR)
5000000
4000000
3000000
2000000
1000000
0
0
5
10
15
20
25
30
35
40
TIME (MIN.)
······ FRCMAS/FRMELT = 0/0
—— FRCMAS/FRMELT = 1/1

FIG. 6


MAX. CALANDRIA TUBE TEMP. VS. TIME
TOP ROW (FEPR=27W/CM)
ZIRCALOY M. P.
NO ZIRCALOY-STEAM REACTION
TEMPERATURE (C)
2500
2000
1500
1000
500
0
15
20
25
30
35
40
TIME (MIN.)
STEAM FLOW RATE — — 322,000LBM/HR —·— 149,000 LBM/HR

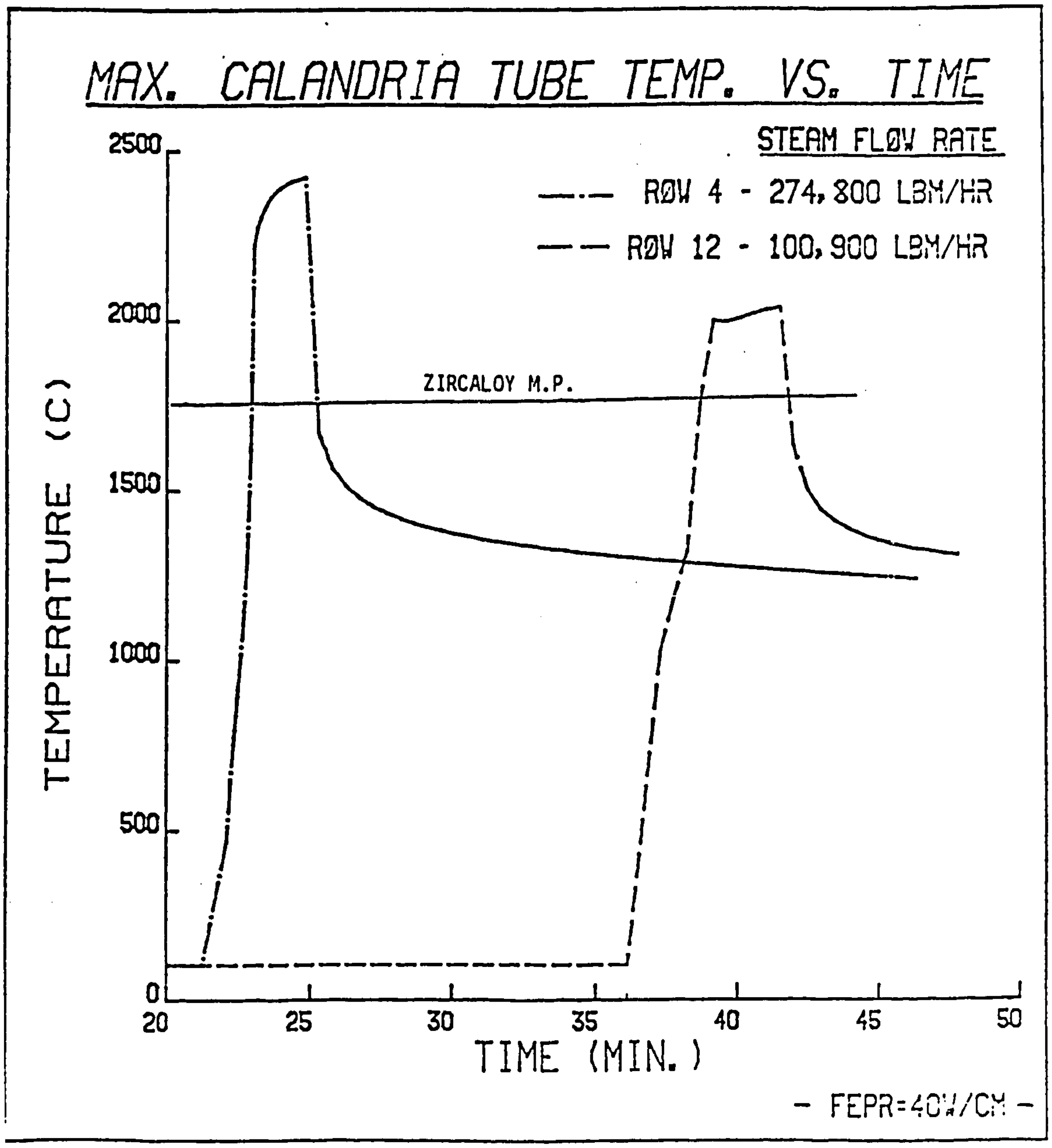
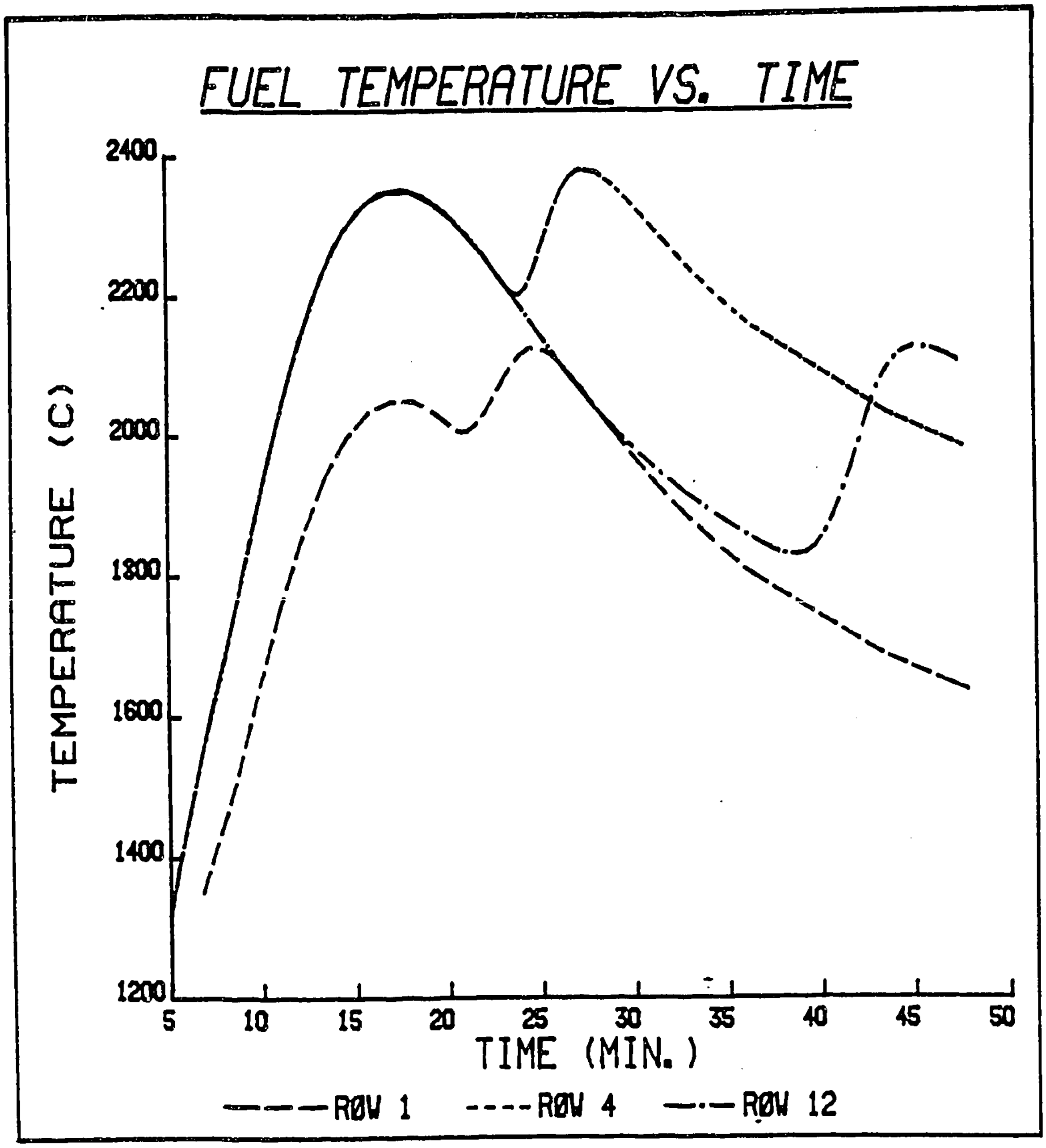

MAX. CALANDRIA TUBE TEMP. VS. TIME
STEAM FLOW RATE
ROW 4 - 274,800 LBM/HR
ROW 12 - 100,900 LBM/HR
ZIRCALOY M.P.
TEMPERATURE (C)
2500
2000
1500
1000
500
0
20
25
30
35
40
45
50
TIME (MIN.)
- FEPR=40W/CM -

Fig. 7

FIG. 8


FUEL TEMPERATURE VS. TIME
TEMPERATURE (C)
2400
2200
2000
1800
1600
1400
1200
5
10
15
20
25
30
35
40
45
50
TIME (MIN.)
———ROW 1
----ROW 4
—·—ROW 12

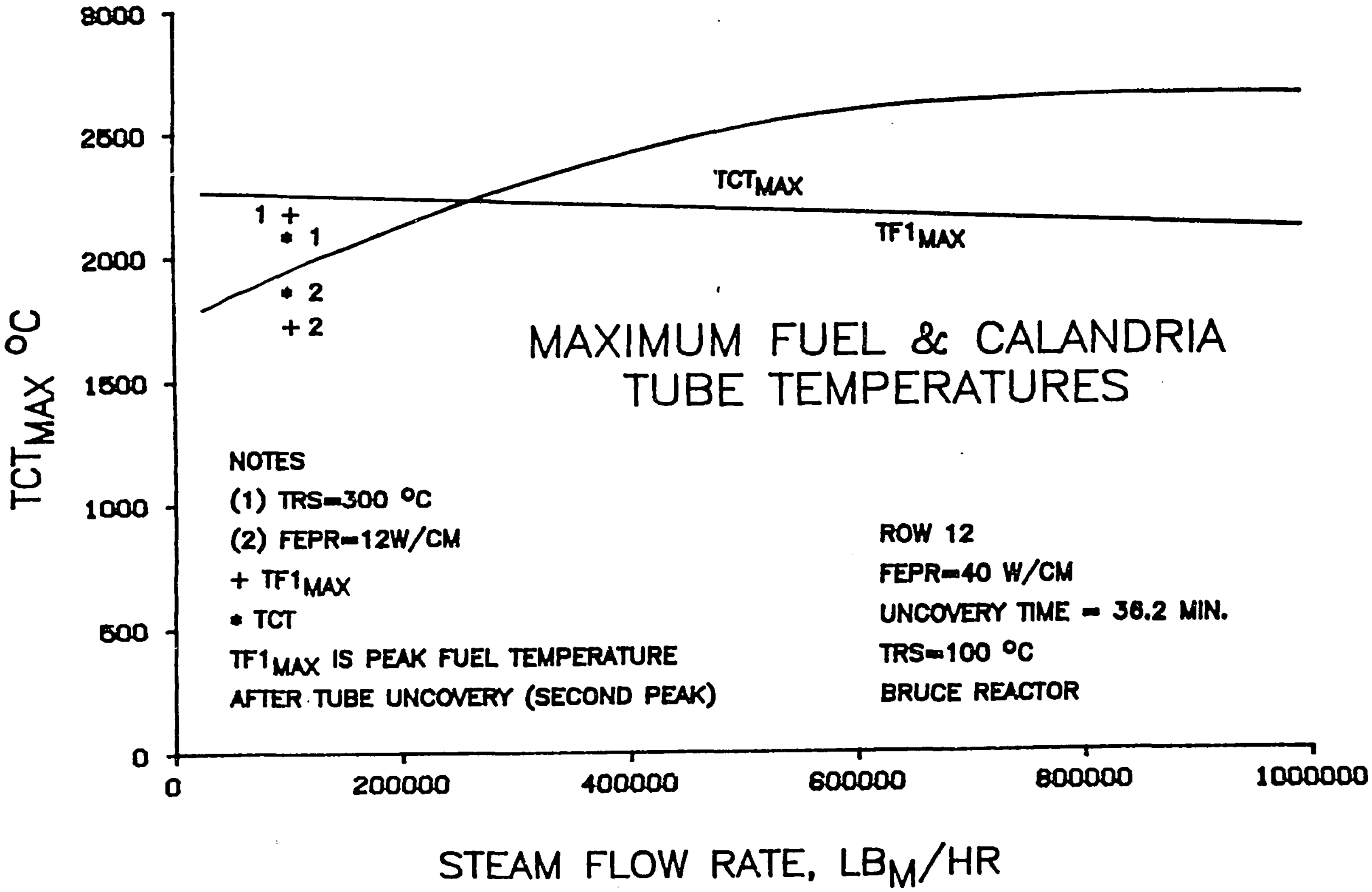
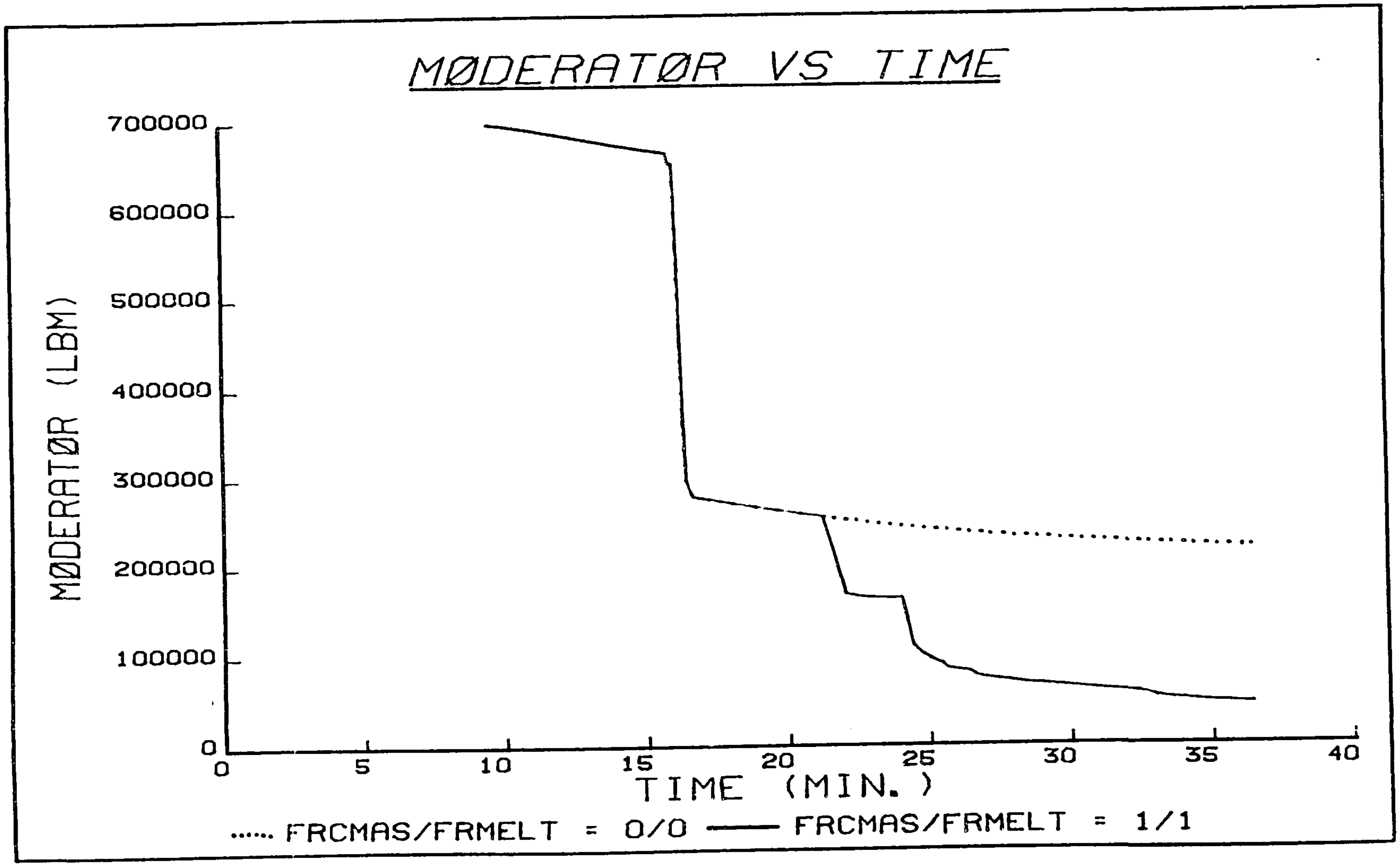

3000
2500
2000
1500
1000
500
0
0
200000
400000
600000
800000
1000000
TCT_{MAX} °C
STEAM FLOW RATE, LB_M/HR
TCT_{MAX}
$TF1_{MAX}$
1 +
* 1
* 2
+ 2
MAXIMUM FUEL & CALANDRIA
TUBE TEMPERATURES
NOTES
(1) TRS=300 °C
(2) FEPR=12W/CM
+ $TF1_{MAX}$
* TCT
$TF1_{MAX}$ IS PEAK FUEL TEMPERATURE
AFTER TUBE UNCOVERY (SECOND PEAK)
ROW 12
FEPR=40 W/CM
UNCOVERY TIME = 36.2 MIN.
TRS=100 °C
BRUCE REACTOR

Fig. 9

FIG. 10


MODERATOR VS TIME
MODERATOR (LBM)
700000
600000
500000
400000
300000
200000
100000
0
0
5
10
15
20
25
30
35
40
TIME (MIN.)
...... FRCMAS/FRMELT = 0/0 —— FRCMAS/FRMELT = 1/1