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EGG-TMI-7485
December, 1986

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INFORMAL REPORT

TMI-2 PRIMARY COOLANT MASS FLOWRATE DATA REPORT

R. D. McCormick

EG&G Idaho

Work performed under DOE Contract No. DE-AC07-76ID01570

EGG-TMI-7485

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BY

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Prepared for the
U.S. Department of Energy
Idaho Operations Office
Under DOE Contract No. DE-AC07-76ID01570

ABSTRACT

This is a report on the preparation of data from the TMI-2 primary coolant mass flowrate meters for inclusion into the TMI Data Base. The sources of the as-recorded data are discussed, and a description of the instrument is given. An explanation is given of how corrections were made to the as-recorded data and how the uncertainties were calculated. The identifiers attached to each data set in the TMI Data Base are given.

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INTRODUCTION

During the first 100 minutes of the TMI-2 accident, the reactor coolant pumps remained in operation forcing coolant through the core. At about 75 minutes into the accident the two B loop pumps were shut off and at just under 100 minutes the A loop pumps were shut off. During this 100 minutes the reactor coolant gradually changed from all subcooled water to saturated water with a high void fraction. The measurement of primary coolant mass flowrate was made in each hot leg up to the time their respective pumps were shut off.

This report concerns the primary loop coolant mass flowrate measurement data which were recorded during the TMI-2 accident. The mass flowrate meter transducers measured velocity head and coolant temperature in each hot leg. These basic measurements were converted to mass flowrate by the meter electronics and the measurements were recorded on a plant computer system called the reactimeter.

The purpose of this report is to provide background information on the mass flowrate meter data which are being put into the TMI-2 Data Base. The information given here indicates where the data originated along with the data identifiers, qualification categories and the associated uncertainty. In addition, descriptions are given of the instruments and circuits. Zero time for all data was set at the reactor turbine trip time of 04:00:37.

The uncertainty in the mass flowrate data was a constant prior to the zero time and for about the first 5.5 minutes. The uncertainty began to increase after this time due to a computational error in the electronics. These computations were effected to a small extent by the depressurization of the coolant system. The major portion of the error in the recorded mass flowrate, however, was caused by the void fraction in the hot legs. This increasing void fraction meant that the liquid density was decreasing and the electronics did not account for this. Separate uncertainty analyses were performed before and after time zero. This report explains the analyses methods and gives the results.

English units are used throughout this report in order to be consistent with TMI-2 physical facilities and data and to reduce round-off problems.

MEASUREMENT CHANNEL DESCRIPTION

This section of the report describes the hot leg mass flowrate meter measurement channel. This is a generic description because the A and B loop systems are identical.

Each of the primary hot leg coolant pipes had a mass flow rate meter mounted at about the 346 foot elevation in a vertical section of pipe. A resistance temperature detector (RTD) was mounted downstream of each flowmeter at an elevation of about 352 feet. The flowmeter sensor is about 50 feet above the bottom of the heated core and about 18 feet below the top of the candy cane. These RTD's were designated RC-4A-TE1 and RC-4B-TE1 for loops A and B, respectively. The designation for the flowmeters was RC-14A-FT and RC-14B-FT for loops A and B, respectively.

The flowmeter consists of a velocity head detector, a signal conditioning and amplifying section, a coolant density computation section, and recording on the reactimeter. The detector was, basically, a pair of pitot tubes, one facing upstream and the other facing downstream with the legs connected to a differential pressure transducer. Actually there were four pairs of pitot tubes in each hot leg loop connected in parallel and spaced 90^o apart azimuthally around the pipe.

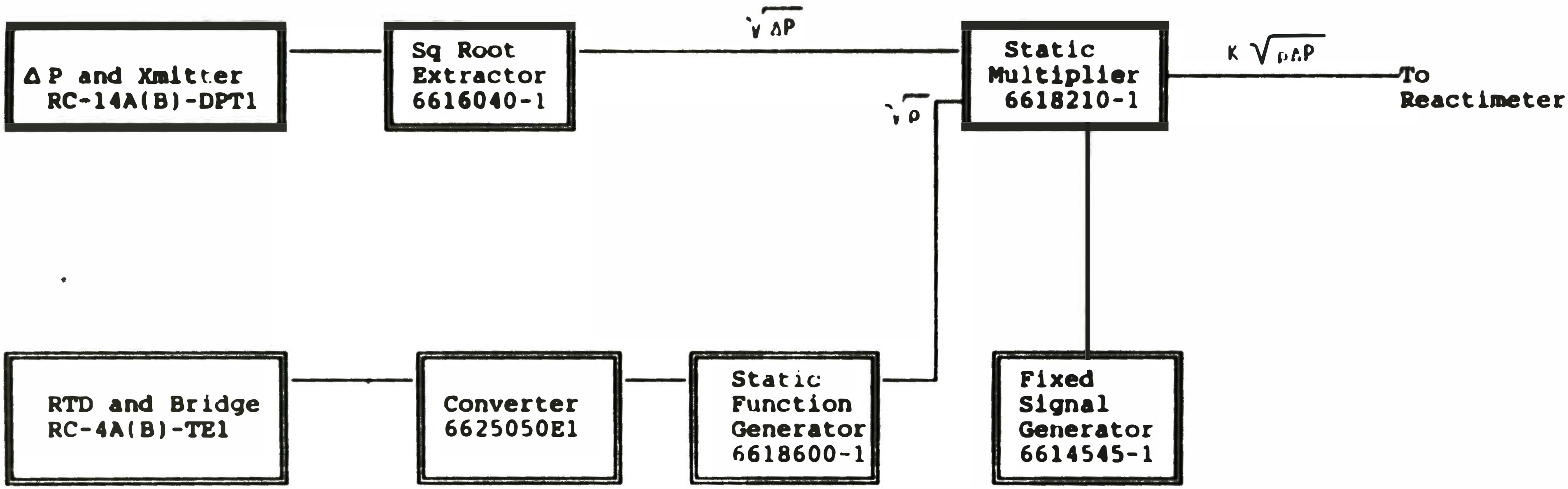
The differential pressure signal (ΔP) was put through a square root extractor and then multiplied by the square root of the coolant density (ρ) (and an appropriate constant) to produce the mass flowrate measurement. All the hot leg temperatures and mass flowrate calculations were recorded on the reactimeter at three second intervals.

The coolant temperature measured by the RTD was used to determine the fluid density from a curve which represented the square root of steam table values around the normal reactor operating point (2150 psi and between 520 and 620^oF). The loop coolant mass flowrate was continually computed according to the equation $\dot{m} = k\sqrt{\rho \Delta P}$ where k is a constant. Figure 1 is a block diagram of the mass flowrate measurement circuit.

The flowmeter was designed to operate near the normal reactor full power conditions. During the accident the flowmeter continued to indicate mass flowrate but was using an erroneous coolant density once the system depressurized and a void fraction appeared. The density was in error by about 2% (high) at 540^oF when the system was saturated with zero void fraction. When the void fraction was 0.2 the density error was about 21% high at 540^oF.

FIGURE 1

BLOCK DIAGRAM OF MASS FLOWRATE METER CIRCUIT



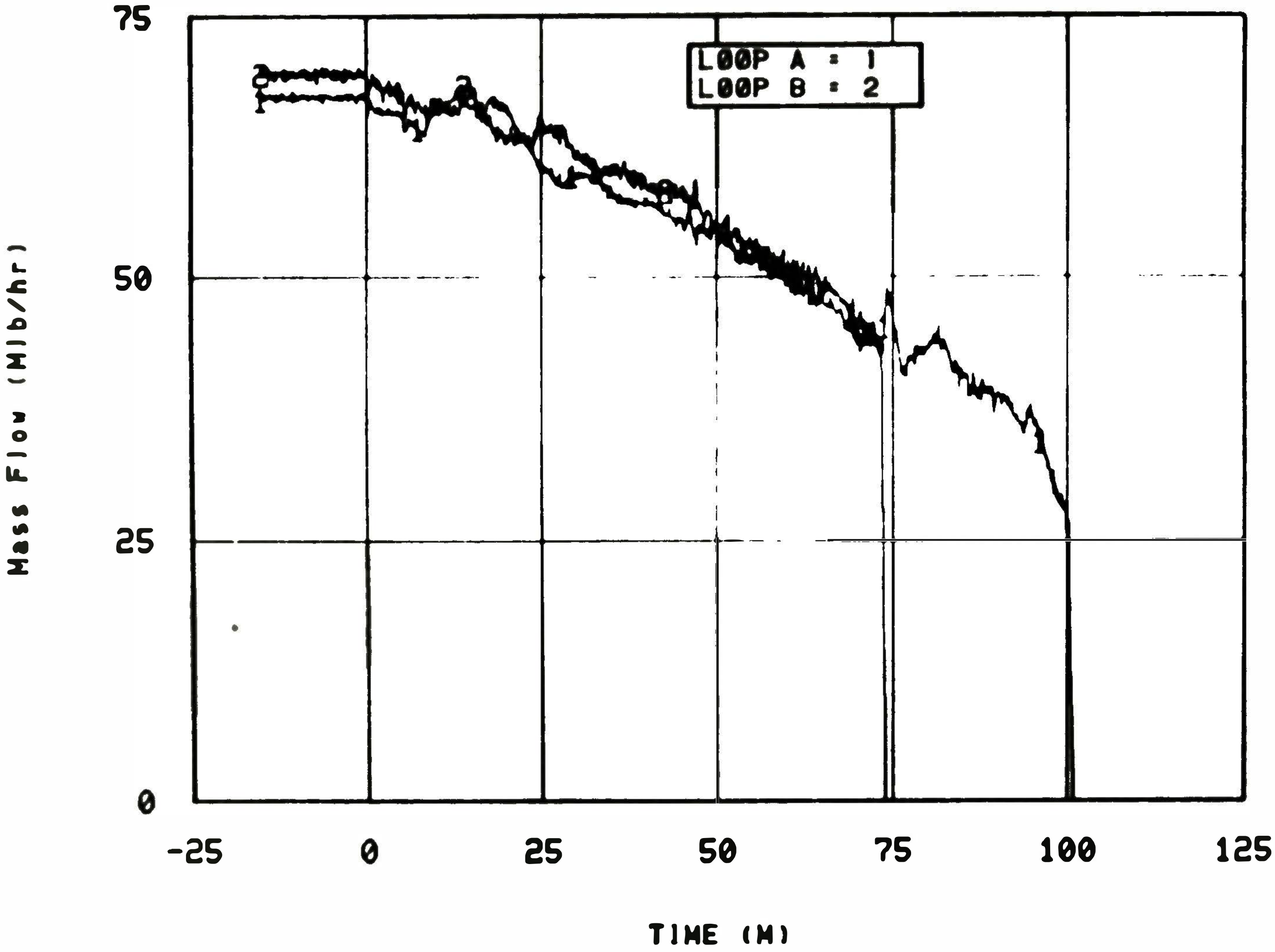
DATA MANIPULATION

The mass flowrate and temperature in the primary coolant system were recorded on the reactimeter prior to and during the accident. Although the mass flowrate data were somewhat noisy it has generally been used as recorded and as shown on Figure 2. The variations in this data were measured over 1.5 minute intervals, 12.5 minutes prior to time zero and at 62.5 minutes into the accident. A one sigma value of approximately 0.4% was calculated for both loops at -12.5 minutes and approximately 2% at 62.5 minutes. Data which were used in calculations however were smoothed by using a 20 second running average. The temperature data needed no smoothing.

The mass flowrate data from each hot leg were corrected for the error caused by the calculation of liquid density by the flowmeter electronic circuits. The correction consisted of calculating the coolant densities at both saturation and at 2150 psi. The mass flowrate was then multiplied by the square root of the ratio of the first to the second value. This correction amounted to less than 1%.

The downcomer void fraction was calculated from the source range neutron flux monitor data as reported in Reference 1. This void fraction data were used to calculate an upper limit to the mass flowrate uncertainty bound.

FIGURE 2
RECORDED HOT LEG MASS FLOW RATE



DATA UNCERTAINTY AND QUALITY

Determination of the uncertainty in the recorded hot leg mass flowrate meter data was made in two different types of analyses. Prior to time zero the analysis was made using a formal method. After time zero, the analysis was based on estimates of maximum and minimum possible void fractions at the flowmeter transducer location.

The uncertainty in the hot leg mass flowrate data after time zero was determined by calculating upper and lower boundaries. The upper boundary to the possible flowrate was determined using the downcomer void fraction. The downcomer region had a void fraction which was consistently lower than that in the hot leg at the flowrate location. This was due mainly to the addition of heat to the liquid flowing from the downcomer and up through the core. Some small increase in void fraction was due to the decrease in pressure from the downcomer to the flowmeter in the hot leg. The lower void fraction mainfested itself as a higher fluid density. It was assumed that at any time during the first 100 minutes that the fluid density at the hot leg location could not be any higher than the density in the downcomer. The mass flowrate equation ($\dot{m} = k\sqrt{\rho\Delta p}$) was then used to calculate the upper limit to the mass flowrate by using the density in the downcomer.

The lower bound to the mass flowrate was calculated using a similar approach. An equation was developed to calculate the void fraction at the flowmeter by using the recorded mass flowrate and temperature data. A void fraction was calculated for the hot leg flow meter location but this void fraction manifested itself as a density which was a lower bound. That is, the actual density would never be lower than this value. A major assumption here is that the volumetric flowrate is highest at the beginning of the accident and declines thereafter, or at least stays lower than the original value. Using the flowmeter equation, a lower limit mass flowrate was calculated.

Uncertainty is a description of the numerical bounds of a measurement error, and the true value of a measurement is predicted with some confidence to lay within these bounds. Uncertainty is an arbitrary substitute for a statistical confidence interval and can be interpreted as the largest expected error. The confidence level of the TMI-2 data uncertainty is near 95% for data up to about 5.5 minutes as a result of the method used to calculate the total uncertainty. The confidence level of the uncertainties from 5.5 minutes to pump shutdown could not be defined. The uncertainty analysis provided the numerical error bounds of the data.

A formal system exists for determining the uncertainty in the measurement data[2-4]. Basically, this system consists of (1) compiling the useful data in a usable form, (2) gathering all available technical information on transducers, signal conditioning, and recording instruments, (3) gathering all available calibration data, (4) performing an uncertainty analysis on each measurement channel.

The technique used to determine the data uncertainty prior to time zero was a modification of the system described in Reference 2 through 4. The basic difference was in the separation of errors into bias and precision categories. Most of the technical data on errors were taken from equipment calibration sheets where a tolerance in calibration was given for the circuit. This tolerance was basically a bias and was applicable to the circuit range. Design and performance specifications did not give a statistical basis for their error values and mostly specified range errors. In only a few cases were errors found to be specified as a function of reading. A conservative range error was substituted for the errors given as a function of reading. Details of the analysis are in the Appendix.

Data are classified as Qualified, Trend, or Failed. The "Qualified Data" is data which have established uncertainties, have been corrected for all known errors, and are considered a reasonably repeatable representation of the physical phenomenon being measured, i.e., the mass flowrate at the detector location. The "Trend Data" are considered to be only an approximation of the phenomenon being measured, may not be repeatable, and have unacceptably large uncertainties. "Failed Data" contain no useful information. All data reported herein were categorized as Qualified data.

Table 1 summarizes the mass flowrate values and uncertainties at some specific times during the accident. The mass flowrate values at time 0 were determined from the reactimeter reading and the uncertainties were calculated using normal methods.

After time 0, upper and lower bounds of the mass flowrates were calculated using estimated lower and upper bound void fractions, respectively. It was not possible to determine an expected value of mass flowrate so a mean value was used in Table 1 and Figures 3 and 4. It was believed that the expected value should lay between the mean value and the upper bound of the mass flowrate. Details of the analysis and calculations are given in the Appendix.

Table 1 lists the measurement identifiers and the quality category of these data. Figures 3 and 4 show the same data but with error bands showing the uncertainties in the data around the mean value.

TABLE 1

MASS FLOWMETER VALUES AND UNCERTAINTY

Measurement	Time After Turbine Trip (minutes)	Value (mph)*	Quality Category
RC-14A-FT-R	0	67.25 ± 1.41	Qualified
(Loop A)	20	63.98 ± 1.41	Qualified
	40	51.12 ± 3.97	Qualified
	60	41.70 ± 4.44	Qualified
	80	32.51 ± 4.31	Qualified
RC-14B-FT-R	0	69.73 ± 1.46	Qualified
	20	60.28 ± 2.5	Qualified
	40	52.61 ± 3.95	Qualified
	60	41.24 ± 4.83	Qualified
	72.5	33.07 ± 5.57	Qualified

*Millions of pounds per hour.

FIGURE 3 HOT LEG LOOP A MASS FLOWRATE
UPPER AND LOWER UNCERTAINTY BOUNDS

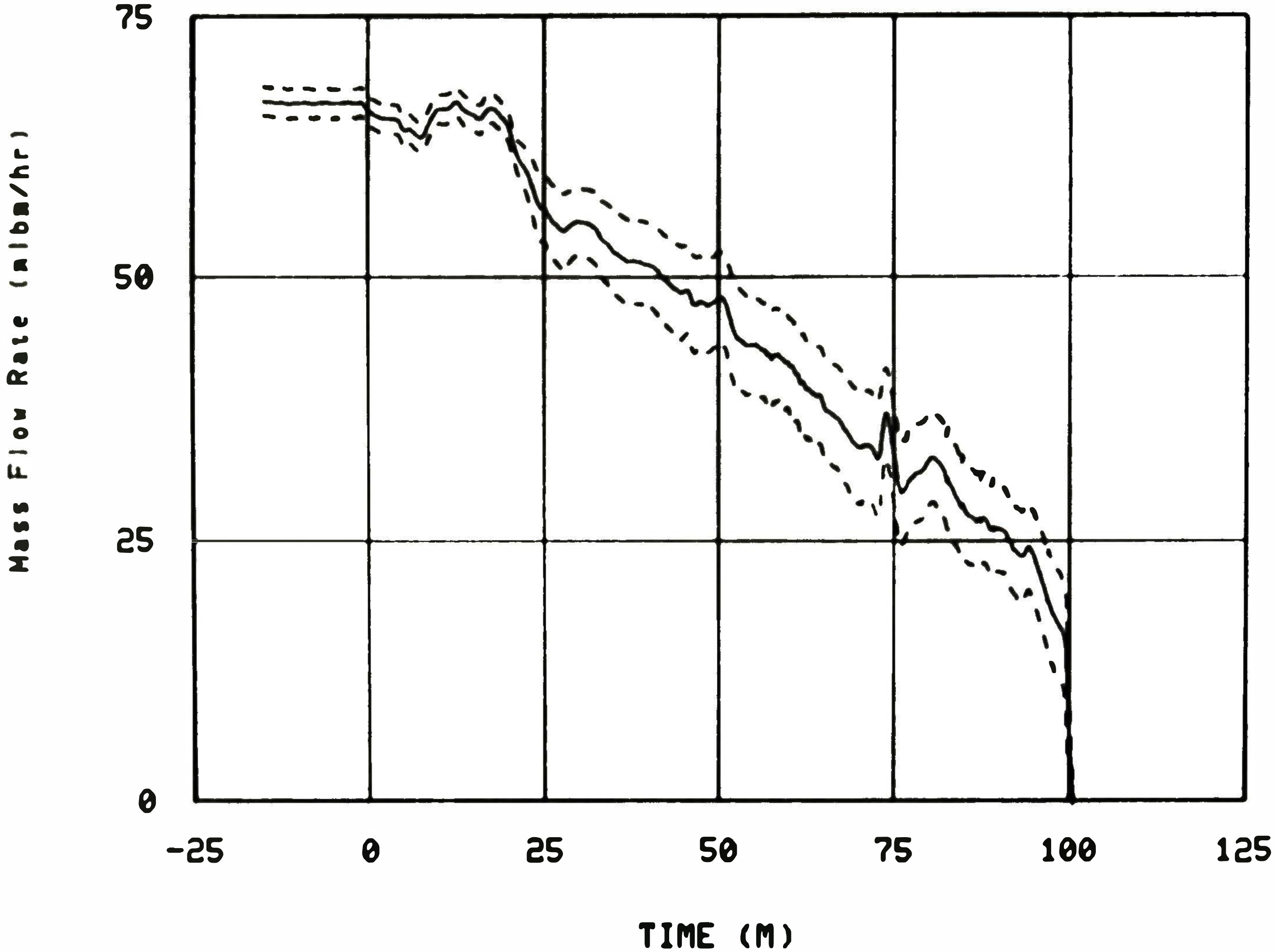
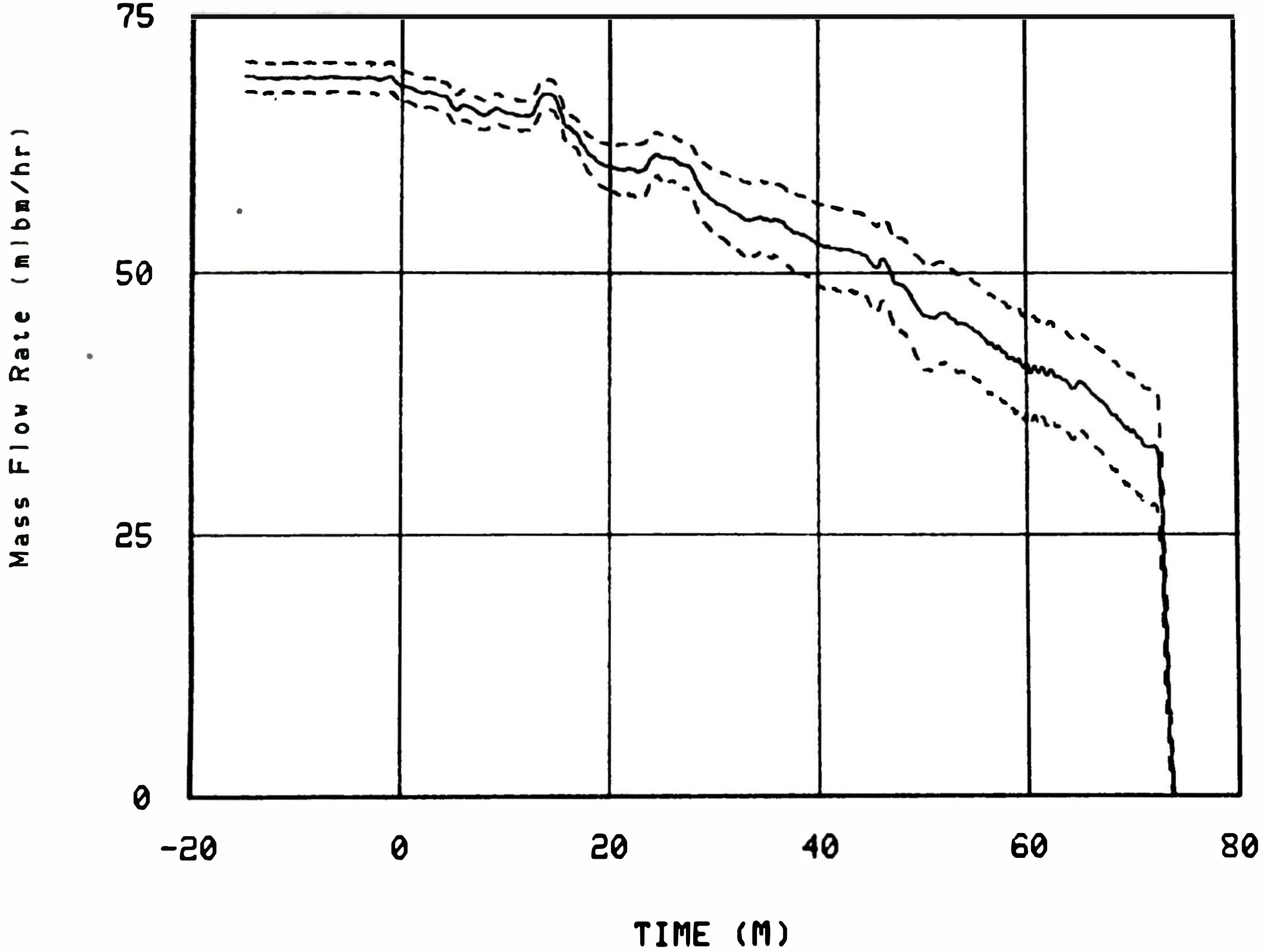


FIGURE 4 HOT LEG LOOP B MASS FLOWRATE
UPPER AND LOWER UNCERTAINTY BOUNDS



SUMMARY

The hot leg mass flowrates which were recorded on the reactimeter were known to be in error. This error was caused by the flowmeter electronics which continued to calculate the flowrate using a density from a electronically contained subcooled steam table curve at 2150 psi. It was impossible to correct the recorded flowrates without a knowledge of the liquid density in the hot legs. The reduction in liquid density was due to the increased void fraction in the liquid but there was no way of knowing the temporal void fraction. A method was devised to estimate the maximum and minimum void fractions that the hot leg liquid could possibly have, and from this lower and upper densities were calculated. The recorded mass flowrate data were then corrected using the upper and lower density limits to yield a maximum and minimum probable mass flowrate. The mean value between the upper and lower limits was used as a substitute for the expected value. The actual expected value is thought to be between the mean value and the upper flowrate bound.

REFERENCES

1. R. D. McCormick, "Determination of Void Fraction from Source Range Monitor and Mass Flowrate Data," EGG-TMI-7324, September 1986.

2. R. B. Abernethy, R. P. Benedict, "Measurement Uncertainty: A Standard Methodology," ISA Transactions, Vol. 24, Number 1, 1985.

3. R. B. Abernethy, et. al., "Measurement Uncertainty Handbook," AEDC-TR-73-5, Revised 1980.

4. "Measurement Uncertainty for Fluid Flow in Closed Circuits," ANSI/ASME MFC-2M-1983.

5. R. D. McCormick, "TMI-2 Source and Intermediate Range Neutron Flux Monitor Data Report," EGG-TMI-7174, March 1986.

APPENDIX

This appendix contains the analyses used to determine the uncertainty in the hot leg mass flowrate measurement data prior to and during the accident. Since the flowmeter in the two hot legs were identical, the analyses are not loop specific. The mass flowrate meters were designed for measurement at the normal operating pressure of the reactor and within an expected range of temperature, i.e., 2150 psig and between 520°F and 620°F. The flowmeter electronic circuits computed mass flowrate according to the equation

$$\dot{m} = k\sqrt{\rho\Delta P}$$

The velocity head (P) came from the pitot tube sensors in the hot leg pipes. The k value was a constant which represented the conversion of the flowing-liquid forces (exerted on the sensors) into a velocity-head value. The density (ρ) was determined by using the measured coolant temperature and a steam table 3-point curve (for 2150 psi and 520°F to 620°F) built into the electronics. After the system depressurized and a void fraction appeared, the electronics circuit continued to calculate density as if the coolant were subcooled at 2150 psi. This resulted in a continuously increasing error in the calculated density (and thus in the calculated mass flowrate) as the void fraction increased. Without a knowledge of the hot leg temporal void fraction, the mass flowrate data cannot be corrected for this density error effect. For time prior to about 5.5 minutes after the turbine trip there was no significant error in the mass flowrate measurement due to the decreasing density because the void fraction stayed constant. For times after a void fraction appeared it was possible to establish minimum and maximum limits on the mass flowrate data while the reactor coolant pumps were operating. This was done by estimating the maximum and minimum possible void fractions, calculating the corresponding densities and then correcting the recorded flowrates with the densities.

There are two separate and distinct uncertainty analyses discussed in this appendix. The first one covers the time prior up to 5.5 minutes and the second is from this time until the last two coolant pumps were shut off at 100 minutes.

ANALYSIS NEAR ZERO TIME

An analysis was performed to determine the uncertainty in the mass flowrate meter data prior to the accident and shortly thereafter. The task consisted of determining the errors in each of the electronic components in the measurement channel and combining these to find the uncertainty in the density and velocity head (ρ and ΔP) at the flowmeter location. The determination of the uncertainty in the velocity head and density consisted of determining the errors in the differential pressure transducer and transmitter; the temperature transducer and transmitter, the converter, the square root extractor, the static multiplier, the adjustable and fixed signal generators, the summer, and the reactimeter.

Information used in the uncertainty analysis came from Bailey Meter Company product instructions and specification, TMI-2 calibration records, Rosemount Engineering Company specifications, and engineering estimates.

The overall mass flowrate measurement uncertainty was determined using the Taylor series expansion. Tables A-1, A-2 and A-3 describe the errors and uncertainty calculation in temperature and differential pressure measurements, and density calculation. An explanation is then given of the error propagation technique used to calculate the total uncertainty from the elemental uncertainty components.

TABLE A-1

HOT LEG TEMPERATURE ERROR
RTD Range 520 to 620°F
RC4A-TE-1-R and RC 4B-TE-1-R
RC Hot Legs

Item	± Error (B)	Comment
RTD Element[a]	0.05°F	0.05% span
Calibration of [a] (RTD and X Miter)	0.15°F	Temperature to Resistance
Calibration[b] (X Miter)	0.1°F	Resistance to Millivolts
Converter[c]	0.21°F	Millivolts to Volts
RTD Drift[d]	0.45°F	Per year
System Drift[e]	1.0°F	Per year

$$\text{Error} = [\Sigma B^2]^{1/2}$$

$$B_T = 1.13^\circ F$$

Using the root-sum-square (RSS) method, the error component is calculated assuming that all error values are at the 95% confidence level

NOTES

(a) These values were taken from the Bailey Meter Company specifications.

(b) These values were taken from TMI-2 Instrument Calibration Sheets.

(c) Taken from Bailey Meter Company Product Instruction E92-19-6 for Signal Converter A.

(d) From Rosemount Engineering Company product data sheets. Value given was less than 0.45°F drift per year in platinum element.

(e) Estimate based on engineering judgment to account for measurement system drift. Bailey Meter Company specification sheet No. 1595L167 states that the accuracy of the RTD as a measurement system is 1°F. Because of the long time between calibrations of parts of the system, this much error is more than likely.

TABLE A-2

DENSITY ERROR COMPONENT

Item	± Error (B)	Comment
Water Temperature[a]	0.17%	Range
Temperature[b] Compensation	0.25%	Range
Adjustable[c] Signal Generator	0.25%	Range
Summer[c]	0.25%	Range
Static[c] Multiplier	0.5%	Range

B_ρ = 0.69% of range.

Combining errors using RSS method $B_\rho = [\Sigma B^2]^{1/2}$

NOTES

(a) This error is due to the fact that the temperature compensation made by the electronics uses a temperature with error in it. The value here is an estimate based on circuitry in the mass flowrate meter and the temperature error. A 1.13°F error in water temperature was taken from Table A-1.

(b) This error is an estimate. It is due to error in electronically fitting the steam table curve for calculating density from temperature.

(c) These values were taken from the TMI-2 Instrument Calibration Data Sheets and were listed as a tolerance value.

TABLE A-3

DIFFERENTIAL PRESSURE ERROR COMPONENT

Item	± Error (B)	Comment
Transmitter Accuracy[a]	0.25%	Range
Temperature Compensation[a]	0.5%	Range
Drift[b]	0.3%	Range
Calibration[c]	0.25%	Range
Square Root Extractor[d]	0.64%	Range
Multiplier[d]	0.5%	Range
Fixed Signal[d] Generator	0.25%	Range
Reactimeter	0.1%	Range

$B_{\Delta P}$ = 1.09% of range

Using the RSS method and including the reactimeter error for expediency

$$B_{\Delta P} = [\Sigma B^2]^{1/2}$$

NOTES

(a) These values were taken from the Bailey Meter Company specification sheets. The temperature at specification was 75°F and reactor building was 120°F hence the 0.01% range per °F yields 0.5% error.

(b) Taken from Design and Performance Specification sheets showing a 0.15% drift in three months.

(c) Pressure-to-voltage calibration from transmitter calibration data sheets.

(d) From TMI-2 Instrument Calibration Data Sheets.

The uncertainty in the mass flowrate measurement data was calculated using the uncertainties in the velocity head (ΔP) and the density (ρ) of the coolant at the flowmeter location in the hot leg. In addition there was uncertainty in the velocity head sensor, which manifested itself as an uncertainty in the constant (K). The flowmeter system used a theoretical numerical factor to convert the force of the moving liquid on the sensor into a differential pressure value representative of the average flow in the 36 inch diameter pipe. There are many factors which could cause error in this conversion constant such as: (1) variation in density or flowrate causing change in K, (2) miss alignment of pitot tubes, (3) an unexpected or variable velocity profile across the pipe.

The mass flowrate value ($\dot{m}$) was determined from the equation

$$\dot{m} = k\sqrt{\rho \Delta P}$$

by the electronic system and was recorded on the reactimeter. The Taylor series equation for uncertainty when $\dot{m} = f(K, \Delta P, \rho)$ is:

$$B_{\dot{m}}^2 = \left(\frac{\partial \dot{m}}{\partial k} B_k\right)^2 + \left(\frac{\partial \dot{m}}{\partial \Delta P} B_{\Delta P}\right)^2 + \left(\frac{\partial \dot{m}}{\partial \rho} B_\rho\right)^2$$

$$\text{Uncertainty} = \frac{B_{\dot{m}}}{\dot{m}} = \left[\left(\frac{B_k}{k}\right)^2 + \left(\frac{B_{\Delta P}}{2\Delta P}\right)^2 + \left(\frac{B_\rho}{2\rho}\right)^2\right]^{1/2}$$

where B_K = uncertainty in the K
$B_{\Delta P}$ = uncertainty in ΔP
B_ρ = uncertainty in ρ
K = calibration constant
ΔP = velocity head (differential pressure)
ρ = fluid density
$\dot{m}$ = mass flowrate value

Table A-4 gives the details of the total uncertainty computation for the mass flowrate in each loop and for the combined or total coolant flow through the reactor.

TABLE A-4

TOTAL MASS FLOWRATE UNCERTAINTY
NEAR ZERO TIME

Item	Error Component	Comment
B_{ρ}	± 0.69%	From Table A-2
$B_{\Delta p}$	± 1.094%	From Table A-3
B_K[a]	± 2.0%	Uncertainty in calibration

Uncertainty Loop A[b] = ± 2.1% range or ± 1.89 x 10^6 lb per hr

Loop B = ± 2.1% range or ± 1.89 x 10^6 lb per hr

Loop A plus Loop B[c] = ± 2.67 x 10^6 lb per hr

NOTES

(a) The uncertainty in K was estimated to be 2%. This was an engineering judgment based upon the fact the transducer unit used a theoretical calibration.

(b) The mass flowrate meter range was 0 to 90 x 10^6 lb per hour for each loop.

(c) The uncertainty in the total reactor mass flowrate is the RSS of the two individual loop uncertainties.

ANALYSIS AFTER TIME ZERO

The scenario of events within the primary coolant system from zero to 100 minutes into the accident is as follows: Immediately after turbine trip (zero time) the pressure relief valve opened and stuck open. The primary pressure dropped to 1200 psi in about 10 minutes and stabilized slightly above 1000 psi. Coolant saturation was reached at approximately 5.5 minutes and the system remained in saturation until after 100 minutes. The coolant temperature did not vary more than 60°F after the system depressurized and up to 100 minutes. The void fraction of the flowing coolant increased from zero at 5.5 minutes to a high value at 100 minutes, not necessarily linearly. The void fraction was not the same everywhere in the loop. The void fraction of the coolant was expected to be higher in the hot leg than in the downcomer due to (1) the slight depressurization from flowing through the core and change in elevation, (2) addition of heat from the core, and (3) possibly flow slip between the liquid and vapor phases.

As discussed in the previous section, the measured hot leg mass flowrate was determined according to the equation for pitot sensors[A-1].

$$\dot{m} = k\sqrt{\rho_{to}\Delta P} \qquad \text{(A-1)}$$

The P value (velocity head) used in this equation accurately represented the primary coolant parameter throughout the accident. The ρ value, however, continued to be calculated as if the system were subcooled at 2150 psi. Changes in the liquid density (ρ) due to changes in temperature were made accurately by the electronics. There was, however, a small error due to the incorrect pressure assumption. This error was less than 1% and was removed from the data. As the coolant void fraction increased from zero, the real fluid density fell as described by the equation for homogeneous two phase flow[A-2].

$$\rho_t = \alpha\rho_g + (1 - \alpha)\rho_\ell \qquad \text{(A-2)}$$

where ρ_t = coolant density
α = void fraction
ρ_g = density of saturated steam
ρ_ℓ = density of saturated liquid.

The value of density calculated by the flowmeter electronics did not reflect the increasing void fraction. This means that the mass flowrate as recorded during the accident was too high since the density was in reality falling due to increasing void fraction. The recorded mass flowrate measurements, therefore, were always higher than the true values during the accident.

The source range monitor (SRM) is an excore neutron flux monitor for reactor startup and low power operation. This monitor essentially measures the neutron flux passing through the downcomer region[A-3]. The void fraction in the downcomer region during the accident has been calculated using the SRM data during that period[A-4]. This void fraction is expected to be lower than the one in either hot leg because of the differences in pressure between the locations and the addition of heat as the fluid passes through the core. This means that the density is always higher in the downcomer region than in the hot leg. The density in the downcomer can be calculated using Equation A-1 and the temporal void fraction from the SRM (Reference A-4). The downcomer density values calculated using SRM void fractions can be used to correct the measured mass flowrate values using Equation 3. This equation merely replaces the erroneous ρ_{to} in Equation A-1 with the correct density ρ_t. Use of Equation A-3 will lower the recorded mass flowrate values closer to the true values.

$$\dot{m}_a = \dot{m}_o \sqrt{\frac{\rho_t}{\rho_{to}}} \tag{A-3}$$

$\dot{m}_a$ = true mass flowrate
$\dot{m}_o$ = recorded mass flowrate
ρ_{to} = flowmeter calculated density
ρ_t = true density.

Using SRM determined void fraction to correct the mass flowrate using Equations A-1 and A-3 produces an upper bound to the system mass flowrate. This upper bound is always lower than the recorded values when there is a coolant void fraction.

A similar approach was taken to calculate a lower bound to the mass flowrate. A void fraction was calculated for the hot leg which was an estimated maximum value. From this the lower boundary of the flowrate was determined. Equation A-4 expresses the volumetric flowrate at any time[A-2]

$$Q = \frac{\dot{m}a}{\rho_t} \tag{A-4}$$

Equations A-2, A-3, and A-4 are used to find an Equation A-5 for the void fraction in the hot leg.

$$\alpha = \frac{\frac{\dot{m}_o^2}{\rho_\ell \rho_{to}} \left(\frac{1}{Q}\right)^2 - 1}{\frac{\rho_g}{\rho_\ell} - 1} \tag{A-5}$$

Equation A-5 has been developed to calculate the void fraction from mass flowrate meter data as recorded. This equation corrects for the density error inherent to the flowmeter electronics when there is a coolant void fraction. It can be seen from this equation that void fraction varies in the same direction as Q. That is, for a given set of conditions void fraction is reduced as Q is reduced. At the beginning of the accident when the void fraction is still known to be zero but the system is depressurized, a Q value can be calculated. As the accident progressed, the Q value varied in a complex manner. Pump speed, fluid density, and pump head were all variables. It is suspected that the Q may have actually risen above the initial condition value within the first 20 minutes of the accident, and then dropped continually until the pumps were shut off. Since the real variation of Q with time is not known for the first 100 minutes, some assumptions had to be made. (1) It is assumed that the Q value rises somewhat above the initial condition value then drops continually after about 15 minutes. (2) There is no significant effect of the Q value on the mass flowrate lower bound calculation during the first 20 minutes if the initial condition Q is used because Q does not vary much. (3) After approximately 20 minutes the real Q value is always below the initial condition value. There is some evidence to support these assumptions in References A-5 and A-6 and in hand calculations using recorded data.

If this constant initial condition Q value is used in Equation A-5 while calculating void fraction as a function of time, the calculated void fraction values will be higher than the real void fraction. The density in the hot leg at this calculated void fraction would be too low, and the mass flowrate would in turn be too low. This technique of calculating the mass flowrate produces a lower bound for the real primary system hot legs provided the Q value used is higher than the true value. Figures A-1 and A-2 show the mass flowrate maximum and minimum bounds for the hot legs calculated in the preceding manner. The initial condition Q value was calculated using hot leg conditions at 5.5 minutes.

Figures A-1 and A-2 are the best estimates of the primary coolant hot leg mass flowrates during the first 100 minutes of the accident. These figures consist of a band which is estimated to contain the true value of the mass flowrate, and a mean value. The expected value is thought to lay between the mean value and the upper bound.

FIGURE A1 HOT LEG LOOP A MASS FLOWRATE
UPPER AND LOWER UNCERTAINTY BOUNDS

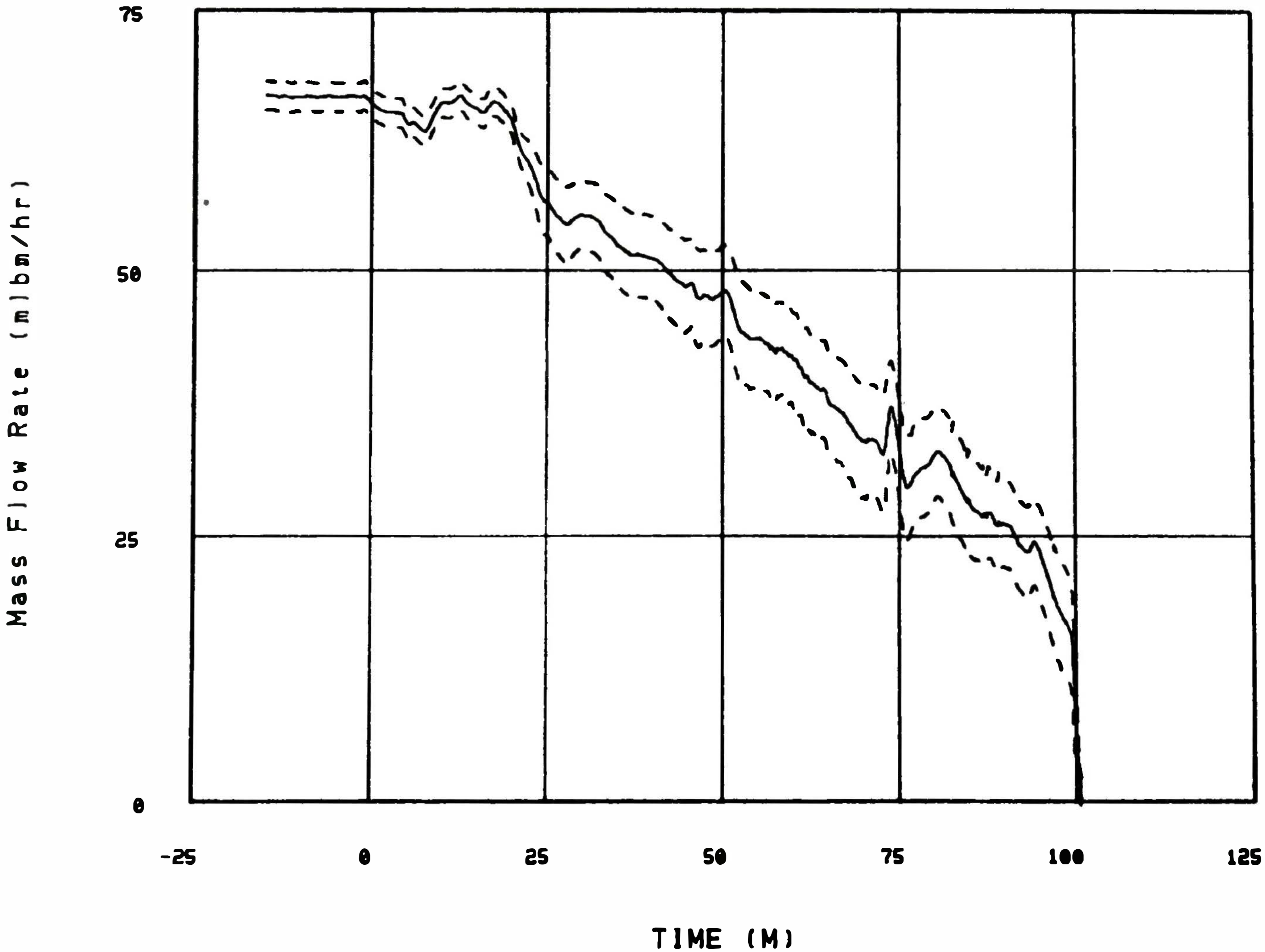
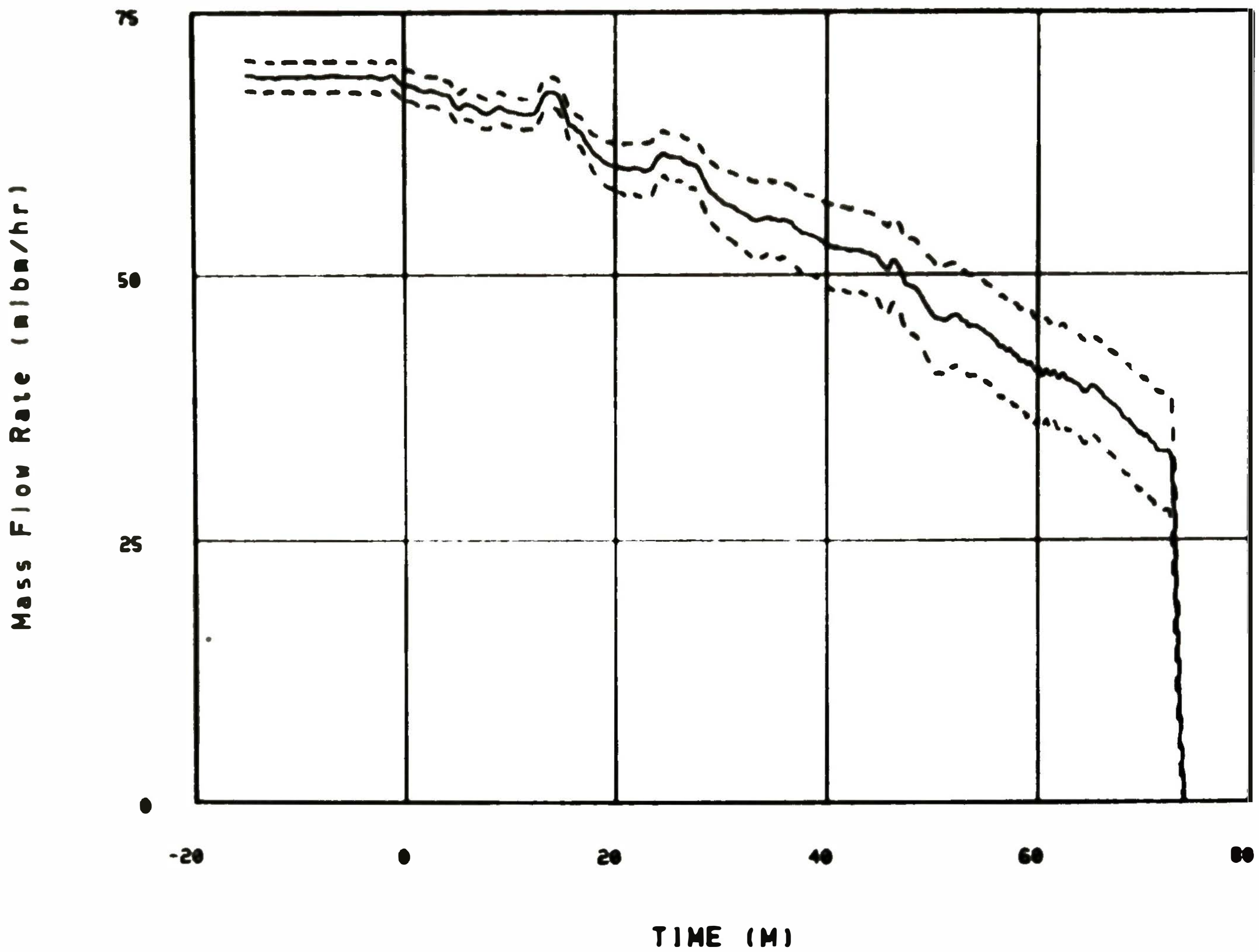


FIGURE A2 HOT LEG LOOP B MASS FLOWRATE
UPPER AND LOWER UNCERTAINTY BOUNDS



APPENDIX REFERENCES

A-1. H. W. King, et. al., "Hydraulics," New York, John Wiley & Sons, Inc., 1955.

A-2. J. J. Ginoux, "Two-Phase Flows and Heat Transfer with Applications to Nuclear Reactor Design Problems," Hemisphere Publishing Company, 1978.

A-3. R. D. McCormick. "TMI-2 Source and Intermediate Range Neutron Flux Monitor Data Report." EGG-TMI-7174, March 1986.

A-4. R. D. McCormick, "Determination of Void Fraction from Source Range Monitor and Mass Flowrate Data," EGG-TMI-7324, September 1986.

A-5. G. E. McCreery, et. al., "Primary Pump Power as a Measurement of Fluid Density During Bubbly Two-Phase Flow," Proceedings on Nuclear Reactor Thermal-Hydraulics, Volume II, 1983, pp 1519.

A-6. J. P. Adams, et. al., "Reactor Coolant Pump Trip Criteria and Transient Identification Technique for Pressurized Water Reactors," EPRI report in preparation, 1986.