UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

SEP 19 1983

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NO. 135, "HEAT TRANSFER AND HYDRAULICS IN FULL LENGTH 17 x 17 ROD FUEL BUNDLE DURING REFLOOD PHASE OF PWR LOCA

References:
(1) Letter from B. C. Rusche to S. Levine, "Extension of the PWR FLECHT Program" February 9, 1977
(2) Research Information Letter No. 67, "Reflooding of Simulated PWR Cores at Low Flow Rates," November 6, 1979
(3) L. E. Hochreiter, et al., "PWR FLECHT-SEASET Unblocked Bundle, Forced and Gravity Reflood Task: Data Report, NRC/EPRI/Westinghouse Report No. 7," NUREG/CR-1532, June 1980
(4) S. Wong and L. E. Hochreiter, "Analysis of the FLECHT-SEASET Unblocked Bundle Steam Cooling and Boiloff Tests," NRC/EPRI/Westinghouse Report No. 8, NUREG/CR-1533, January 1981
(5) N. Lee, et al., "PWR FLECHT-SEASET Unblocked Unbundle Forced and Gravity Reflood Task, Data Evaluation and Analysis Report," NRC/EPRI/Westinghouse Report No. 10, NUREG/CR-2256, November 1981

This memorandum transmits the results of a completed research task investigating the heat transfer and hydraulic in a full length 17 x 17 rod fuel bundle during the reflood phase of a pressurized water reactor (PWR) large-break loss-of-coolant accident (LOCA). This research was conducted as part of the Full-Length Emergency Core Heat Transfer-Separate Effects and System Effects Tests (FLECHT-SEASET). It is jointly sponsored by the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute and Westinghouse Electric Corporation. This 7-year research program is conducted by Westinghouse under the direction of the Program Management Group (PMG) from the three sponsoring parties.

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Part of the request of Reference 1 is that reflood experiments be conducted on the 17 x 17 rod design because the present nonproprietary data base is limited

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to the Westinghouse 15 x 15 rod design. The goals of the FLECHT-SEASET 17 x 17 Rod Unblocked Bundle Task were:

A. Provide an expanded reflood data base that will be useful in the development or verification of computational methods to predict the reflood thermal-hydraulic behavior of the new 17 x 17 core rod geometries.

B. Establish a baseline for comparison with the future FLECHT-SEASET 21-rod and 17 x 17 rod flow blockage tasks.

C. Evaluate the effects of bundle geometry on reflood heat transfer when compared to previous FLECHT 15 x 15 unblocked tests.

These goals were accomplished and the significant results can be summarized as follows:

A. Compared with the FLECHT (15 x 15) data, both bundle geometries produce approximately the same parametric effects for flooding rate, pressure, subcooling, initial cladding temperature, and peak power, if the integrated power per unit bundle flow area is preserved.

B. The existing PWR reflood data base has been expanded to include the new 17 x 17 rod experiments. A new and more general correlation has been developed which can predict the new data as well as the old 15 x 15 data.

C. The data supports the conclusion of RIL 67 that substantial heat transfer is available for reflood rate below 1 inch/second. This is due to the significant dispersed flow heat transfer observed for low flooding rates.

D. An improved data-based steam cooling correlation for low Reynolds number has been developed.

We recommend that these results be used to update the existing evaluation method and incorporated into any substantial revision to Appendix K to 10 CFR 50. The blockage task is expected to be completed in FY 1984 and a RIL to address the blockage issue will then be issued.

Robert B. Minogue

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosure: FLECHT-SEASET 17 x 17 Unblocked
Bundle Reflood Heat Transfer
Experiment Results

FLECHT-SEASET 17 x 17 UNBLOCKED BUNDLE REFLOOD HEAT TRANSFER EXPERIMENT RESULTS

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1.0 Introduction

This paper presents significant results of the FLECHT-SEASET Unblocked Bundle, Forced and Gravity Feed Task. The FLECHT-SEASET data (using 161 heater rods for the 17 x 17 core rod array) is compared with the earlier FLECHT data (15 x 15 core rod array) to illustrate the effect of bundle geometry (rod diameter and pitch) on PWR bottom reflood heat transfer (Section 4.0). Significant new data obtained from the FLECHT-SEASET program which was not obtained from the earlier FLECHT program are also presented (Section 5.0). Included are droplet diameter and velocity distributions above the quench front and steady-state steam cooling data. A summary of the results is given in Section 3.0.

The information presented is considered applicable for addressing the requirements of Appendix K to 10 CFR 50.46 relative to the evaluation of emergency cooling system performance in pressurized water reactors.

2.0 Background

Numerous experiments have been performed that provide data for the cooling of simulated pressurized water reactor (PWR) cores during bottom reflood at low flood rates. A summary of this data base was presented in Research Information Letter (RIL) No. 67 (Reference 1). The results of those experiments with regard to low flooding rate heat transfer are summarized in the following:

> Substantial heat transfer is available with reflood rates below 2.5 centimeters (1 inch) per second in unblocked bundles. Cooling by dispersed droplet flow was observed for reflood rates less than 2.5 centimeters per second.

The primary information base for RIL No. 67 was provided by the PWR Full-Length Emergency Cooling Heat Transfer (FLECHT) experiments. The FLECHT experiments, which are typical of reflood experiments using electrically heated rods, simulated the older 15 x 15 PWR nuclear fuel arrays. The earlier FLECHT experiments have been expanded with Separate Effects and System Effects tests (SEASET) in the FLECHT-SEASET program. These tests simulate the newer 17 x 17 PWR nuclear fuel arrays.

The goal of the FLECHT-SEASET Unblocked Bundle Forced and Gravity Feed Task were:

A. Provide an expanded reflood data base that will be useful in the development or verification of computational methods used to predict the reflood thermal-hydraulic behavior of the newer 17 x 17 core rod geometries (CRG).

B. Establish a baseline for comparison with the future FLECHT-SEASET 21-rod and 17 x 17 rod flow blockage tasks.

C. Evaluate the effects of bundle geometry on reflood heat transfer when compared to previous FLECHT 15 x 15 unblocked tests.

D. Provide single phase steam cooling heat transfer data.

3.0 Evaluation Summary

Significant conclusions supported by the FLECHT-SEASET Unblocked Bundle, Forced and Gravity Reflood Task include the following:

A. Core Rod Geometry (CRG) Effects

A comparison of the FLECHT data (15 x 15) with the FLECHT-SEASET data (17 x 17) supports the following conclusions:

1. Both CRGs produce approximately the same parametric effects for constant and variable flooding rate, pressure, subcooling, initial cladding temperature, and peak power. Significant dispersed flow heat transfer was observed for flooding rates less than 2.5 centimeters (1 inch) per second.
2. The 15 x 15 and 17 x 17 data can be correlated if the integrated power per unit bundle flow area and the initial stored energy are preserved. Thus, the FLECHT and FLECHT-SEASET data form a single PWR reflood data base.

B. Significant New Data

1. Droplet Distribution

   FLECHT-SEASET movies show the drop diameter frequency distribution above the quench front is well characterized by a log-normal distribution for all flooding rates including rates less than 2.5 centimeters (1 inch) per second. These data are very useful in the development of phenomenological and semi-empirical models for disperse flow heat transfer.

2. Steam Cooling

   The single-phase steam heat transfer correlation for 17 x 17 CRGs (in the low Reynolds number range of 2,500-33,000) is generally higher than the widely used Dittus-Boelter correlation. For Reynolds numbers above 33,000 the heat transfer correlation approaches the classical Dittus-Boelter correlation.

4.0 Core Rod Geometry Effects

A primary objective of the FLECHT-SEASET tests was to determine the effect of core rod geometry by comparison with earlier FLECHT data. A summary of the comparison is delineated in the following sections.

4.1 Parametric Effects

The FLECHT tests studied cladding temperature, heat transfer, rod quenching times, and bundle mass effluent fraction as a function of the parameters and parameter ranges listed in Table I. These same parameters were also examined in the FLECHT-SEASET tests. Table II lists the parameters and the ranges for the FLECHT-SEASET reflood tests. Both tests showed the following parametric effects:

A. Higher pressure causes a lower cladding peak temperature rise, a higher quench front velocity, and a shorter quench time; and

B. Higher power and initial cladding temperature cause a lower quench front velocity and a longer quench time.

C. Higher power causes an increase in rod temperature rise and higher initial temperature causes a decrease in rod temperature rise.

Quench time and cladding temperature rise for the above parameters are given in Appendix A for both FLECHT and FLECHT-SEASET tests.

Both FLECHT and FLECHT-SEASET showed the same trends in dispersed flow cooling. Increases in cladding temperature were terminated by dispersed flow cooling. A significant quantity of liquid in droplet form existed above the quench front which aided in cooling the upper rod elevation. Movies indicated typical droplet sizes of 1-2 mm. Heat transfer coefficients were influenced by the amount of water in the vapor, with both heat transfer and water content generally increasing with reflooding velocity. Except for the highest flooding velocities, vapor superheat was found to increase sharply with distance above the quench front. Figure 1 shows the sensitivity of peak cladding temperature rise to flooding rate for the FLECHT tests. A similar plot for the FLECHT-SEASET tests is shown in Figure 2. The cladding temperatures indicate there was not a dramatic deterioration in heat transfer at 2.5 centimeters (1 inch) per second.

4.2 Scaling Logic

To quantify the effect of core rod geometry on reflood heat transfer, four overlap tests linking the previous 15 x 15 FLECHT Low Flooding Rate Cosine tests and the current 17 x 17 FLECHT-SEASET tests were performed. A list of these tests is given in Table III. The test conditions for the FLECHT-SEASET overlap tests were based on the assumption that quench times and heat transfer coefficients for the overlap tests would be the same if the integrated power per unit bundle flow area was preserved. For detailed equational forms of the scaling methods see Reference 2.

Figures 3 and 4 show the quench elevation and heat transfer coefficient for overlap runs Test 31805 (FLECHT-SEASET) and Test 02414 (FLECHT). There is good agreement until the time top-down quenching occurs at higher elevations. These differences at higher elevations are believed to be thimble effects and not core rod geometry effects. Comparison plots for the three remaining overlap tests are given in Appendix A.

The applicability of the scaling logic for the overlap tests is further demonstrated by the correlation of the FLECHT and FLECHT-SEASET data. A heat transfer correlation was developed for the earlier FLECHT tests. It was a two-part correlation, one equation to predict quench elevation and another for heat transfer as a function of distance above the quench front. The correlations fit the FLECHT data quite well, such as the 17 x 17 assembly rod bundle of the FLECHT-SEASET tests. A new FLECHT type correlation has been developed in dimensionless form. One of the correlation parameters is the ratio of the integrated bundle power to bundle flow area. This new formulation correlates both the 15 x 15 FLECHT and 17 x 17 FLECHT-SEASET data. Figures 5, 6, and 7 show a comparison of data for quench elevation with the correlation for FLECHT (cosine and skewed) and FLECHT-SEASET tests. The correlation fits all the data up to the time that the top-down secondary quench front becomes important. The heat transfer correlation compared similarly with data. This further indicates that an important parameter for comparing reflood data for different core rod geometries is integrated power per unit bundle flow area. A description and listing of the FLECHT-SEASET heat transfer correlation is given in Appendix B. Also presented is a range of application for the key correlation parameters.

5.0 Significant New Data

Improved instrumentation and high-speed movie techniques, coupled with an expanded test matrix which included steam cooling tests, has resulted in data from the FLECHT-SEASET program which was not obtained in the earlier FLECHT tests. The following sections discuss significant new data.

5.1 Droplet Distribution

High-speed, black-and-white motion pictures were taken through viewing ports of the bundle housing for selected tests of the FLECHT-SEASET 161-rod unblocked bundle task. These films were analyzed to obtain droplet size and velocity distribution data.

5.1.1. Droplet Size Distribution

Movies for selected tests were analyzed to obtain droplet frequency distribution data for several elevations above the quench front. A histogram of the droplet diameter frequency for Test 30518 (FLECHT-SEASET) is shown in Figure 8. Also shown is a curve fit for a log-normal distribution. For all tests examined the log-normal distribution gave a good representation of the data. (This distribution was observed even for flooding rates less than 2.5 centimeters (1 inch) per second.) Droplet distribution data are presented in Appendix A.

5.1.2 Droplet Velocity Distribution

Figure 9 shows the droplet velocity distribution data for Test 30518 (FLECHT-SEASET). The large scatter in the data is thought to be due to variation in local flow due to the complication of the core rod geometry. (The scatter prevented the correlation of the data.)

5.1.3 Parametric Effects

The FLECHT-SEASET droplet data was not sufficient to provide a thorough parametric study; however, the effects of several parameters were observed:

A. System pressure in the range of 1.4E5-2.8E5 Pa (20-40 psia) showed little effect on the mean drop diameter.

B. The mean drop diameter increased with increasing flooding rate.

5.2 Steam Cooling

As part of the FLECHT-SEASET unblocked bundle task, a series of forced convection steam cooling tests at low Reynolds numbers were conducted for 17 x 17 core rod arrays. The forced convection steam cooling data were formulated into a conventional forced convection heat transfer correlation. In Figure 10, the FLECHT-SEASET data based correlation in the range $2,500 < Re < 25,200$ is compared with the conventional Dittus-Boelter correlation. The FLECHT-SEASET data based correlation gives higher heat transfer relative to the Dittus-Boelter correlation in the low Reynolds number range. At higher Reynolds number the correlations begin to merge. The equational form of the FLECHT-SEASET correlation is given by:

$$\begin{aligned}
Nu/Pr^{0.333} &= 7.86 && Re < 2,000 \\
Nu/Pr^{0.333} &= -24.55 + 0.0162\ Re && 2,000 < Re < 2,500 \\
Nu/Pr^{0.333} &= 0.0797\ Re^{0.6774} && 2,500 < Re < 25,200 \\
Nu/Pr^{0.333} &= 0.023\ Re^{0.8} && Re > 25,200
\end{aligned}$$

where:

Nu = Nusselt number
Re = Reynolds number
Pr = Prandtl number

Because the FLECHT-SEASET experiments were conducted at low pressure (2.76×10^5 Pa or 40 psia), the rod to vapor temperature difference was small (~15°C). Thus, the thermal radiation component of the total heat transfer was negligible. In addition, the fluid properties can be calculated at the vapor temperature.

Oak Ridge National Laboratory (ORNL) has developed a convective steam cooling heat transfer correlation for 17 x 17 CRGs at high pressure (3.45×10^6 Pa or 500 psia.) In equational form the ORNL correlation is given by:

$$Nu = 0.021 \left[\frac{\rho_{rod}}{\rho_{vapor}} \right]^{0.8} Re^{0.8}\ Pr^{0.4}$$

where

ρ_{rod} = fluid density at rod temperature

ρ_{vapor} = fluid density at the vapor temperature.

Nu, Re and Pr are evaluated at the rod temperatures.

The above correlation has been correlated with data in the following range:

$$3,500 < Re < 10,000$$

$$1.1 < T_{rod}/T_{vapor} < 1.6$$

where

Re = vapor Reynolds number
T_{rod} = rod temperature
T_{vapor} = vapor temperature.

A comparison with the FLECHT-SEASET correlation indicates significant differences. This is believed to be primarily due to the pressure difference in the test conditions. The FLECHT-SEASET correlation is applicable to low pressure (~40 psia) and the ORNL correlation is applicable to high pressure (~500 psia).

Because of the influence of geometry effects, the FLECHT-SEASET and ORNL correlations are recommended only for square rod bundle geometry with a pitch-to-diameter ratio near 1.33.

6.0 Bundle Distortion and Rod Failure

During the testing of FLECHT-SEASET 161-rod unblocked bundle several hardware problems occurred. The first was heater rod distortion or bowing and the second was electrical failure of heater rods. The effect on the FLECHT-SEASET data is discussed in the following sections.

6.1 Rod Distortion

During the testing of FLECHT-SEASET 161-rod unblocked bundle, distortion of the heater rods was observed through the side viewing windows. A thorough examination of the bundle at the conclusion of the test program indicated the distortion was due primarily to bowing of the bundle filler pieces. Most of the rod distortion occurred between the 1.52-m and 2.13-m (60- and 84-inch) elevations. An analysis was performed to determine the point at which the center region of the bundle bowed such that the center rods could not be utilized for heat transfer correlation development. The analysis included a comparison of repeat tests and a statistical analysis of the heat transfer data. It was concluded that data generated from Test 34711 (FLECHT-SEASET) and following could not be utilized for heat transfer correlation development. Thus, only tests prior to Test 34711 were used in the development of heat transfer correlations.

6.2 Failed Rods

During the testing of the FLECHT-SEASET 161-rod unblocked bundle, eight heater rods either failed or were determined to be defective with a high probability of failure. These eight rods for the remainder of the test program were left unpowered. The power of the remaining rods was increased by 5.3 percent to maintain the same power to bundle flow area ratio. The effects of failed rods on the hot rods' heat transfer coefficients and the two-phase flow structure within the bundle were extensively analyzed in the FLECHT cosine and skewed test series. Results from these analyses showed that only the rods in the first row surrounding a failed rod are affected. Similar analyses were performed for the FLECHT-SEASET unblocked bundle unpowered rods and the same results were obtained. Thus, only data from rods two rows from a failed rod was used for correlation development.

7.0 Conclusions

The FLECHT-SEASET Unblocked Bundle, Forced and Gravity Feed Task has provided an experimental reflood data base for the newer 17 x 17 core rod arrays. Comparisons with the earlier FLECHT 15 x 15 data have shown that the effect of core rod geometry is predictable in terms of integrated power per unit bundle flow area. Thus, both the FLECHT and FLECHT-SEASET form a single data base for PWR reflood heat transfer. In addition, the FLECHT-SEASET data support the conclusions stated in RIL No. 67 that:

> Substantial heat transfer is available for reflood rates below 2.5 centimeters (1 inch) per second in unblocked bundles. Cooling by dispersed droplet flow was observed for reflood rates less than 2.5 centimeters per second.

The FLECHT-SEASET unblocked bundle task has provided new data in the areas of droplet distribution above the quench front and steam cooling for 17 x 17 core rod geometries. Thus, a data base has been established where previously little or none existed. These data will be valuable for understanding, quantifying and modeling reflood thermal-hydraulic phenomena and for the evaluation of existing models for emergency cooling system performance in pressurized water reactors.

8.0 Recommendations

The FLECHT 15 x 15 and FLECHT-SEASET 17 x 17 data form a single PWR reflood data base which is recommended for consideration in the application and appraisal of reflood evaluation models. In addition, the FLECHT and FLECHT-SEASET data can be used to support changes to Appendix K.

References

1. Research Information Letter No. 67, "Reflooding of Simulated PWR Cores at Low Flow Rates."

2. L. E. Hochreiter et al., "PWR FLECHT-SEASET Unblocked Bundle, Forced and Gravity Reflood Task: Data Report," NRC/EPRI/Westinghouse Report No. 7, NUREG/CR-1532, June 1980.

3. S. Wong and L. E. Hochreiter, "Analysis of the FLECHT-SEASET Unblocked Bundle Steam Cooling and Boiloff Tests," NRC/EPRI/Westinghouse Report No. 8, NUREG/CR-1533, January 1981.

4. T. M. Anklam, "ORNL Small Break LOCA Heat Transfer Test Series 1: Rod Bundle Heat Transfer Analysis," ORNL/NUREG/TM-445, July 1981.

5. H. C. Yeh, C. E. Dodge, and L. E. Hochreiter, "Reflood Heat Transfer Correlation," Nuclear Technology, Vol. 46, 473, 1979.

6. G. P. Lilly, H. C. Yeh, C. E. Dodge, and S. Wong, "PWR FLECHT Skewed Profile Low Flooding Rate Test Series Evaluation Report," WCAP-9183, November 1977.

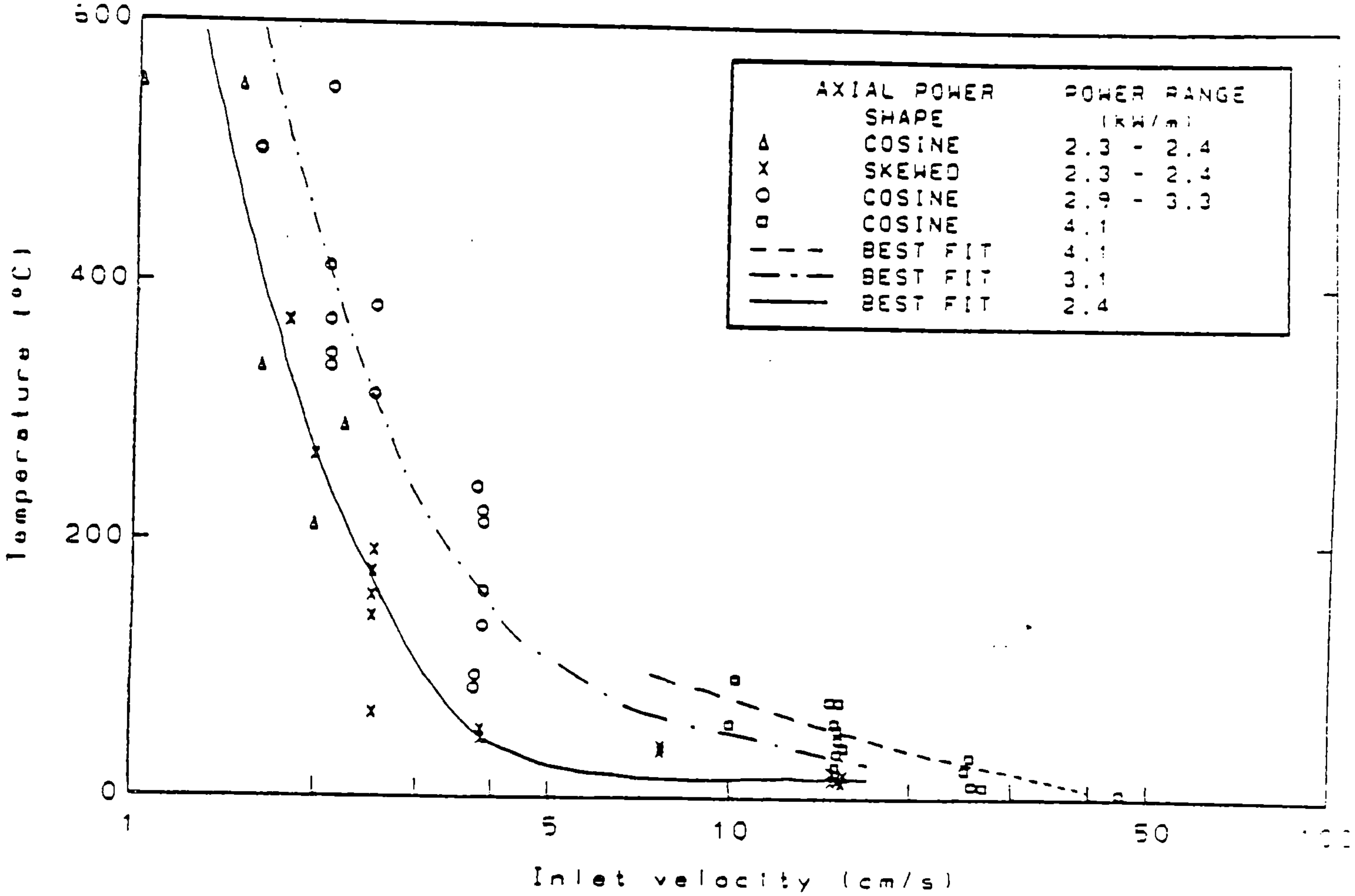

Figure 1. Temperature rise at location of highest temperatures during FLECHT reflood tests as a function of inlet flooding velocity.

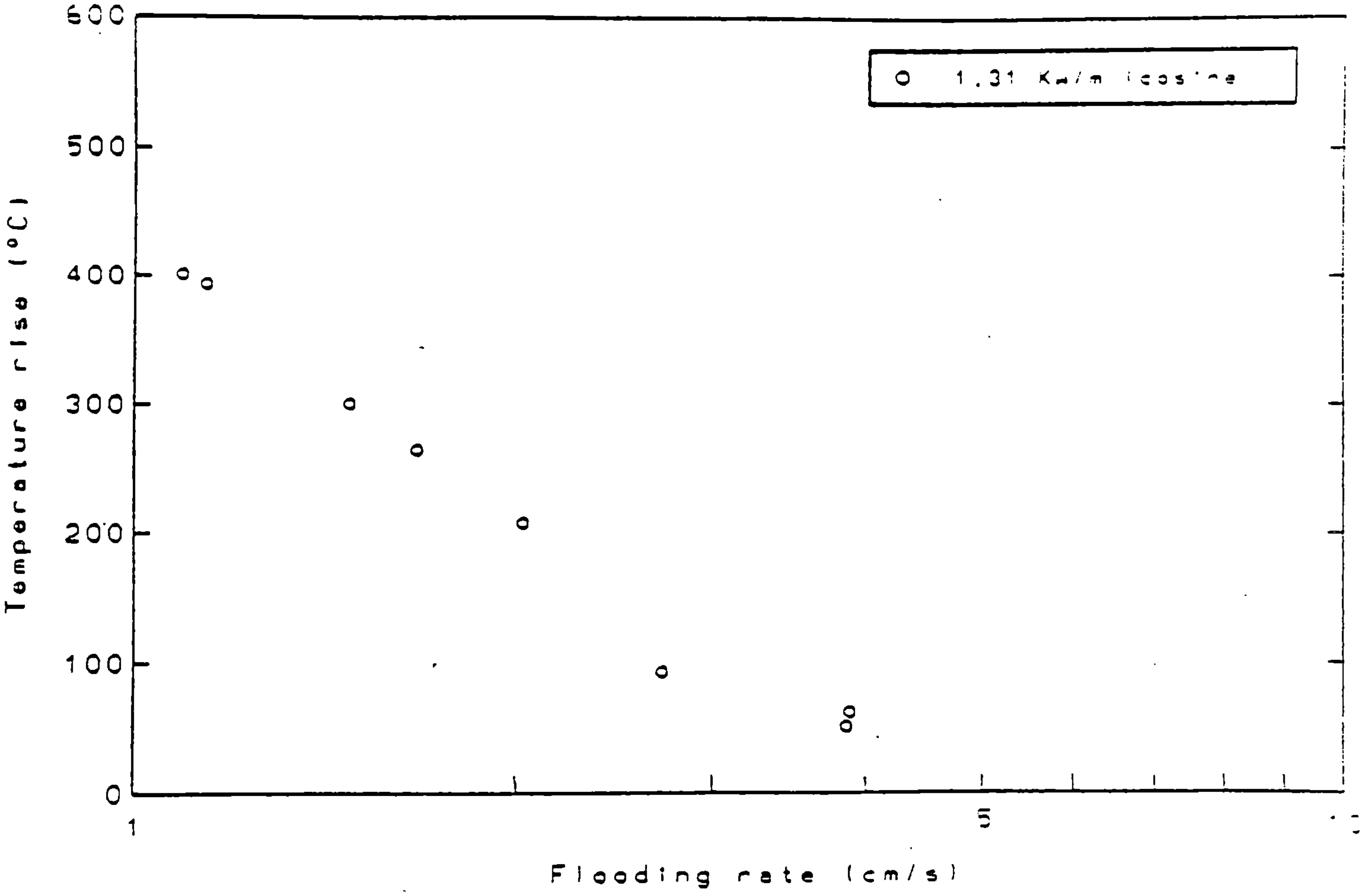

Figure 2. Temperature rise at location of highest temperature during FLECHT-SEASET reflood tests as a function of inlet flooding velocity.

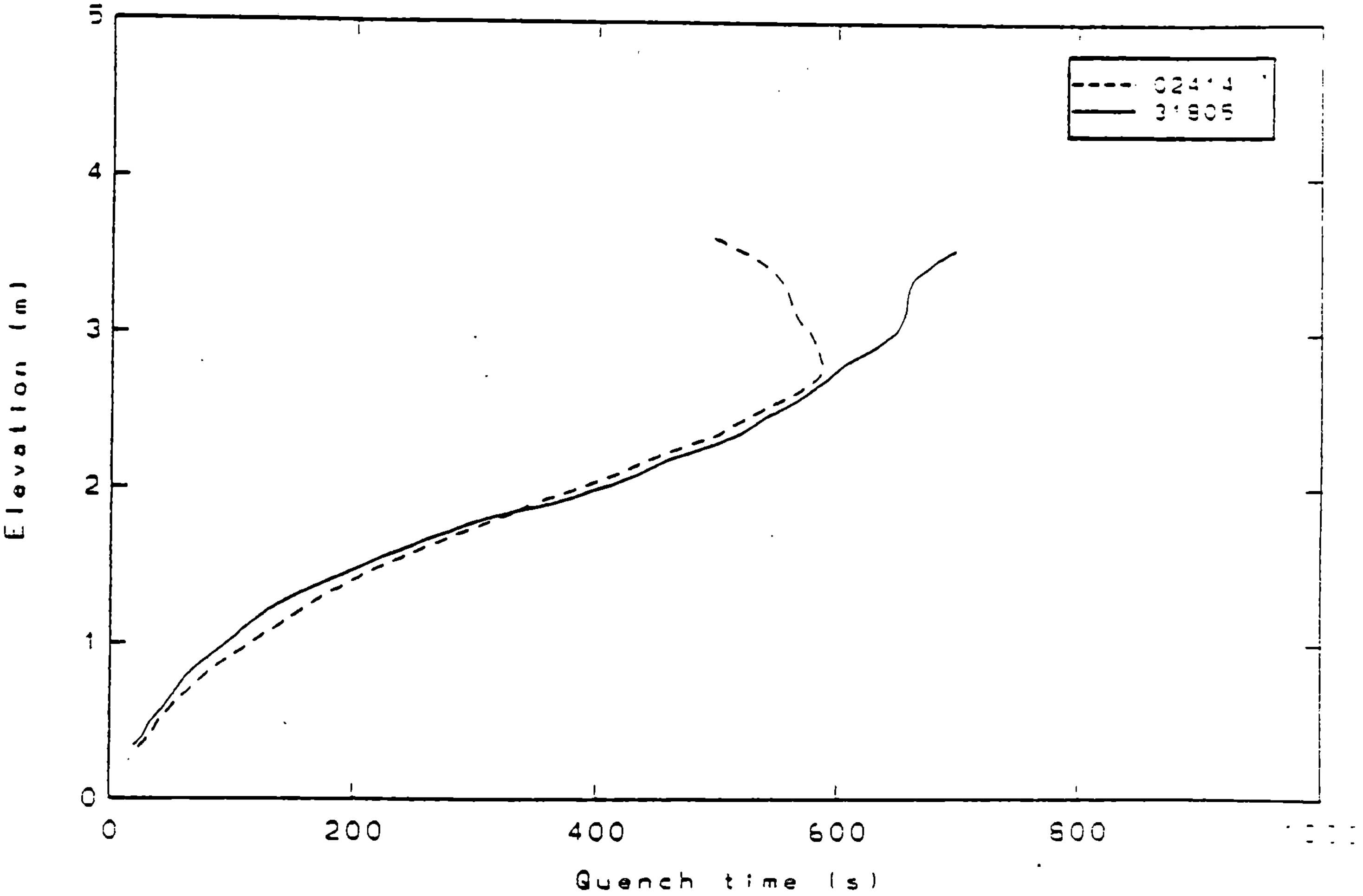

Figure 3. Average quench times for runs 31805 (FLECHT-SEASET) and 02414 (FLECHT).

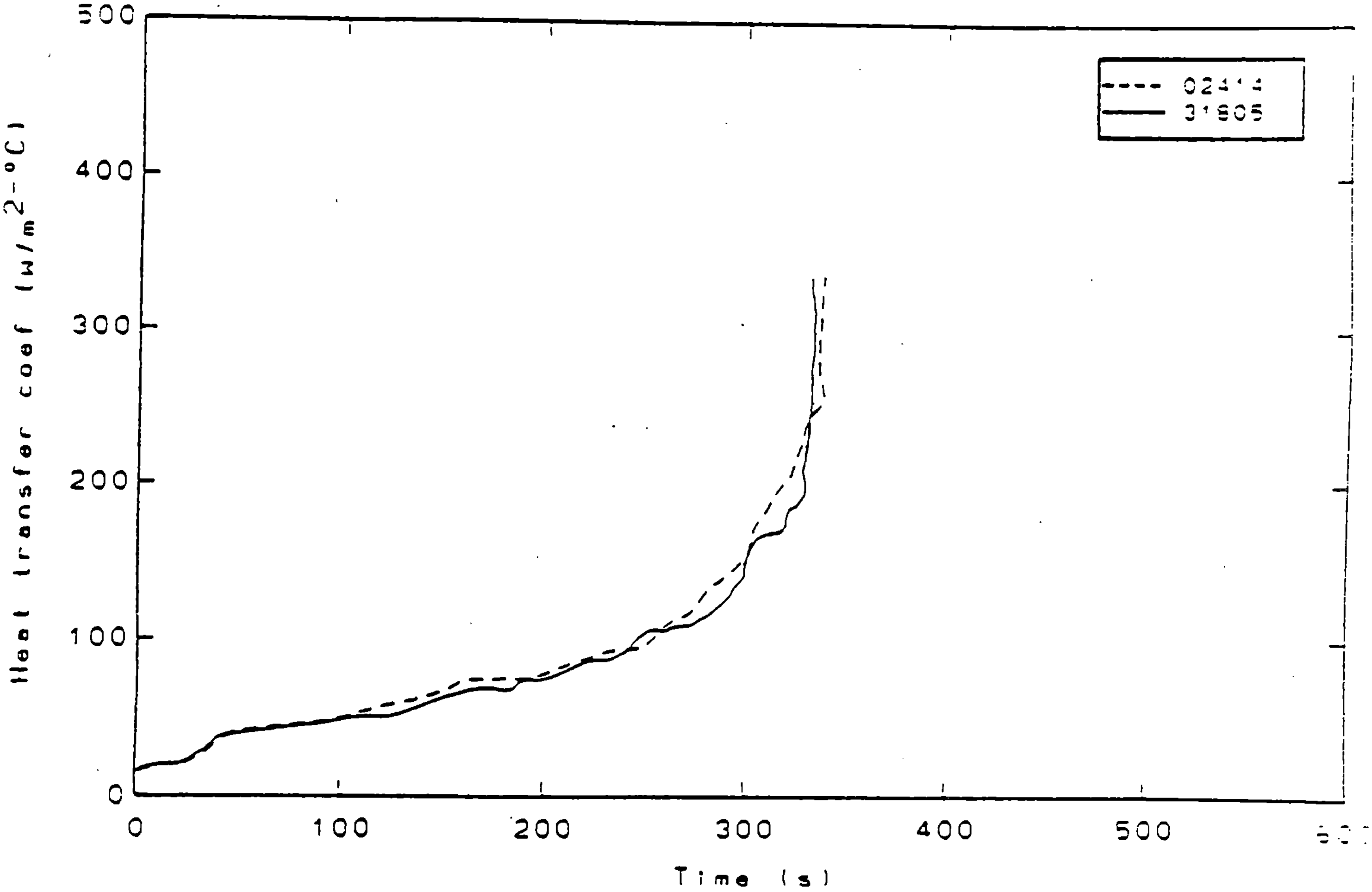

Figure 4. Heat transfer coefficient for runs 31805 (FLECHT-SEASET) and 02414 (FLECHT).

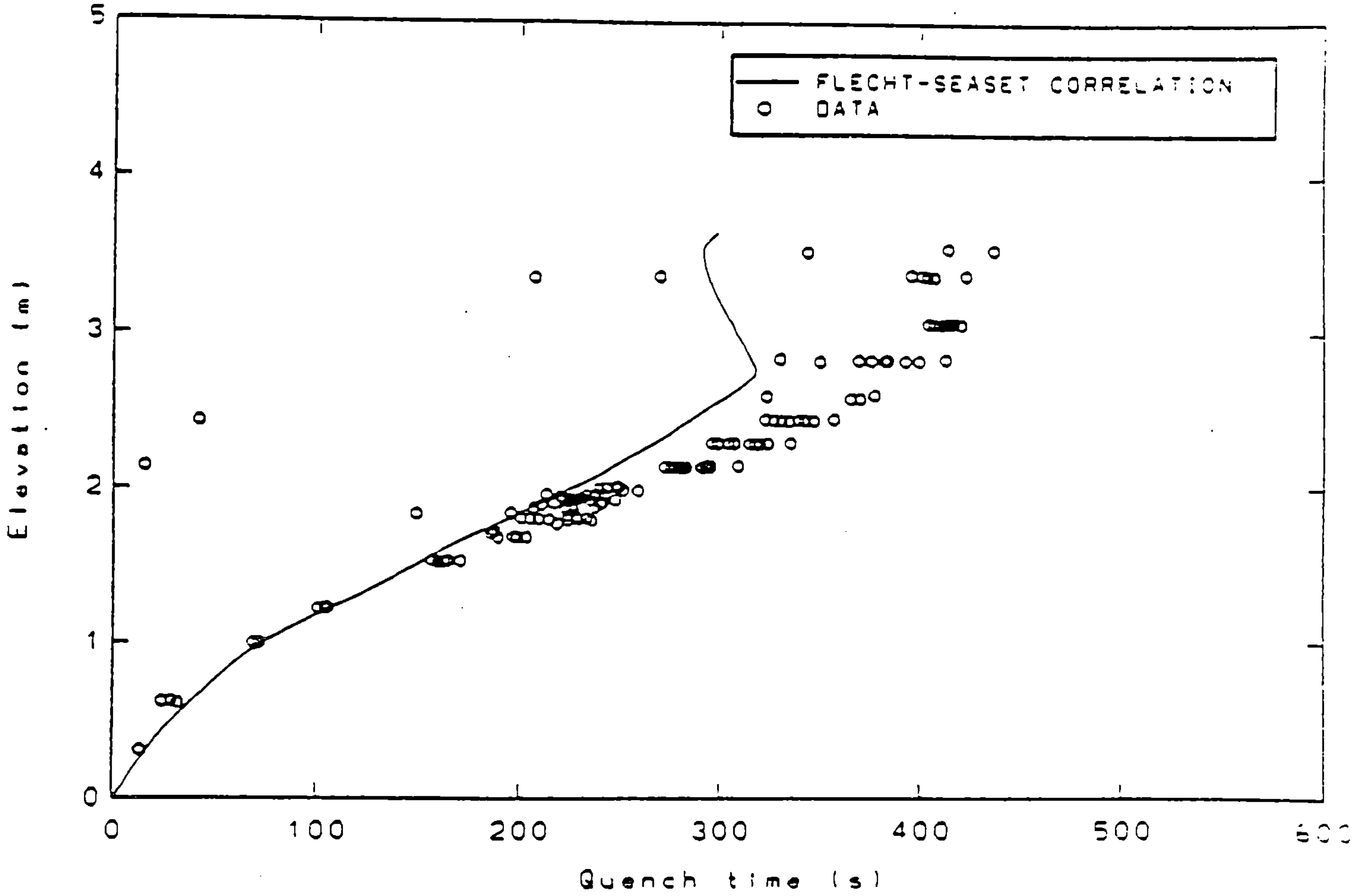

Figure 5. Quench time for FLECHT-SEASET run 31203.

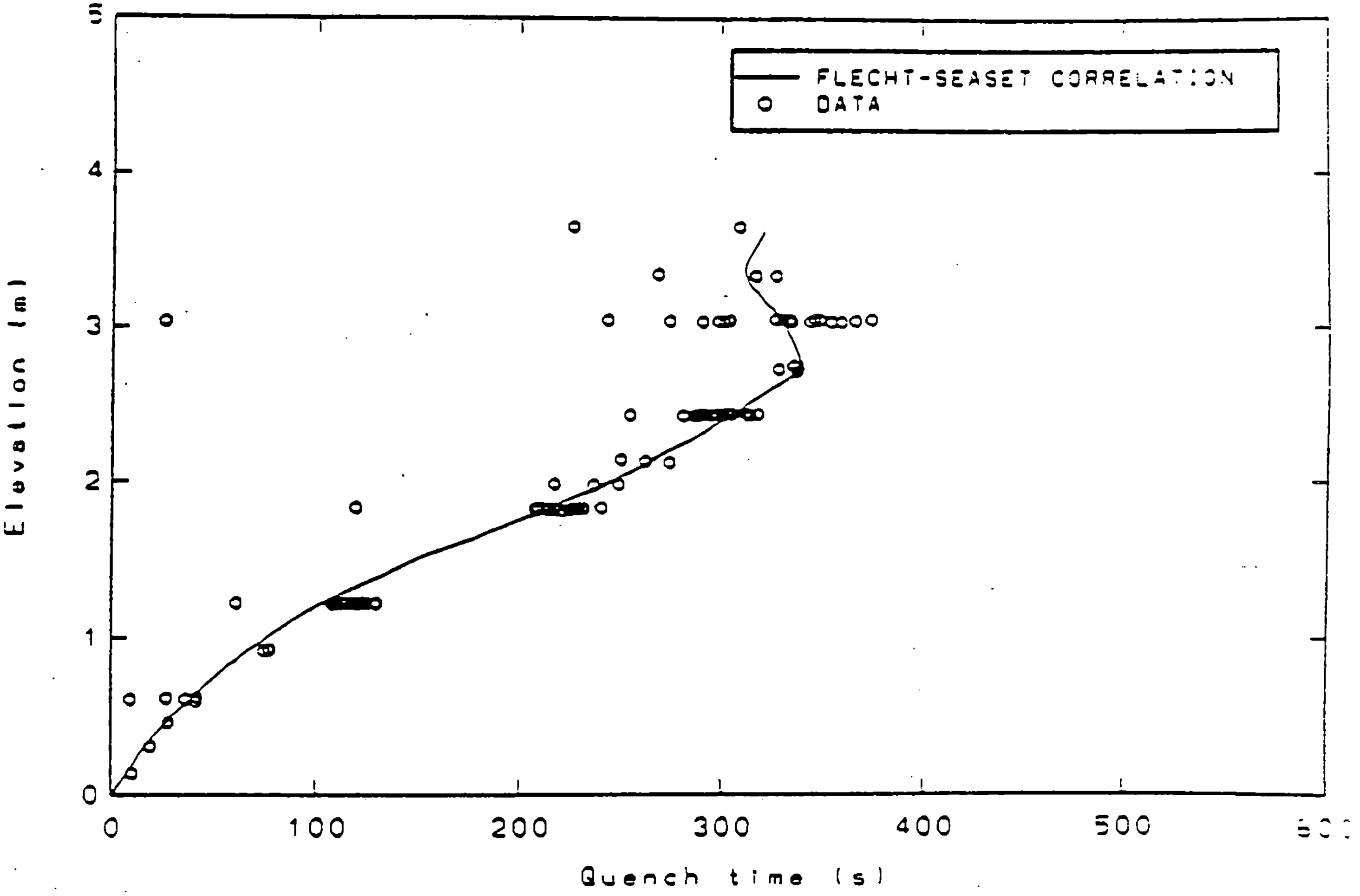

Figure 6. Quench time for FLECHT (COSINE) run 03113.

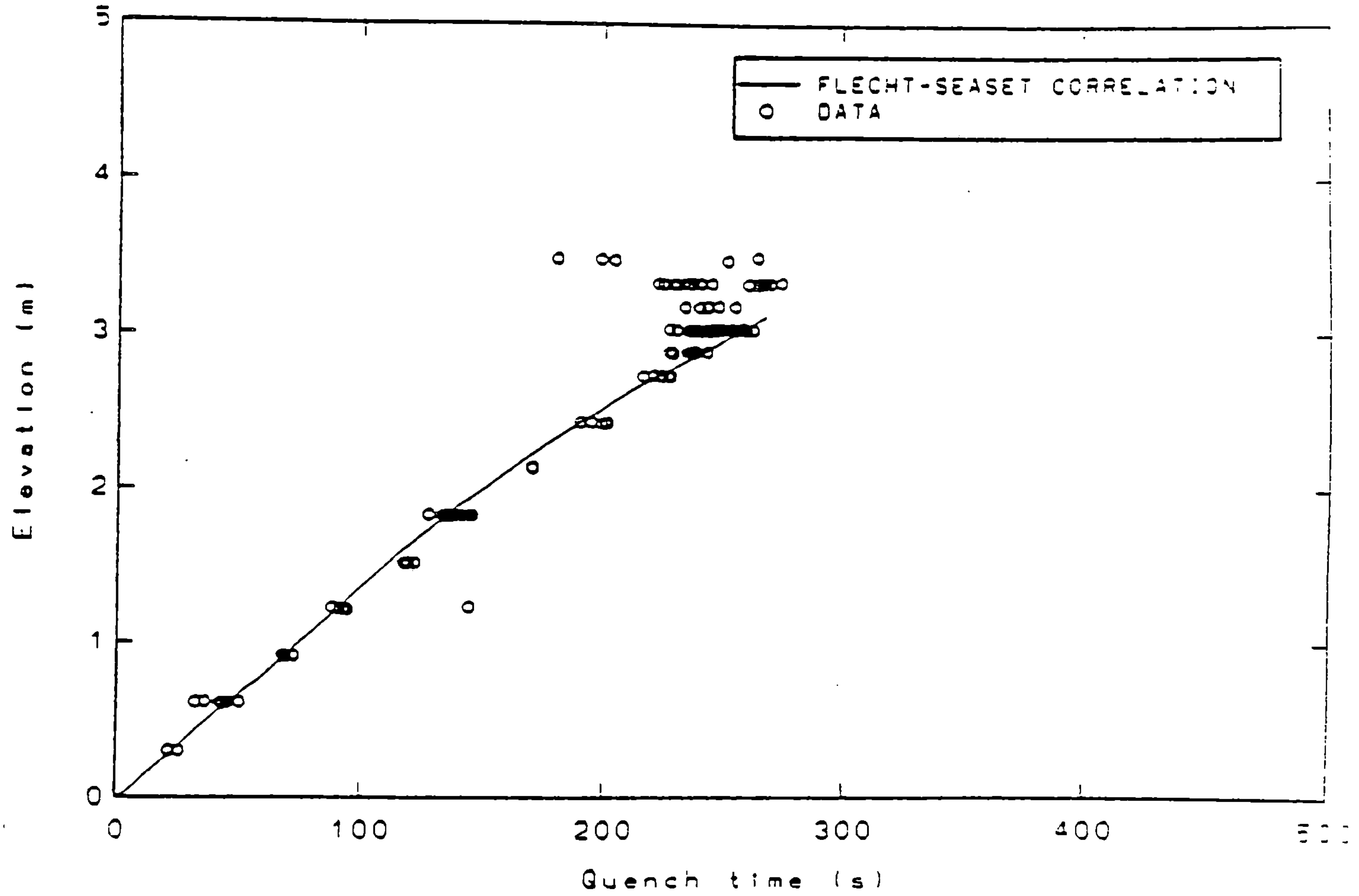

Figure 7. Quench time for FLECHT (SKEWED) run 11618.

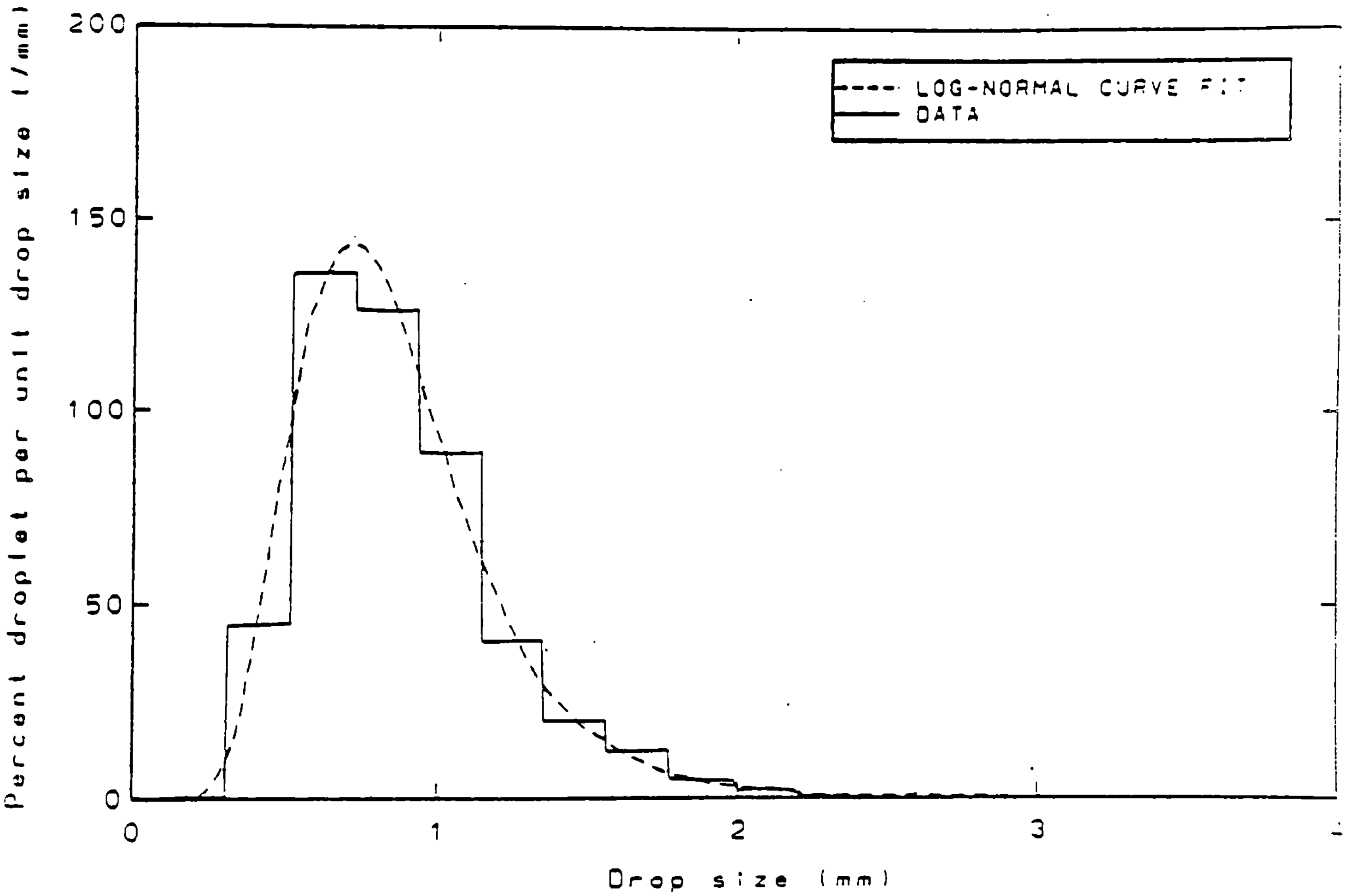

Figure 8. Droplet diameter frequency distribution for run 30518.

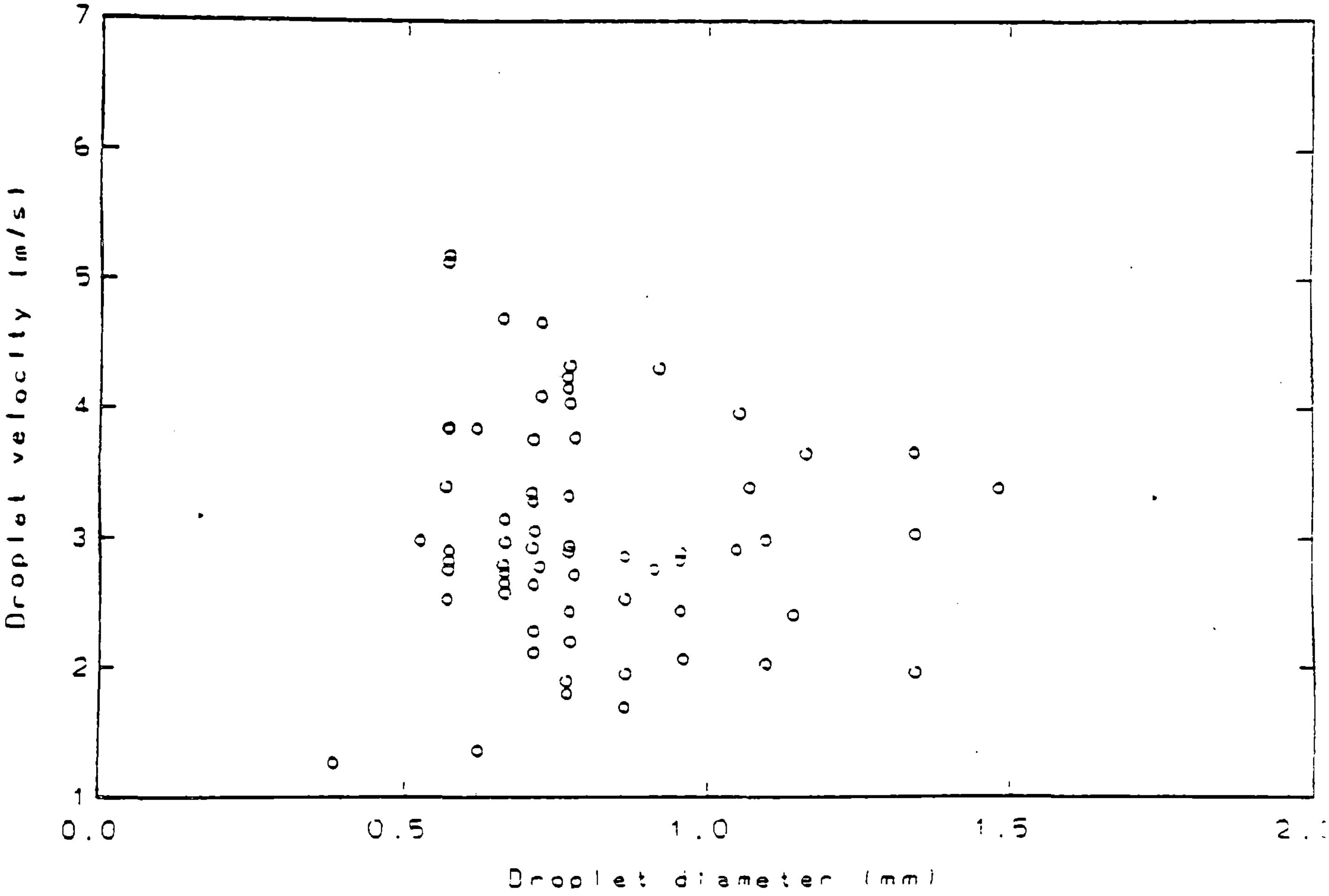

Figure 9. Droplet velocity distribution for run 30518.

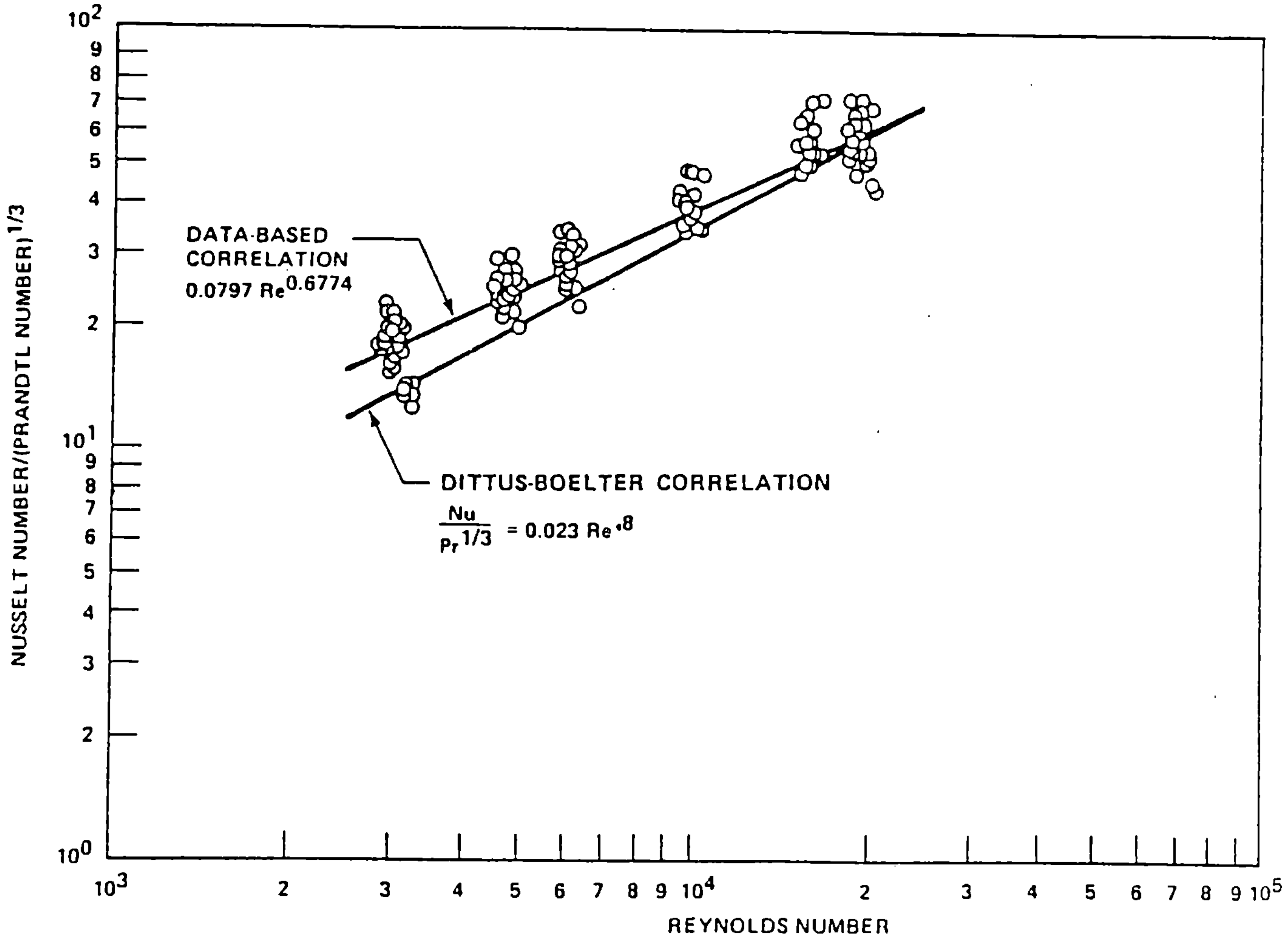

Figure 10. Data-Based Nusselt Number Versus Reynolds Number for Eight Steam Cooling Tests

Table I

RANGE OF PARAMETERS IN THE FLECHT EXPERIMENTS

Parameter	Range (SI Units)	Range (British Units)
Inlet Flooding Rate	1.0 - 46 cm/sec	0.4 - 18 inch/sec
System Pressure	0.1 - 0.62 MPa	15 - 90 psia
Peak Power	0.7 - 4.6 kW/m	0.2 - 1.4 kW/ft
Initial Cladding Temperature	150 - 1200°C	300° - 2200°F
Coolant Inlet Subcooling	9 - 105°C	16 - 189°F
Local Channel Area	0 - 100 Percent	Same
Bundle Area Blockage	0 - 80 Percent	Same
Decay Power	ANS + 20% -- ANS-15%	Same
Axial Power Profile	cosine, skewed	Same
Bundle Radial Power Profile	'FLECHT', uniform	Same

TABLE II

PARAMETRIC EFFECTS, SUMMARY OF RUN NUMBERS AND RANGE OF PARAMETERS

	Pressure		Rod Initial Temperature		Rod Peak Power		Flooding Rate		Subcooling		
Parameter	MPa	(psi)	°C	(°F)	kW/m	(kW/ft)	cm/sec	(in/sec)	°C	(°F)	Run Number
Flooding Rate	0.276	(40)	863	(1585)	2.3	(0.7)	2.46	(0.97)	80	(144)	31504
	0.276	(40)	871	(1600)	2.3	(0.7)	2.06	(0.81)	79	(143)	31805
	0.276	(40)	872	(1601)	2.3	(0.7)	3.84	(1.51)	78	(141)	31203
	0.276	(40)	869	(1597)	2.3	(0.7)	7.65	(3.01)	78	(141)	31302
	0.276	(40)	872	(1601)	2.3	(0.7)	15.5	(6.1)	78	(140)	31701
	0.269	(39)	882	(1620)	1.3	(0.4)	1.5	(0.59)	79	(142)	34006
	0.276	(40)	879	(1615)	1.3	(0.4)	3.86	(1.52)	78	(141)	31021
Pressure	0.276	(40)	863	(1585)	2.3	(0.7)	2.46	(0.97)	80	(144)	31504
	0.138	(20)	891	(1639)	2.3	(0.7)	2.72	(1.07)	98	(177)	34209
	0.138	(60)	887	(1629)	2.3	(0.7)	2.64	(1.04)	65	(117)	32013
	0.276	(40)	869	(1597)	2.3	(0.7)	7.65	(3.01)	78	(141)	31302
	0.131	(19)	871	(1600)	2.3	(0.7)	7.9	(3.11)	98	(176)	31108
Initial Cladding Temperature	0.276	(40)	872	(1601)	2.3	(0.7)	3.84	(1.51)	78	(141)	31203
	0.269	(39)	531	(987)	2.3	(0.7)	3.86	(1.52)	77	(139)	30817
	0.276	(40)	257	(494)	2.3	(0.7)	3.86	(1.52)	78	(141)	30518
Subcooling	0.276	(40)	863	(1585)	2.3	(0.7)	2.46	(0.97)	80	(144)	31504
	0.276	(40)	892	(1638)	2.4	(0.74)	2.49	(0.98)	8	(14)	35114

TABLE II

PARAMETRIC EFFECTS, SUMMARY OF RUN NUMBERS AND RANGE OF PARAMETERS (Continued)

	Pressure		Rod Initial Temperature		Rod Peak Power		Flooding Rate		Subcooling		
Parameter	MPa	(psi)	°C	(°F)	kW/m	(kW/ft)	cm/sec	(in/sec)	°C	(°F)	Run Number
Peak Power	0.138	(20)	891	(1636)	2.4	(0.72)	2.72	(1.07)	98	(177)	34209
	0.138	(20)	883	(1621)	1.3	(0.4)	2.72	(1.07)	96	(172)	31922
	0.276	(40)	872	(1601)	2.3	(0.7)	3.84	(1.51)	78	(141)	31203
	0.276	(40)	879	(1615)	1.3	(0.4)	3.86	(1.52)	78	(141)	31021
	0.276	(40)	878	(1612)	3.28	(1.0)	3.99	(1.57)	79	(142)	34524
Initial Flooding Rate (Variable Flooding Rate Runs)	0.276	(40)	871	(1600)	2.3	(0.7)	2.06	(0.81)	79	(143)	31805
	0.276	(40)	888	(1631)	2.3	(0.7)	16.2 6.36	(5 sec) →2.08 (5 sec) →0.82	79	(142)	32333
	0.138	(20)	891	(1636)	2.4	(0.72)	2.72 16.6 →2.49 →1.57	(1.07) (5 sec) (100 sec)	98	(177)	34209
	0.138	(20)	888	(1630)	2.3	(0.7)	6.53 →0.98 →0.62	(5 sec) (200 sec)	99	(179)	32235
Transient Subcooling	0.276	(40)	863	(1585)	2.3	(0.7)	2.46	(0.97)	80 →65	(144 →11.7)	31504
	0.276	(40)	888	(1631)	2.4	(0.74)	2.46	(0.97)	79 →12	(143 →21)	34316
	0.276	(40)	892	(1638)	2.4	(0.74)	2.49	(0.98)	8	(14)	35114

TABLE III

OVERLAP TESTS

Run	Series	Rod Peak Power kW/m (Kw/ft)	Flooding Rate cm/sec (in/sec)	Rod Initial Temperature °C (°F)	Subcooling °C (°F)	Pressure MPa (psi)
03113	LFC[a]	0.247 (0.81)	3.81 (1.5)	871.1 (1600)	75.6 (136)	0.262 (38)
31203	SS[a]	0.213 (0.7)	3.81 (1.5)	871.1 (1600)	77.8 (140)	0.276 (40)
00904	LFC	0.259 (0.85)	3.81 (1.5)	536.7 (998)	77.8 (140)	0.283 (41)
30817	SS	0.213 (0.7)	3.81 (1.5)	537.8 (1000)	77.8 (140)	0.276 (40)
03709	LFC	0.247 (0.81)	3.81 (1.5)	317.2 (603)	78.3 (141)	0.138 (20)
30619	SS	0.213 (0.7)	3.81 (1.5)	260.0 (500)	77.8 (140)	0.138 (20)
02414	LFC	0.256 (0.84)	2.06 (0.81)	871.1 (1600)	76.7 (138)	0.276 (40)
31805	SS	0.213 (0.7)	2.03 (0.8)	871.1 (1600)	77.8 (140)	0.276 (40)

---

a. LFC: Low flooding cosine test (FLECHT)
SS: FLECHT-SEASET

APPENDIX A

SUPPLEMENTARY DATA

1. Parametric Effects for FLECHT and FLECHT-SEASET Tests

In this section the FLECHT-SEASET rod temperature rise and bundle quench time trends are compared with previous FLECHT results for the test parameters. The test conditions for the comparisons are not always the same. However, the main purpose of the comparisons is to examine the trends with each parameter, rather than the absolute values of temperature rise or quench time. The quench times plotted for the FLECHT skewed tests are at the 3.05 m elevation while the FLECHT and FLECHT-SEASET cosine tests are at 1.83 m elevation. This typically results in longer quench times for the skewed tests. The data are presented in Figures A-1 through A-7.

2. FLECHT and FLECHT-SEASET Overlap Tests

The test matrix of the FLECHT-SEASET tests included four tests which overlapped with the earlier FLECHT tests. These tests are listed in Table III of the RIL. The data for the overlap tests are presented in Figures A-8 through A-15. Presented are plots of quench elevation and heat transfer coefficients.

3. Droplet Distribution

High speed movies were taken of the disperse flow above the quench front for selected reflood tests. The movies were analyzed to determine the droplet diameter frequency distribution. The distributions were plotted as histograms as shown in Figure A-16 through A-28. Also indicated are curve fits of the data. The curves are log-normal functions given by

$$F(x) = \frac{\eta}{(X-\varepsilon)\sqrt{2\pi}} \exp\left[-\frac{1}{2}\eta^2 \left[\frac{\gamma}{\eta} + \mathrm{Ln}(X-\varepsilon)\right]^2\right]$$

where

X = drop diameter

$F(X)$ = percent droplet per unit drop diameter at the drop diameter X

ε = lower bound on X

The log-normal function is normalized such that

$$\int_{\varepsilon}^{\infty} f(x)dx = 1$$

The parameters η and γ were estimated from the following:

$$\mu = \frac{1}{N} \sum_{i=1}^{N} \mathrm{Ln}\,(X_i - \varepsilon)$$

$$S = \left(\frac{N \sum_{i=1}^{N} [\mathrm{Ln}(X_i - \varepsilon)]^2 - [\sum_{i=1}^{N} \mathrm{Ln}(X_i - \varepsilon)]^2}{N(N-1)} \right)^{1/2}$$

with N = total number of drops

and

$\eta = \frac{1}{S}$

$\gamma = -\frac{\mu}{S}$

Parameters estimated using the above formula are presented in Table A-I.

TABLE A-1

LOG-NORMAL PARAMETERS

Run Number	Elevation m	ft	μ	s	η	γ
30518	1.83	6	-0.19655	0.36081	2.77153	0.54474
30921	1.83	6	-0.20457	0.29107	3.43560	0.70281
31504	1.83	6	-0.32740	0.44155	2.26475	0.74148
31701	0.914	3	0.12270	0.33120	3.01936	-0.37047
31701	2.74	9	-0.14903	0.32491	3.07774	0.45868
31805	0.914	3	-0.18088	0.20520	4.87325	0.88146
31805	0.183	6	-0.16237	0.26129	3.82718	0.62143
32114	0.914	3	0.02170	0.44162	2.26439	-0.04914
32114	2.74	9	-0.11898	0.26529	3.76952	0.44850
32235	0.914	3	0.09525	0.43740	2.28622	-0.17204
32333	0.914	3	0.15665	0.33033	3.02726	-0.47422
32333	2.74	9	-0.08385	0.23880	4.18750	0.35112
34524	2.74	9	0.13332	0.32169	3.10862	-0.41448

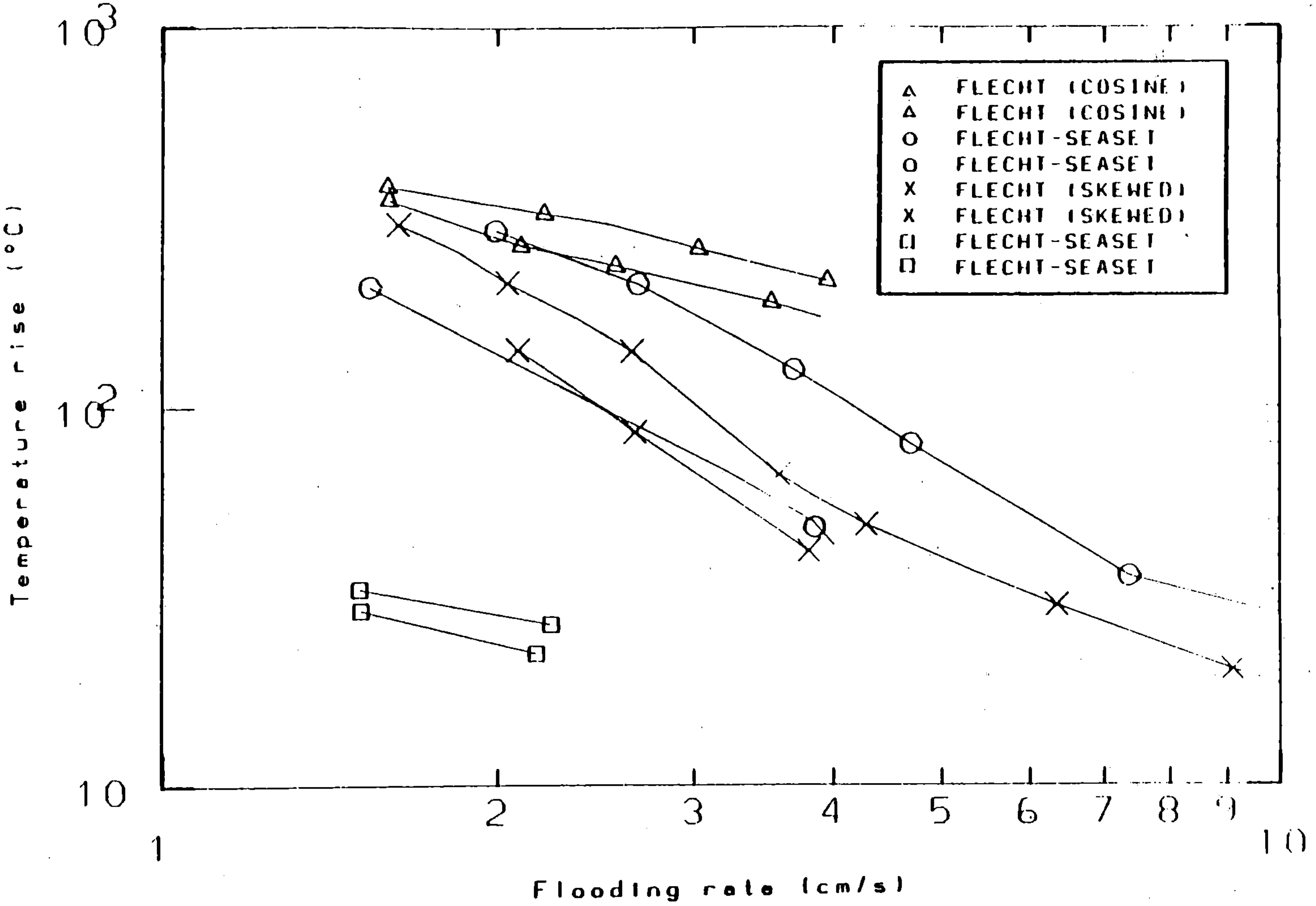

Figure A-1. FLECHT and FLECHT-SEASET temperature rise comparison.

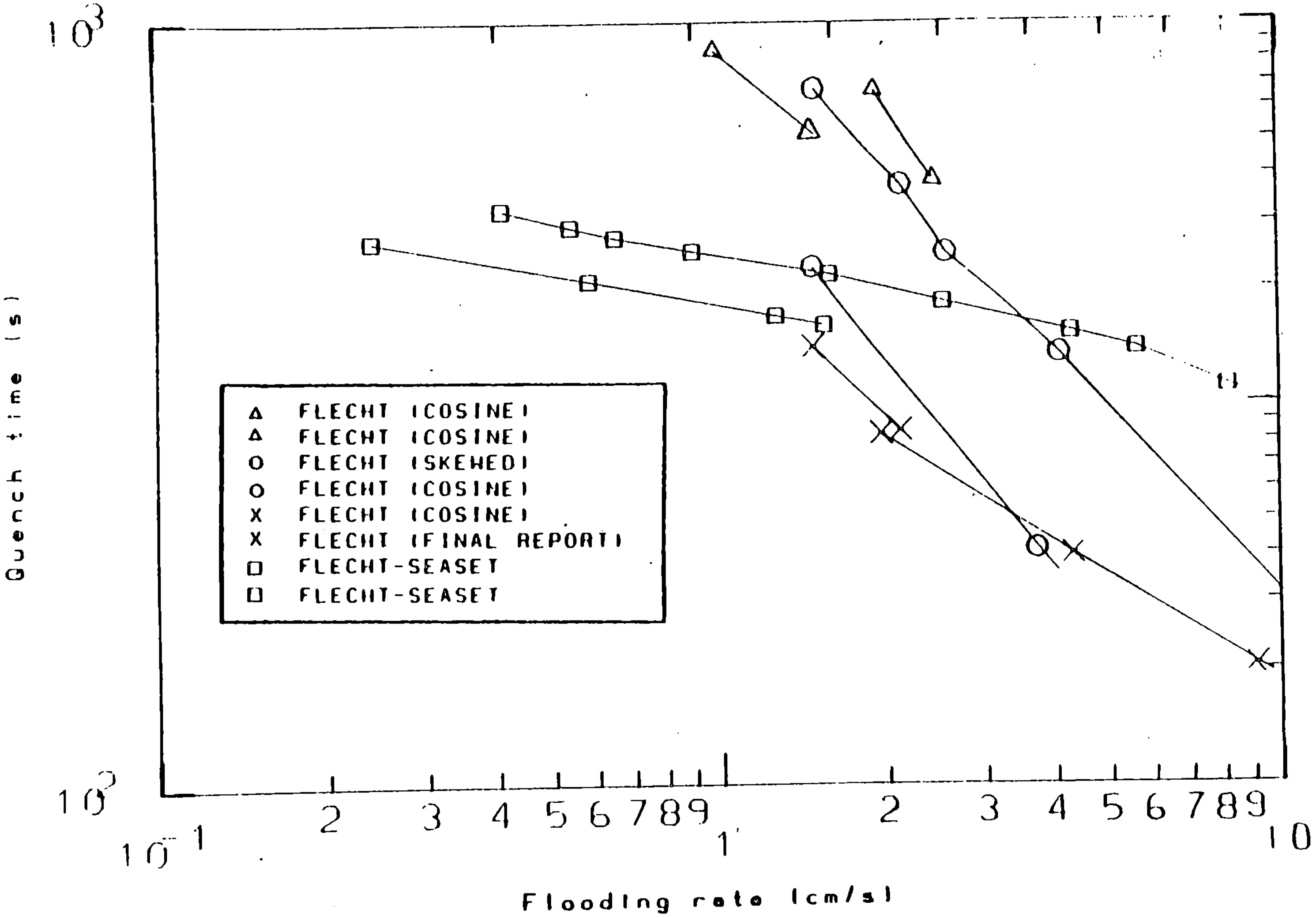

Figure A-2. FLECHT and FLECHT-SEASET quench time comparison.

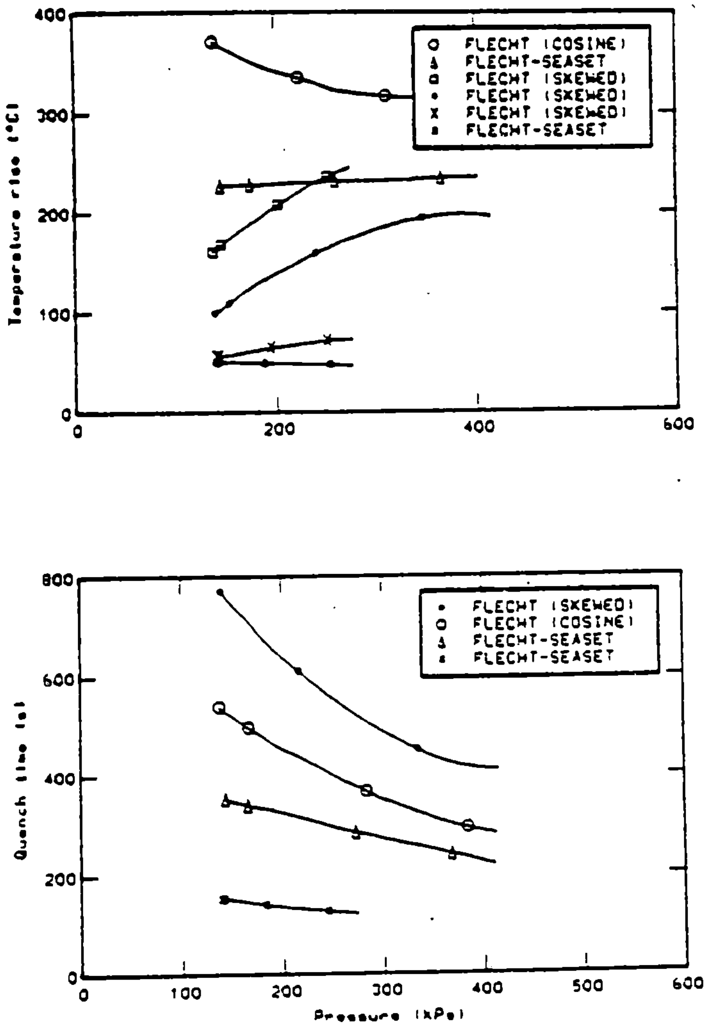

Figure A-3. Pressure parametric effects.

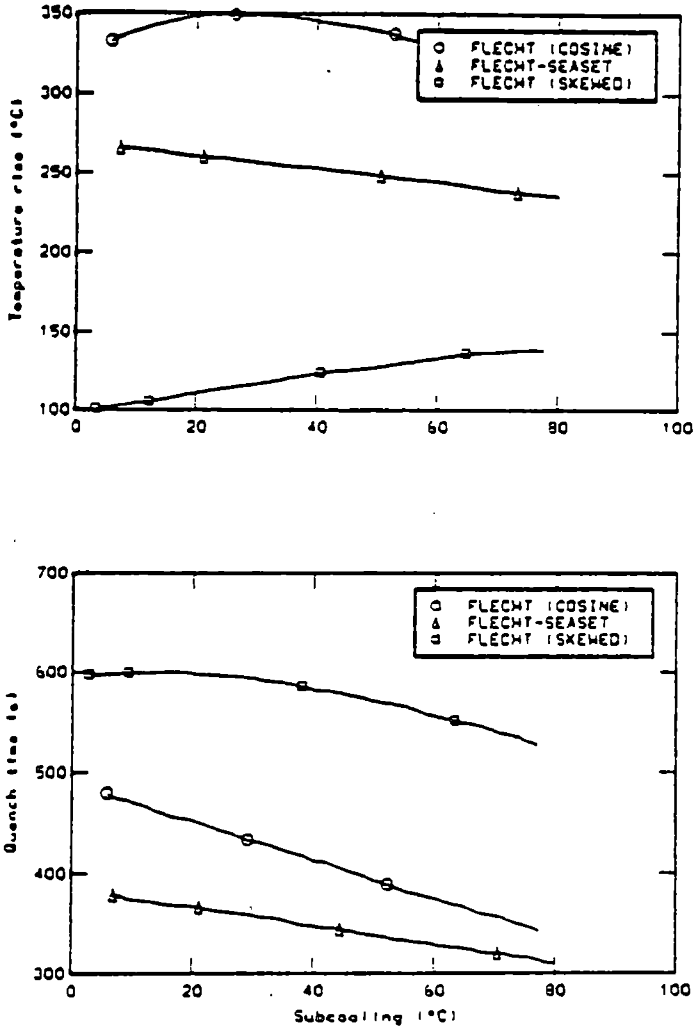

Figure A-4. Subcooling parametric effects.

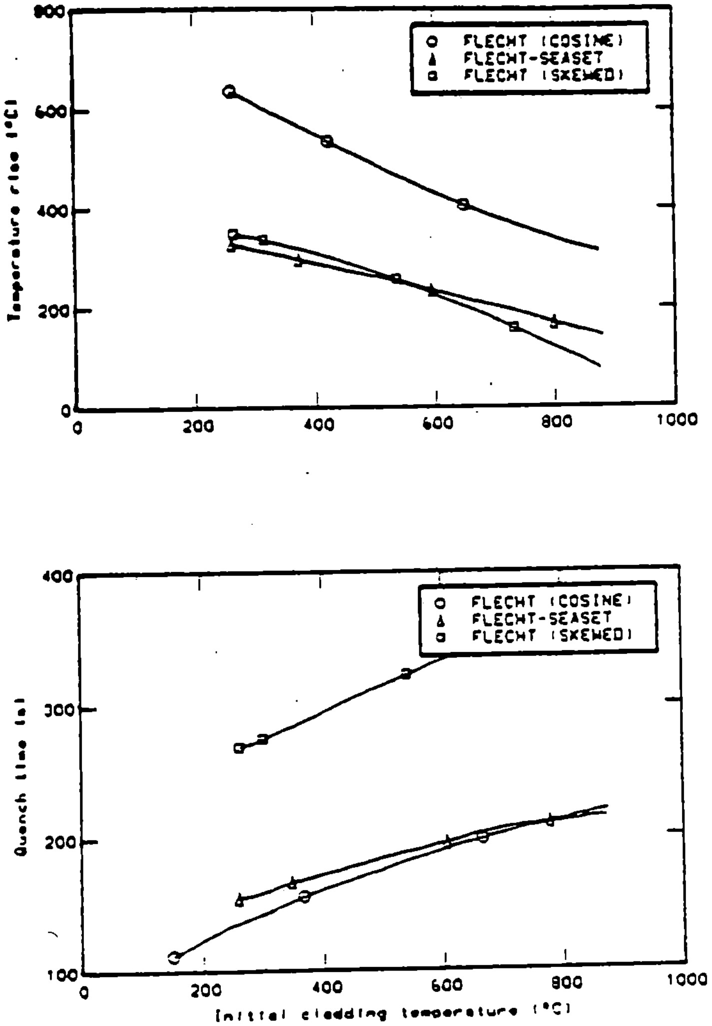

Figure A-5. Initial cladding temperature parametric effects.

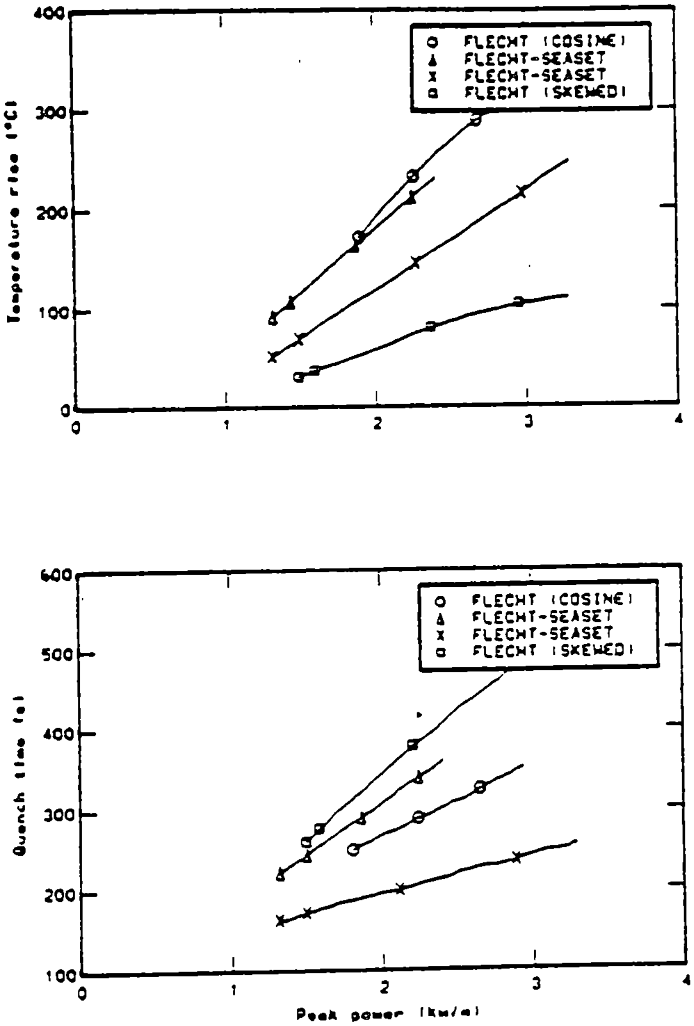

Figure A-6. Peak power parametric effects.

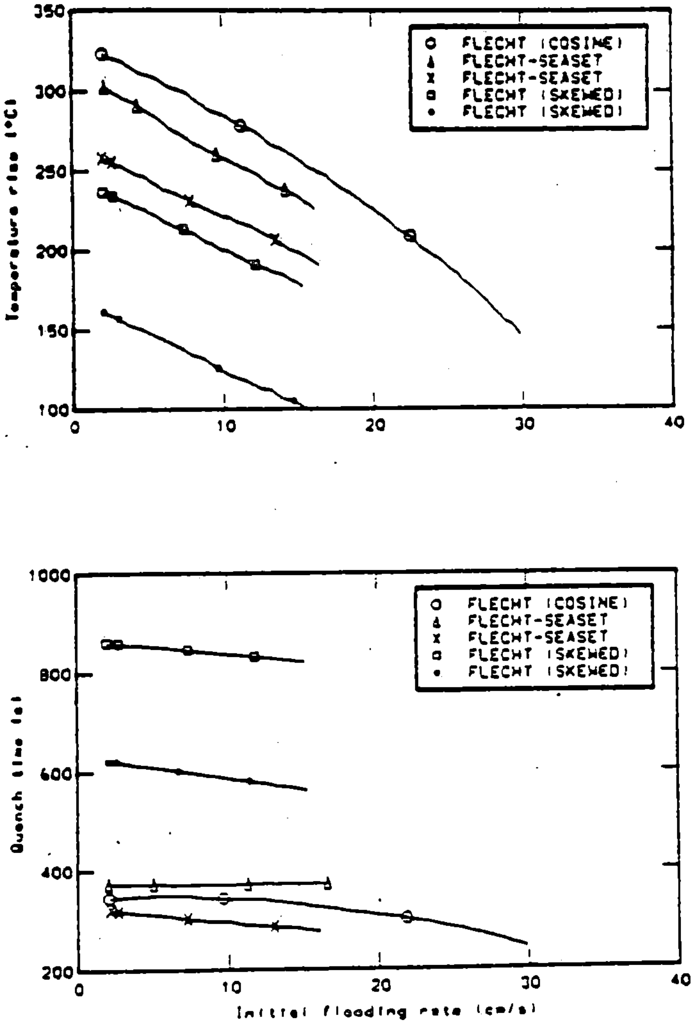

Figure A-7. Initial flooding rate parametric effects.

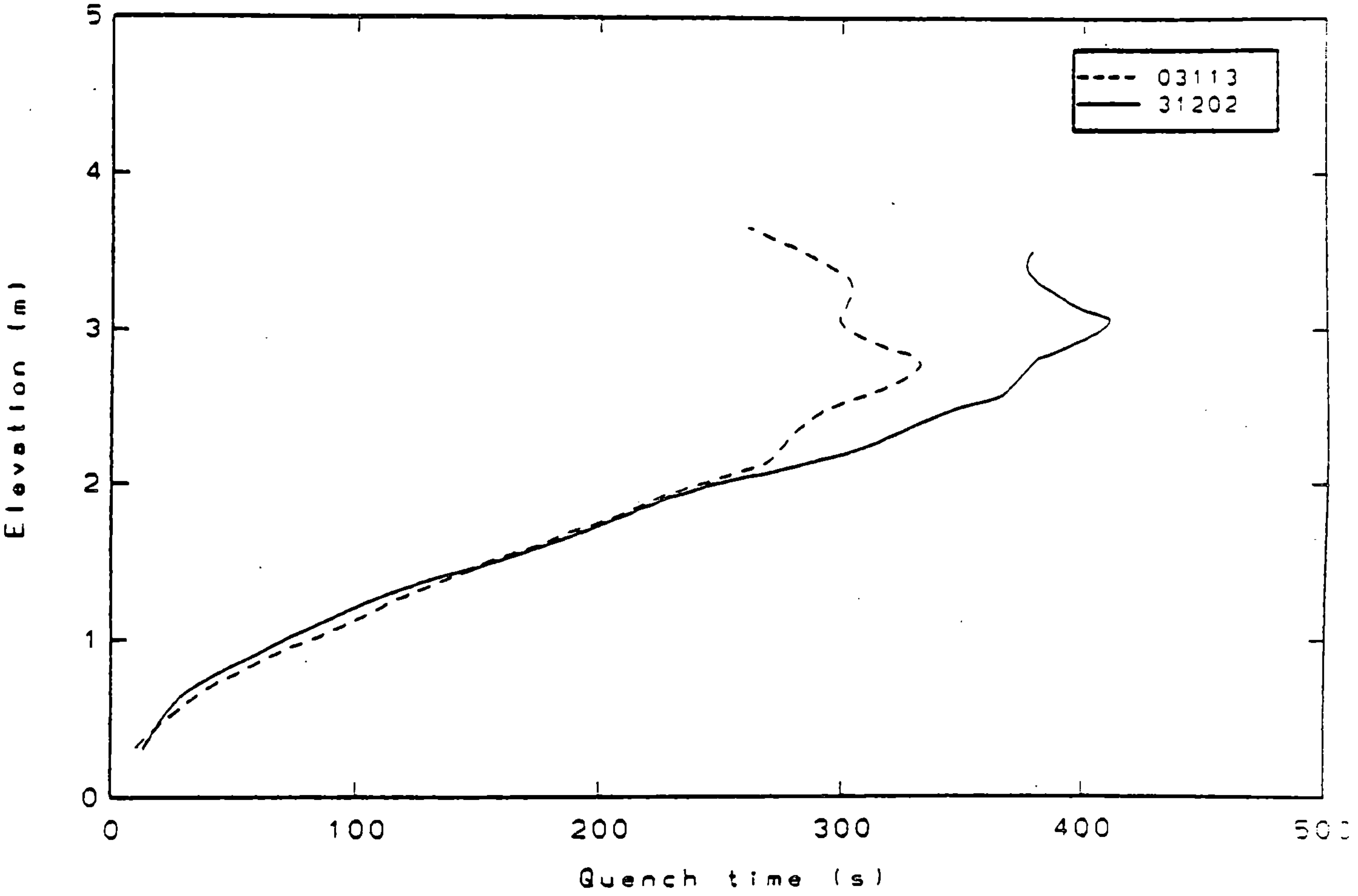

Figure A-8. Quench time comparison for overlay tests 31203 (FLECHT-SEASET) and 03113 (FLECHT).

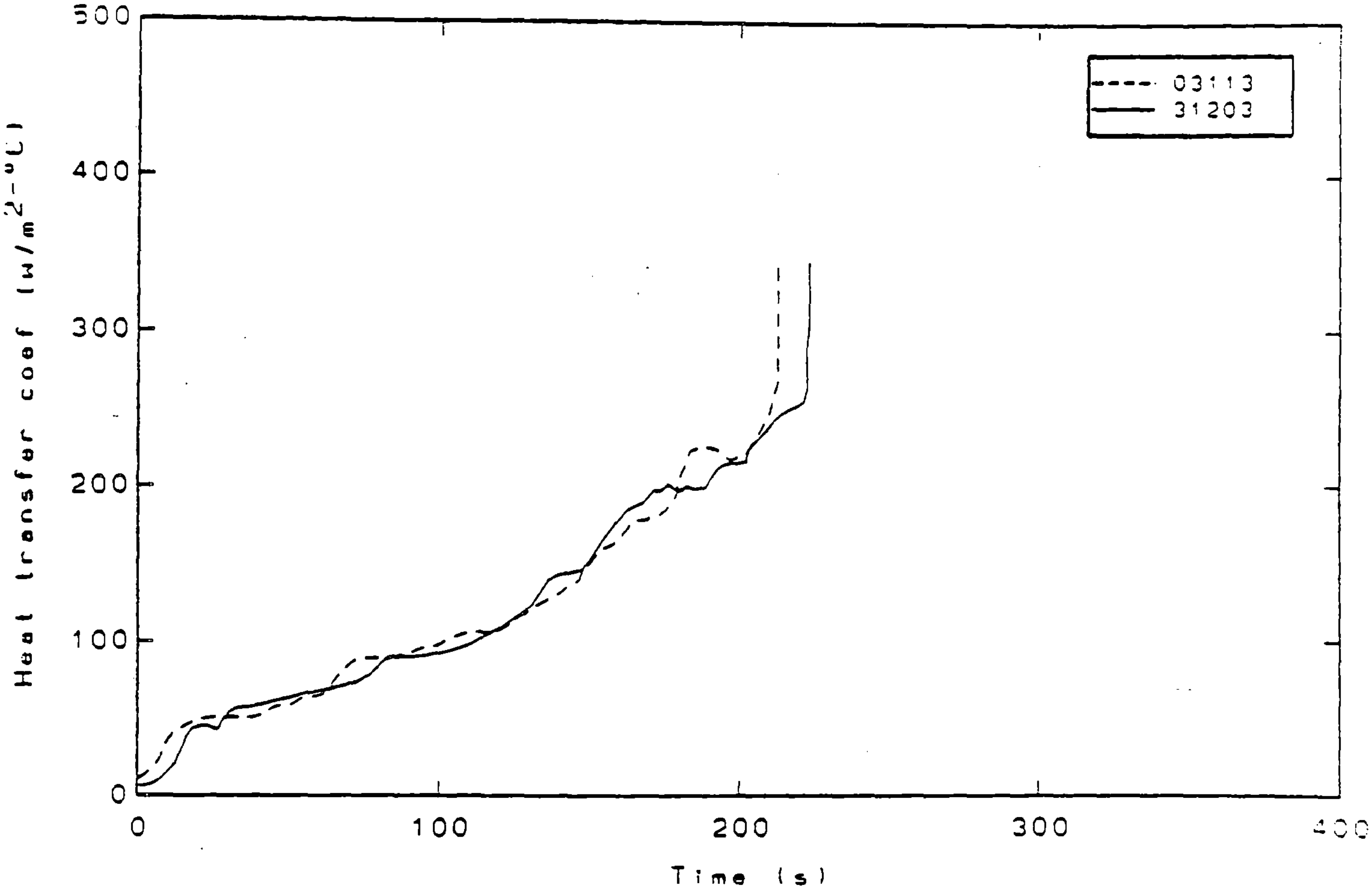

Figure A-9. Heat transfer coefficient comparison for overlay tests 31203 (FLECHT-SEASET) and 03113 (FLECHT)

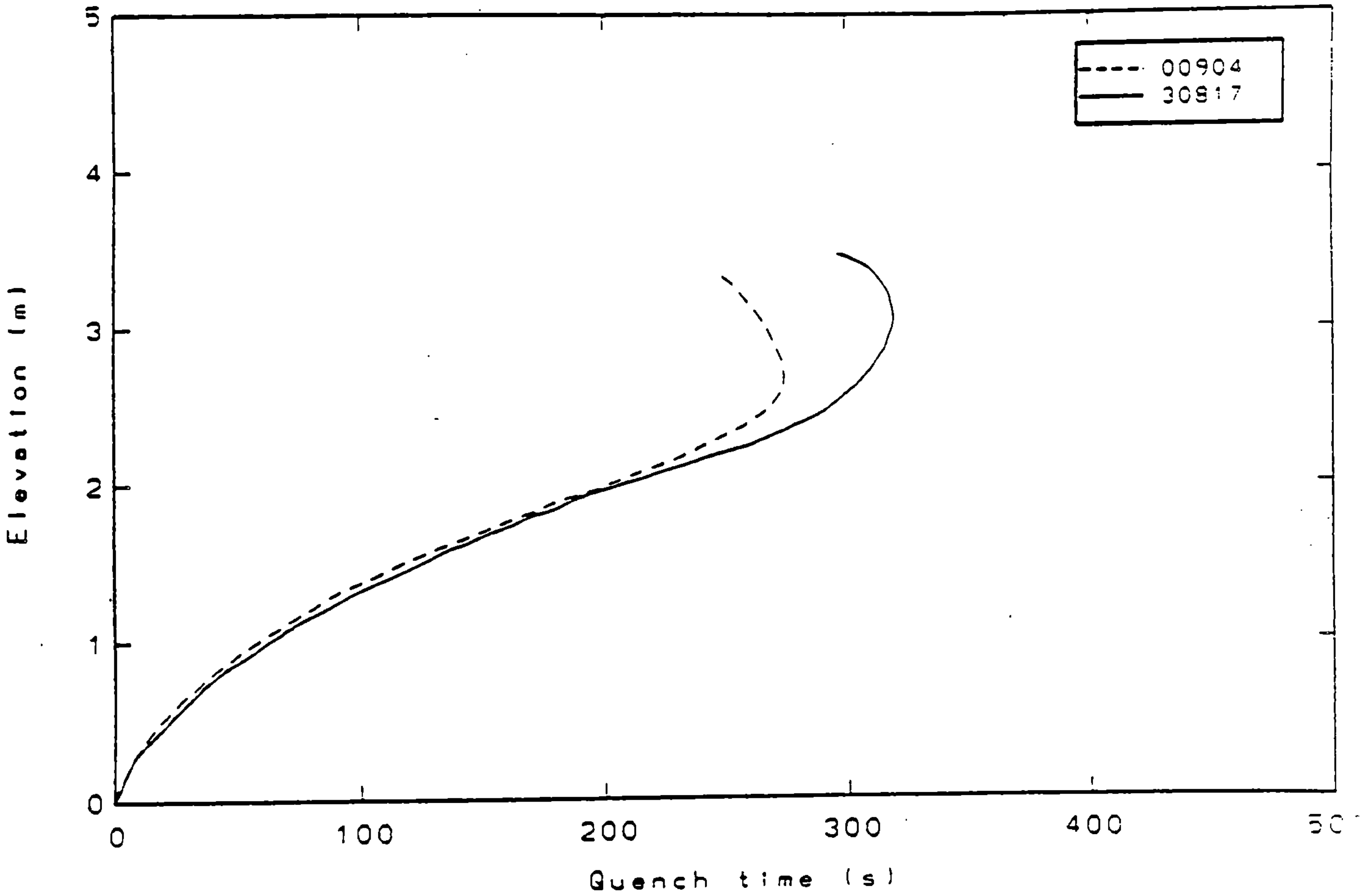

Figure A-10. Quench time comparison for overlay tests 30817 (FLECHT-SEASET) and 00904 (FLECHT).

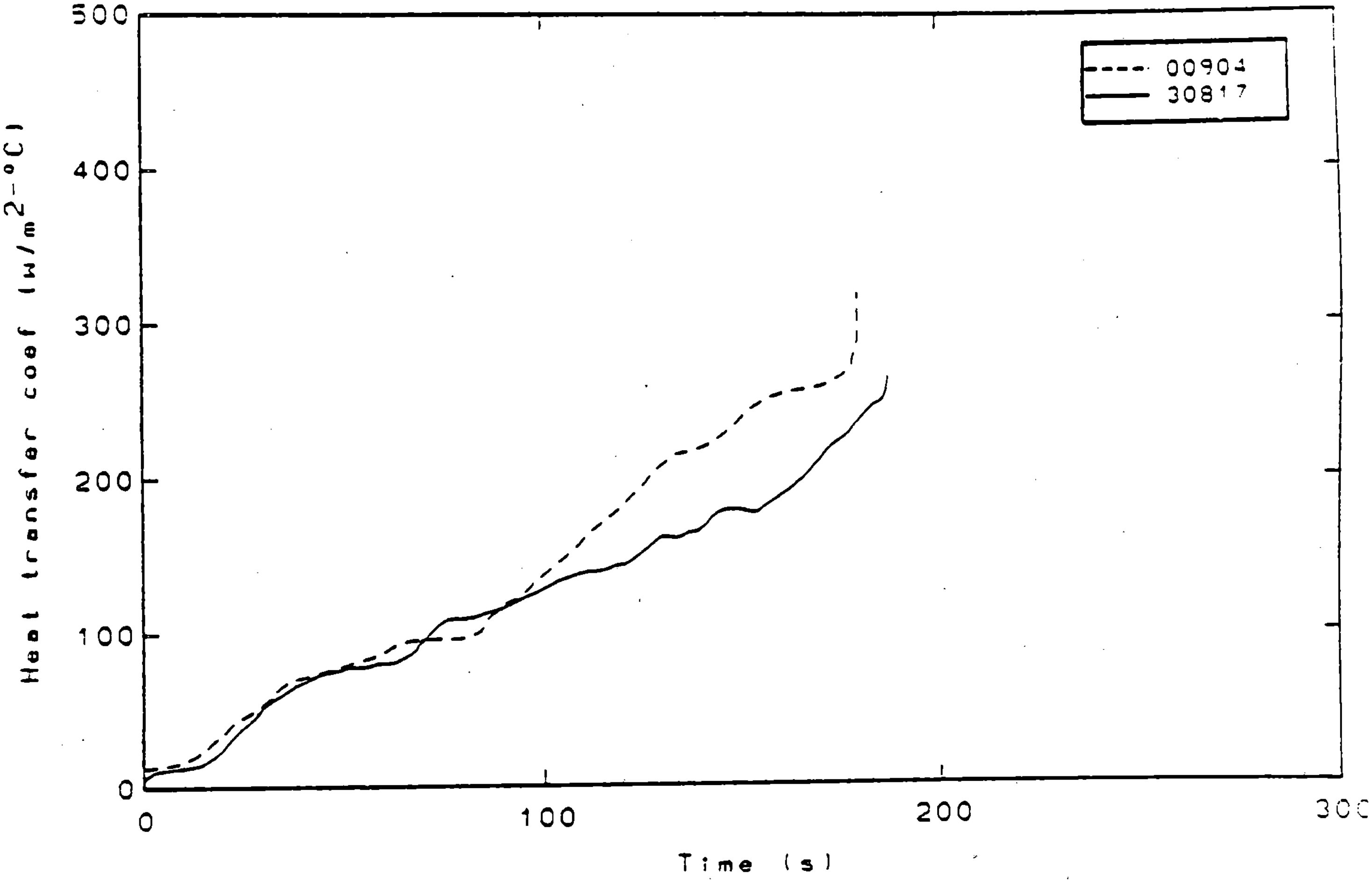

Figure A-11. Heat transfer coefficient comparison for overlay tests 30817 (FLECHT-SEASET) and 00904 (FLECHT

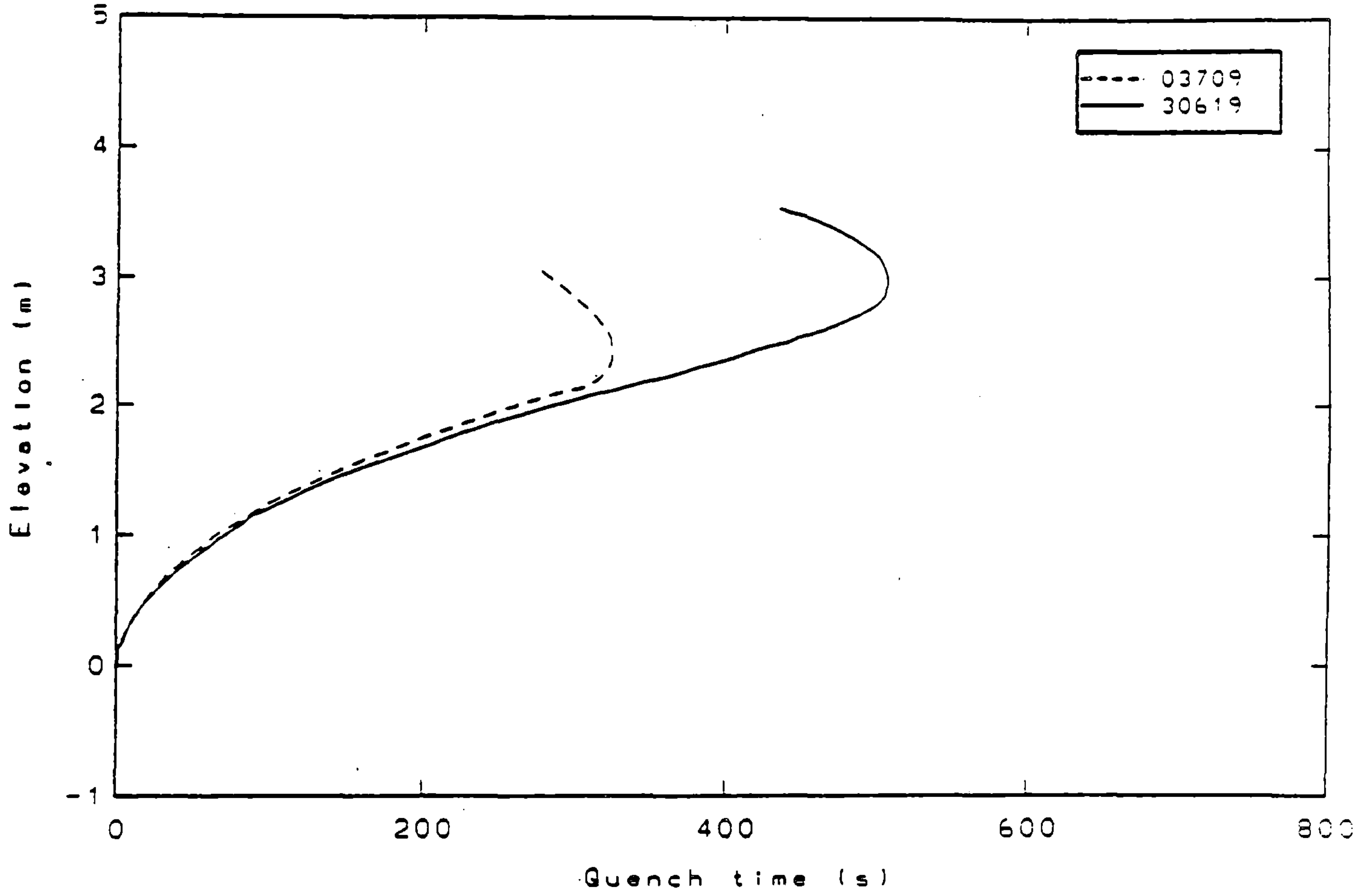

Figure A-12. Quench time comparison for overlay tests 30619 (FLECHT-SEASET) and 03709 (FLECHT).

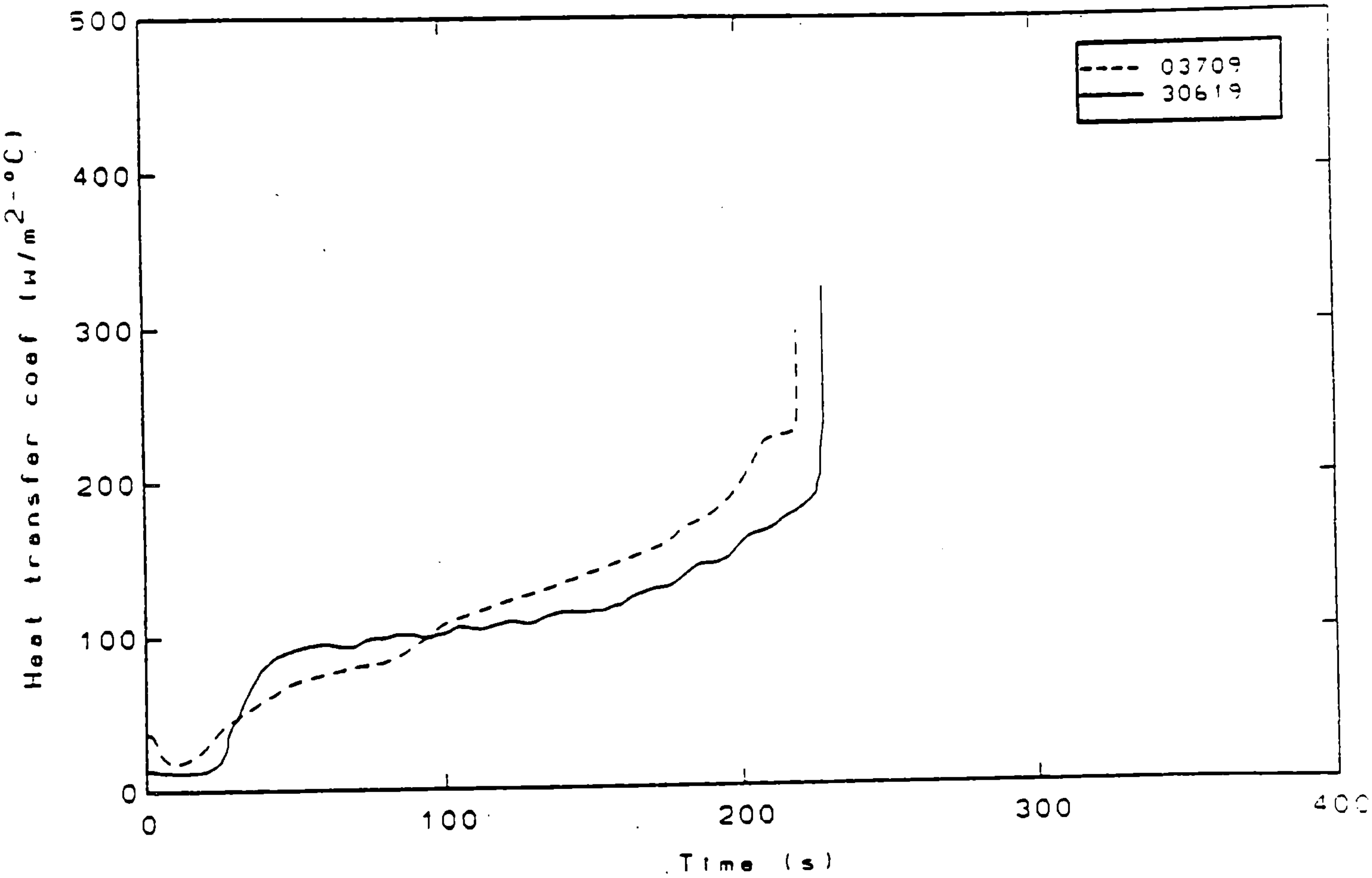

Figure A-13. Heat transfer coefficient comparison for overlay tests 30619 (FLECHT-SEASET) and 03709 (FLECHT

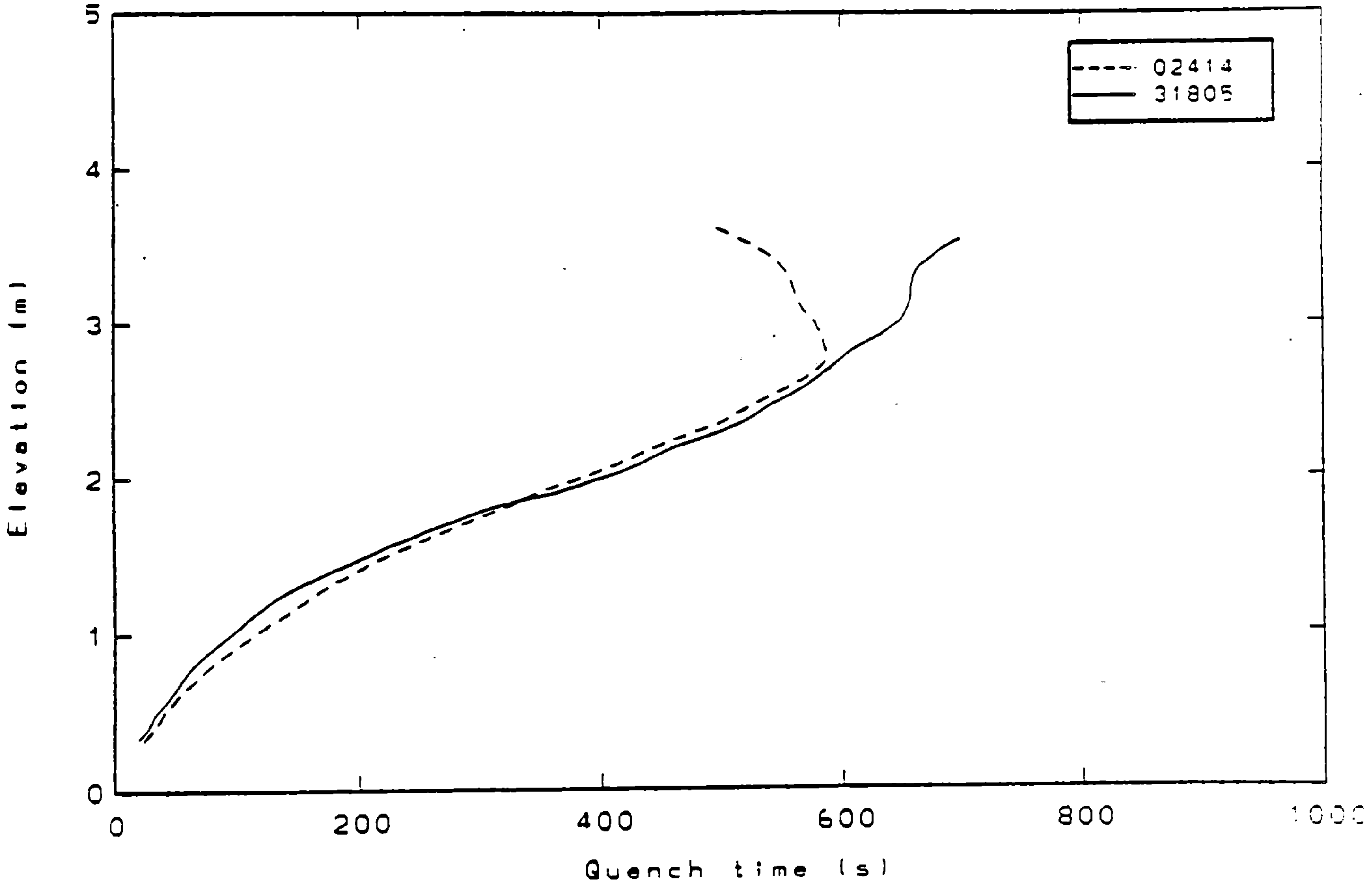

Figure A-14. Quench time comparison for overlay tests 31805 (FLECHT-SEASET) and 02414 (FLECHT).

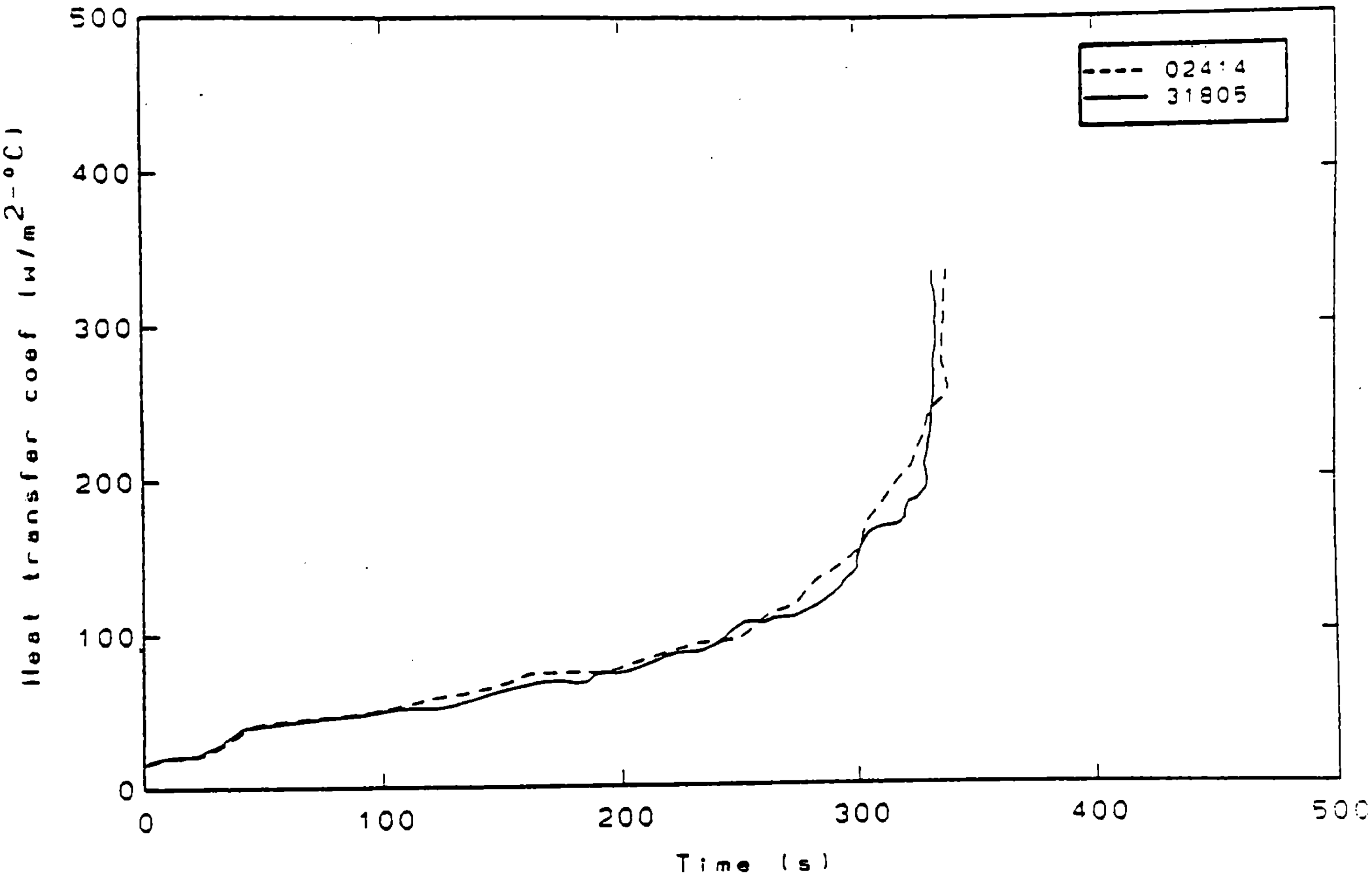

Figure A-15. Heat transfer coefficient comparison for overlay tests 31805 (FLECHT-SEASET) and 02414 (FLECHT

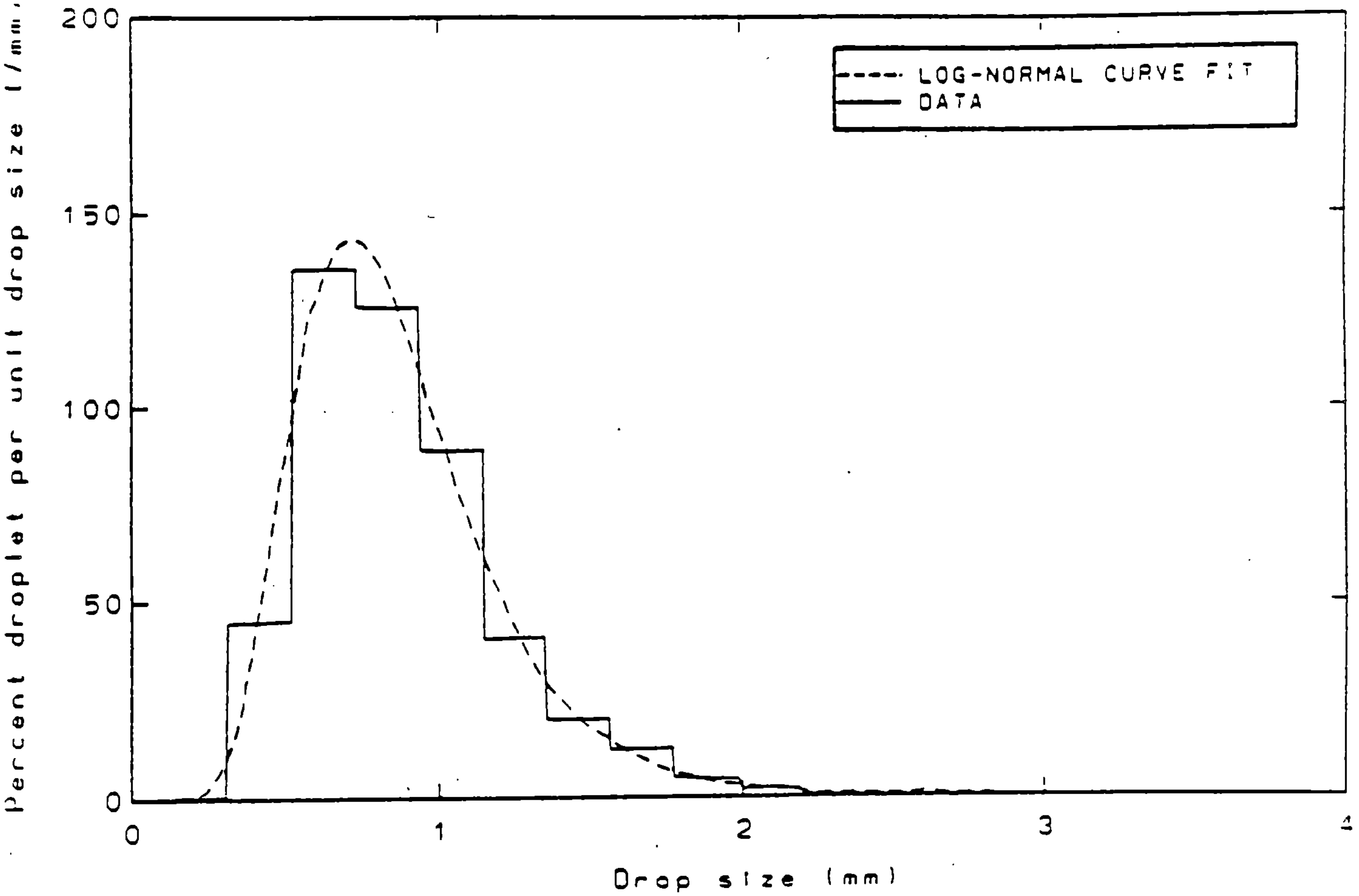

Figure A-16. Droplet diameter frequency distribution for test 30518.

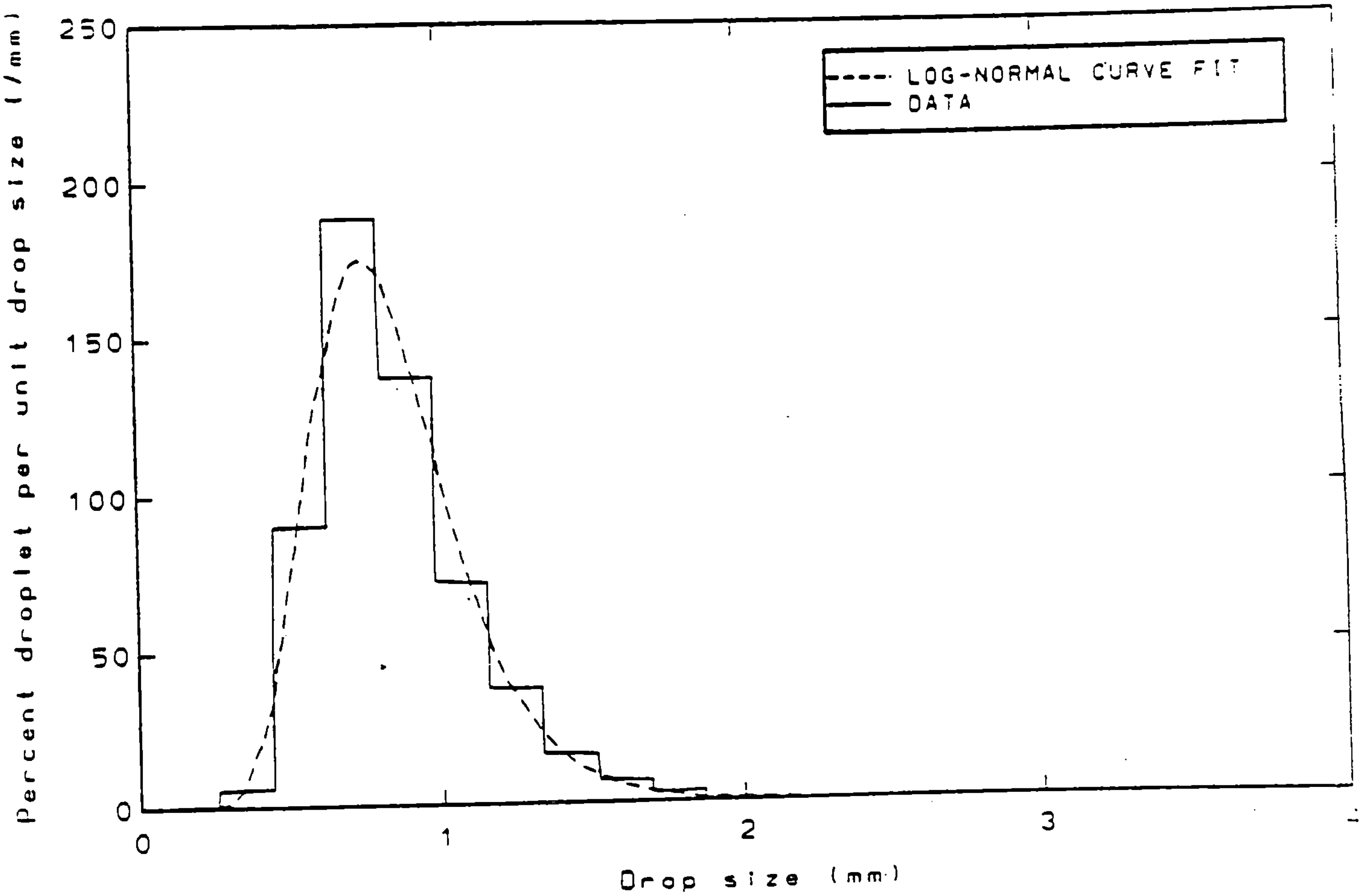

Figure A-17. Droplet diameter frequency distribution f
test 30921.

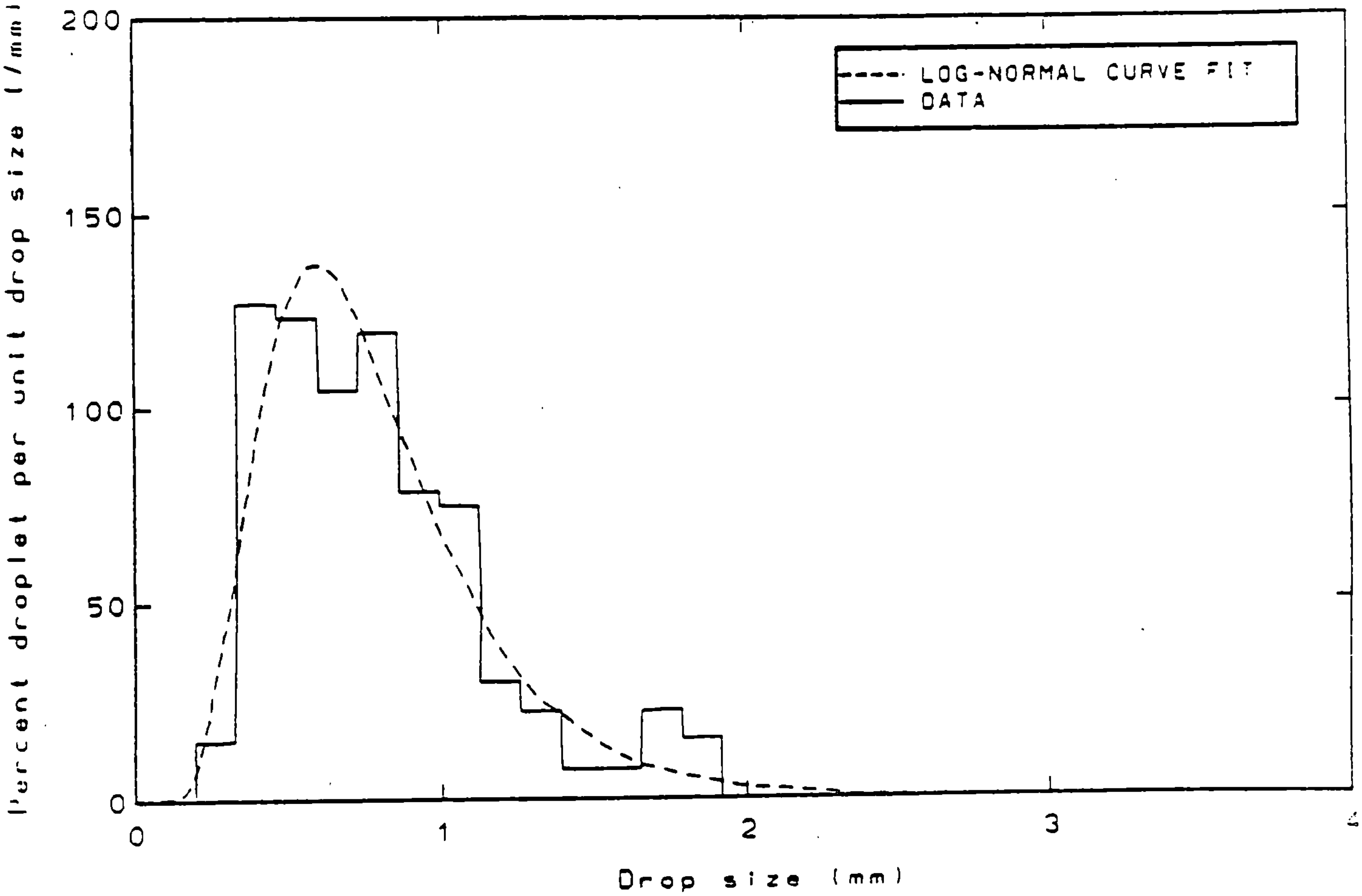

Figure A-18. Droplet diameter frequency distribution for test 31504.

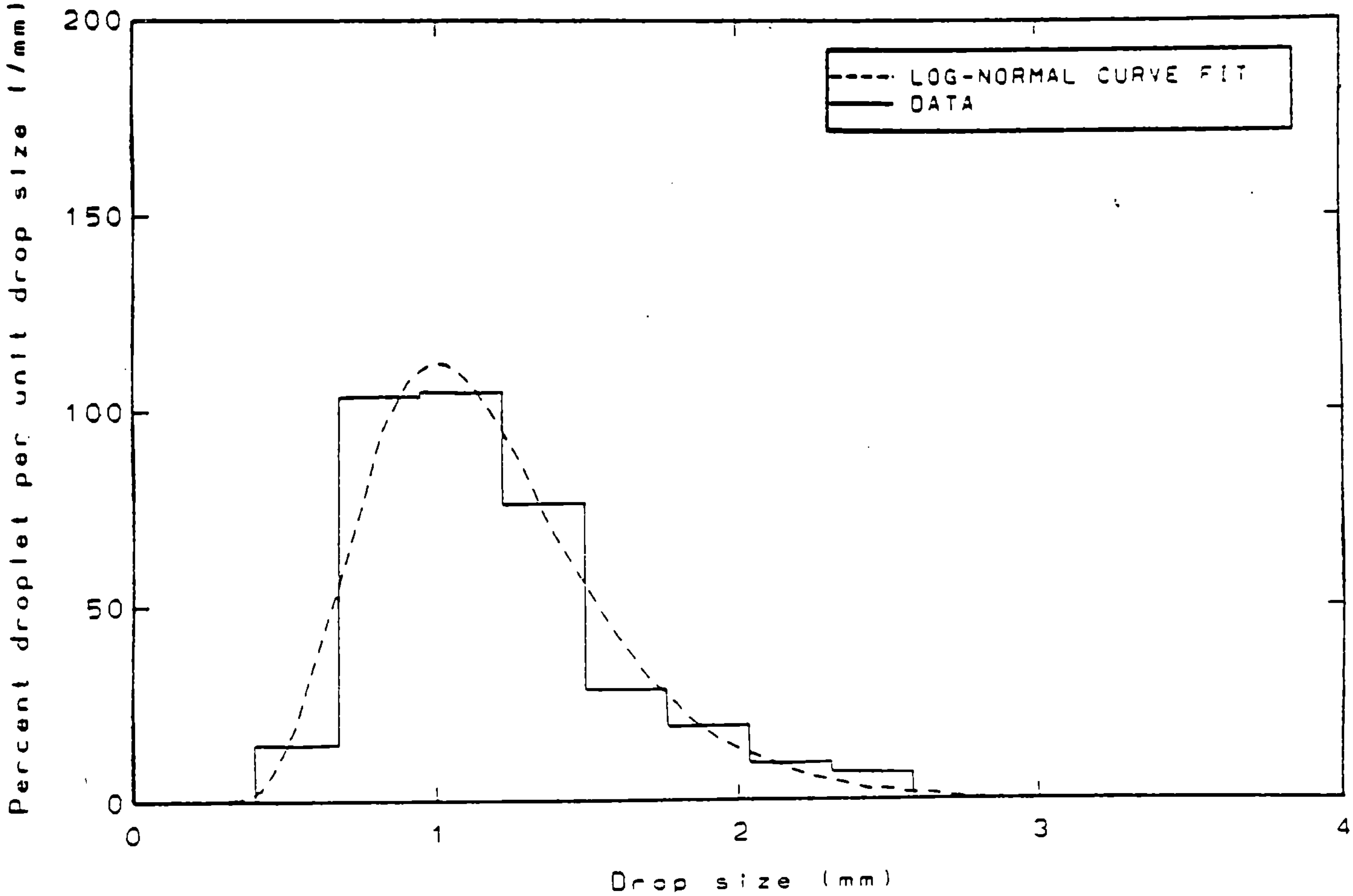

Figure A-19. Droplet diameter frequency distribution for test 31701 (0.91 m elevation).

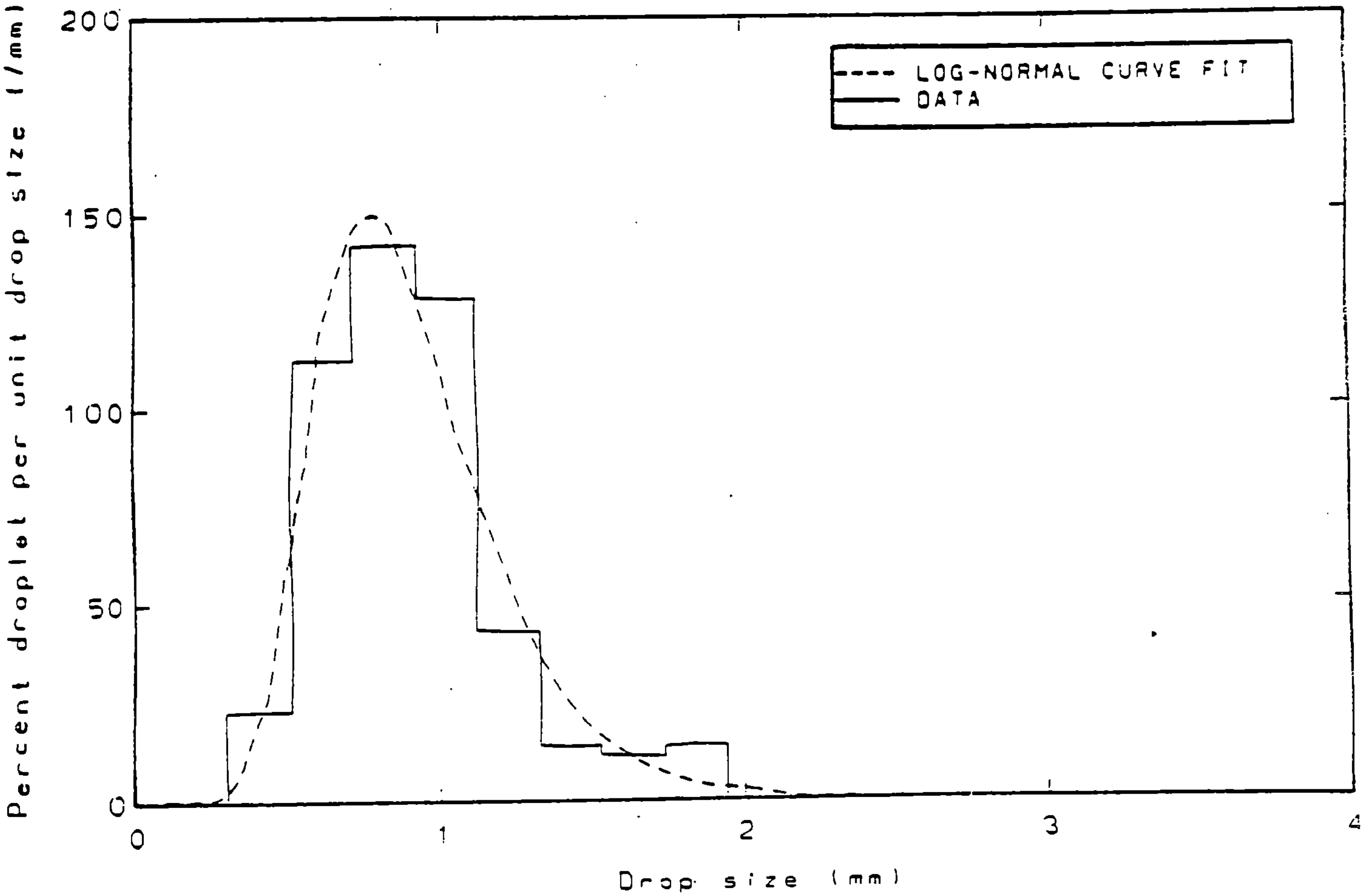

Figure A-20. Droplet diameter frequency distribution for test 31701 (2.74 m elevation).

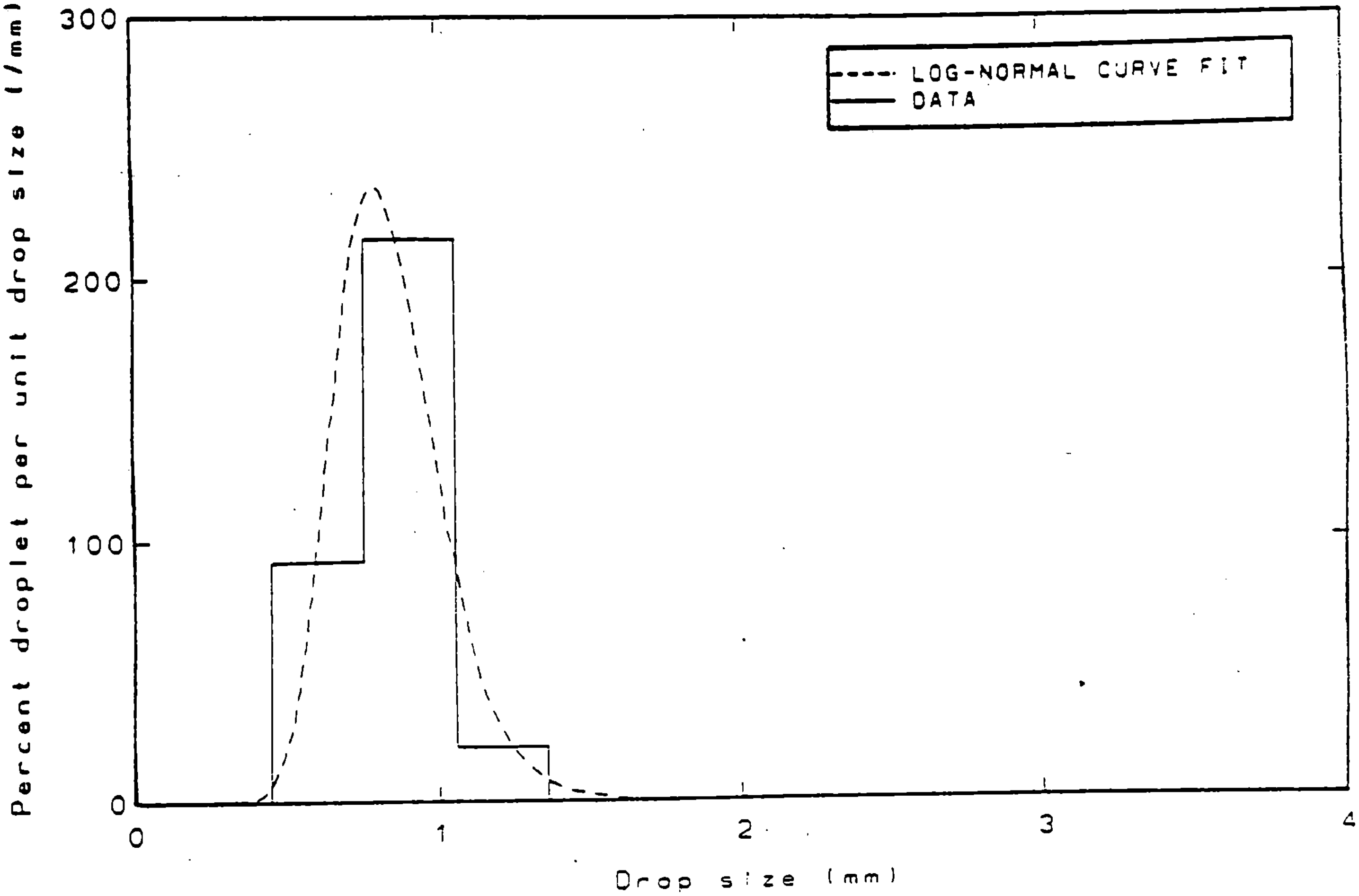

Figure A-21. Droplet diameter frequency distribution for test 31805 (0.96 m elevation).

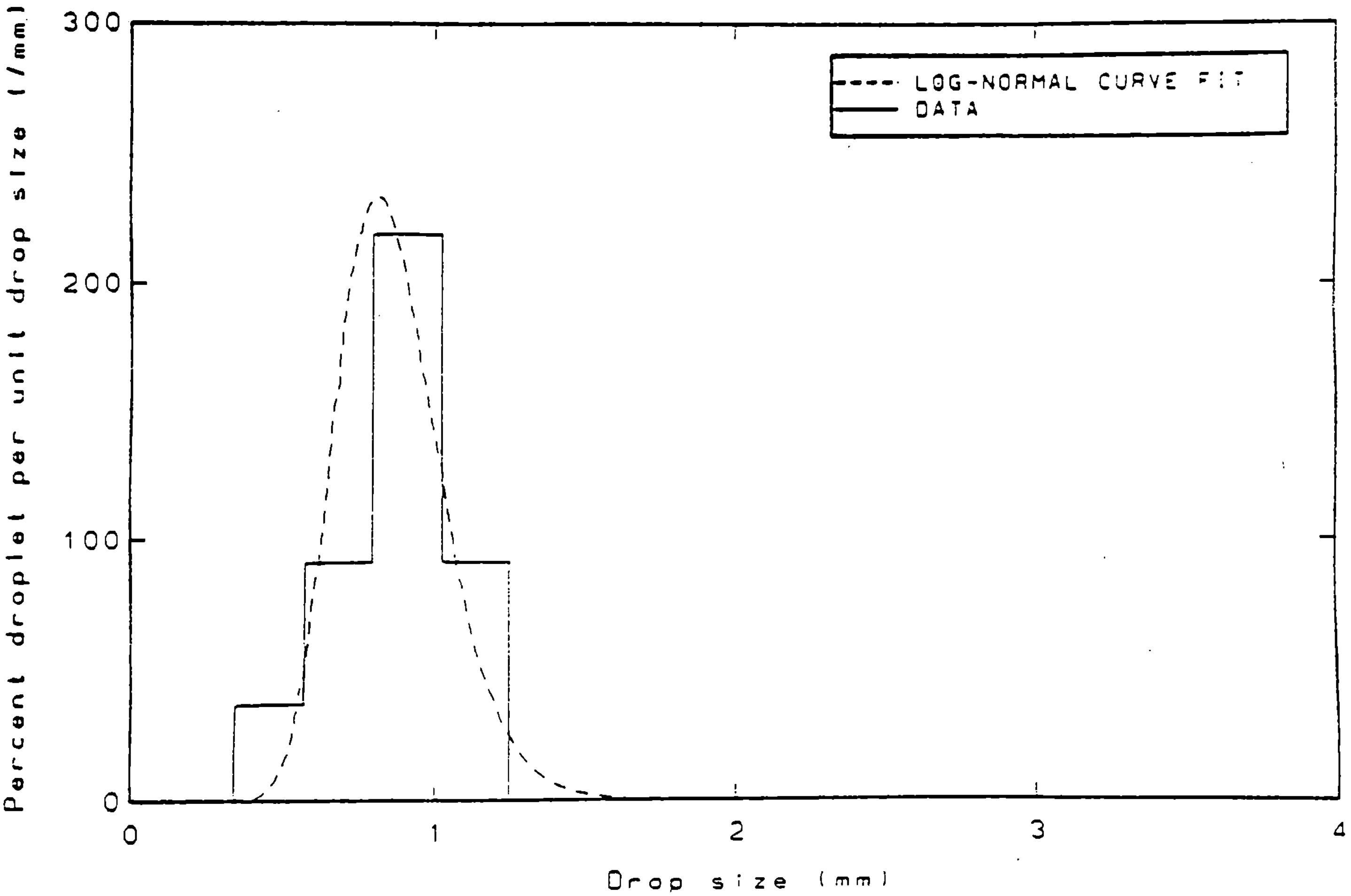

Figure A-22. Droplet diameter frequency distribution for test 31805 (1.83 m elevation).

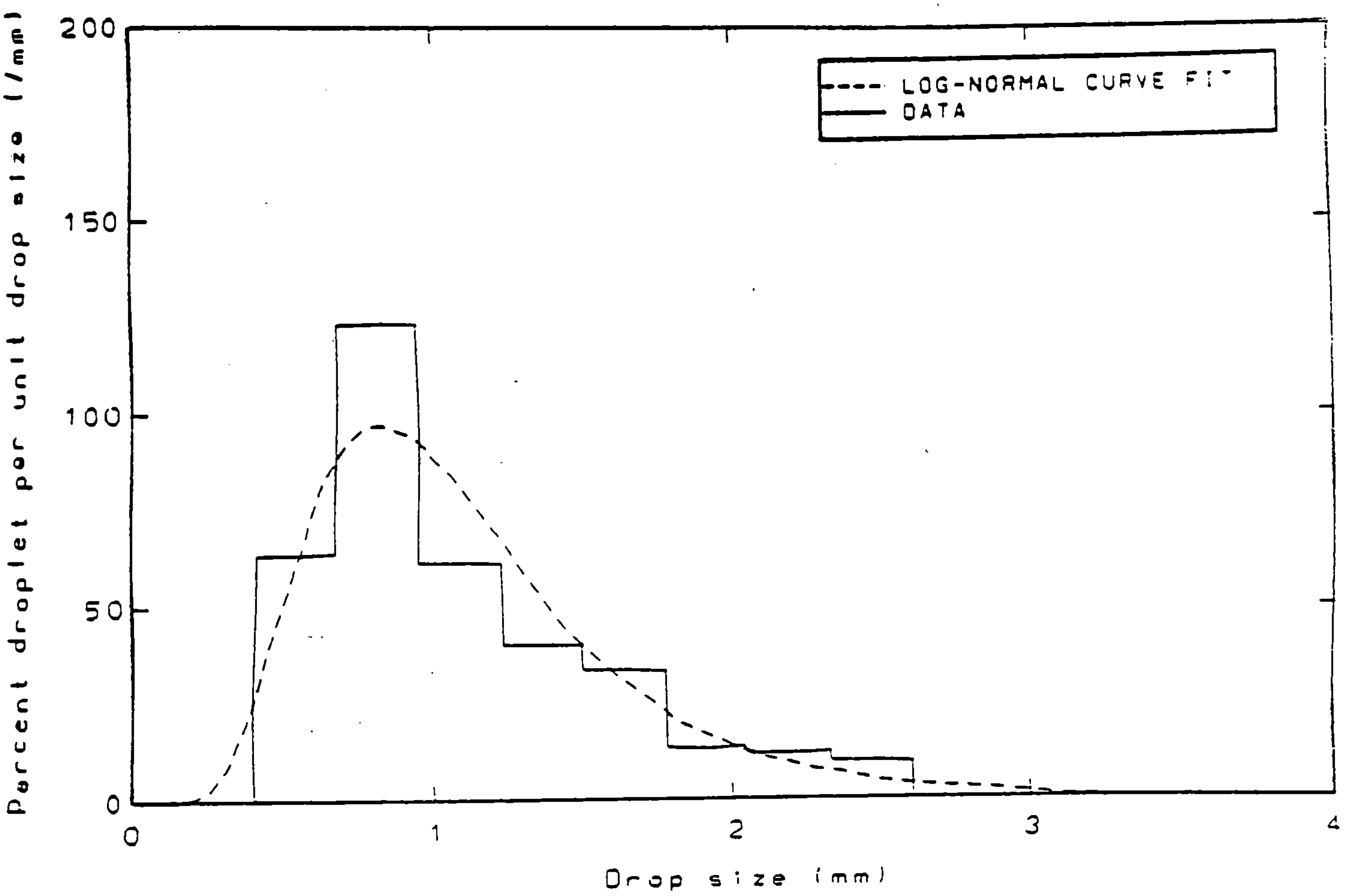

Figure A-23. Droplet diameter frequency distribution for test 32114 (0.93 m elevation).

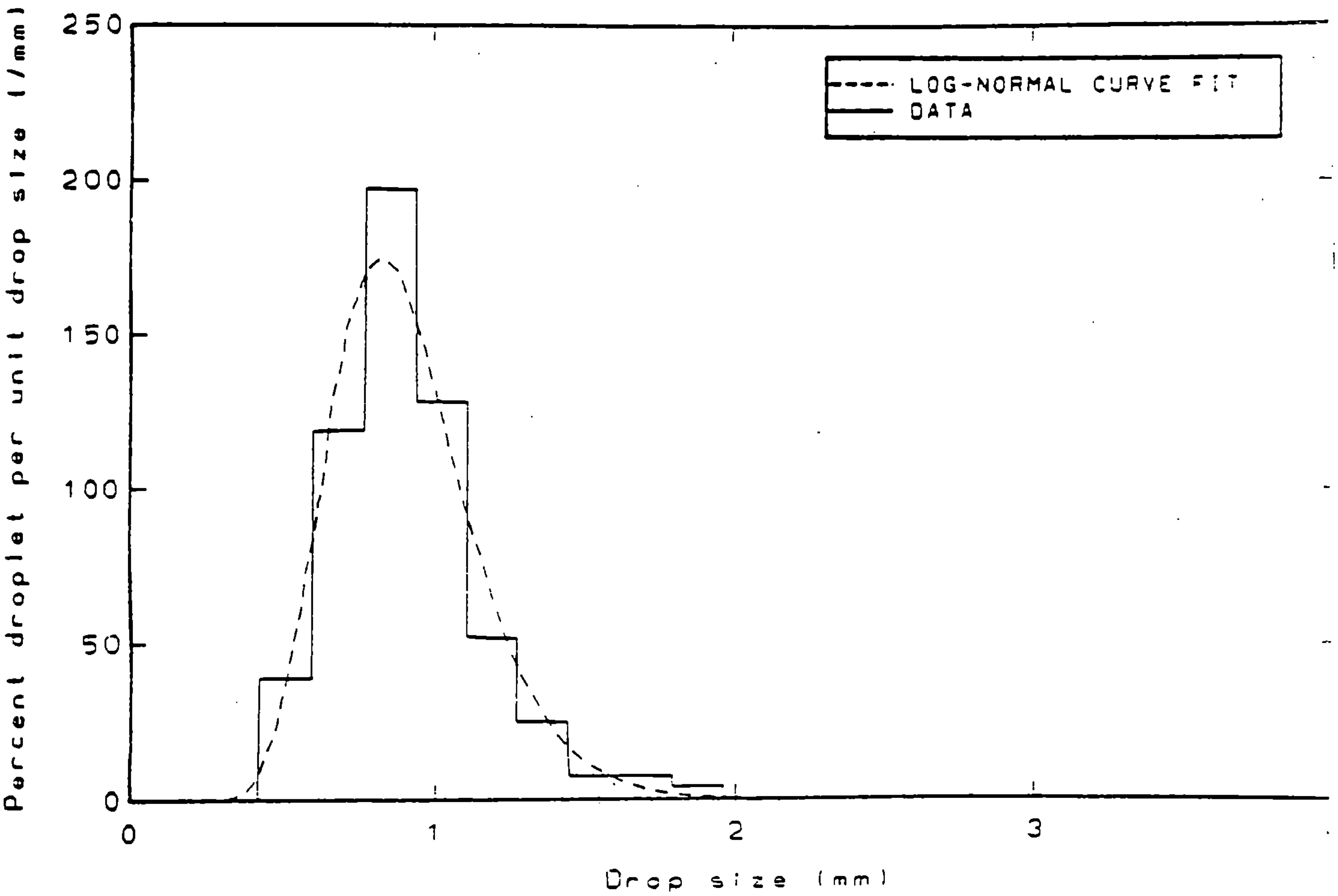

Figure A-24. Droplet diameter frequency distribution fc test 32114 (1.83 m elevation).

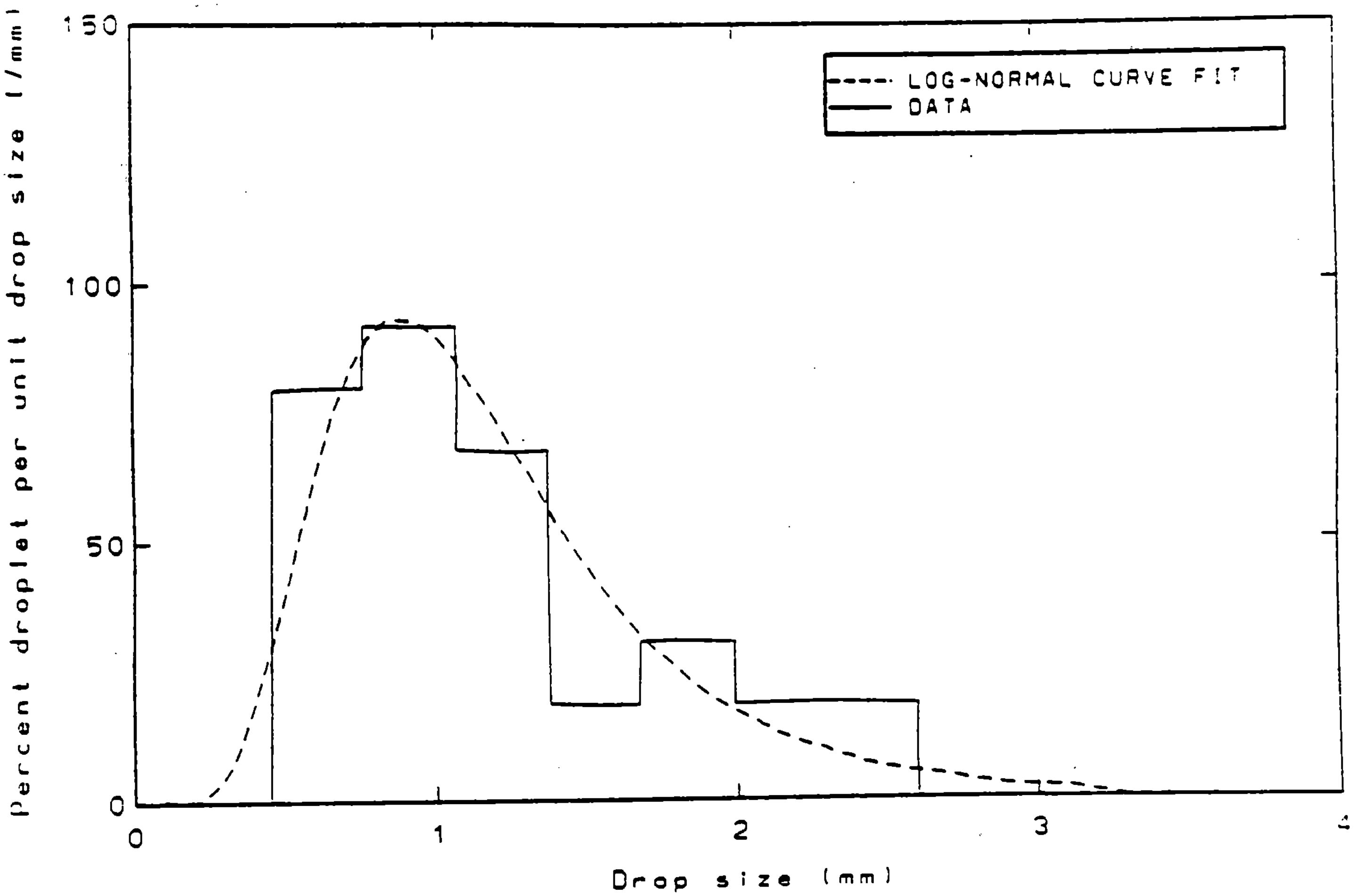

Figure A-25. Droplet diameter frequency distribution for test 32235.

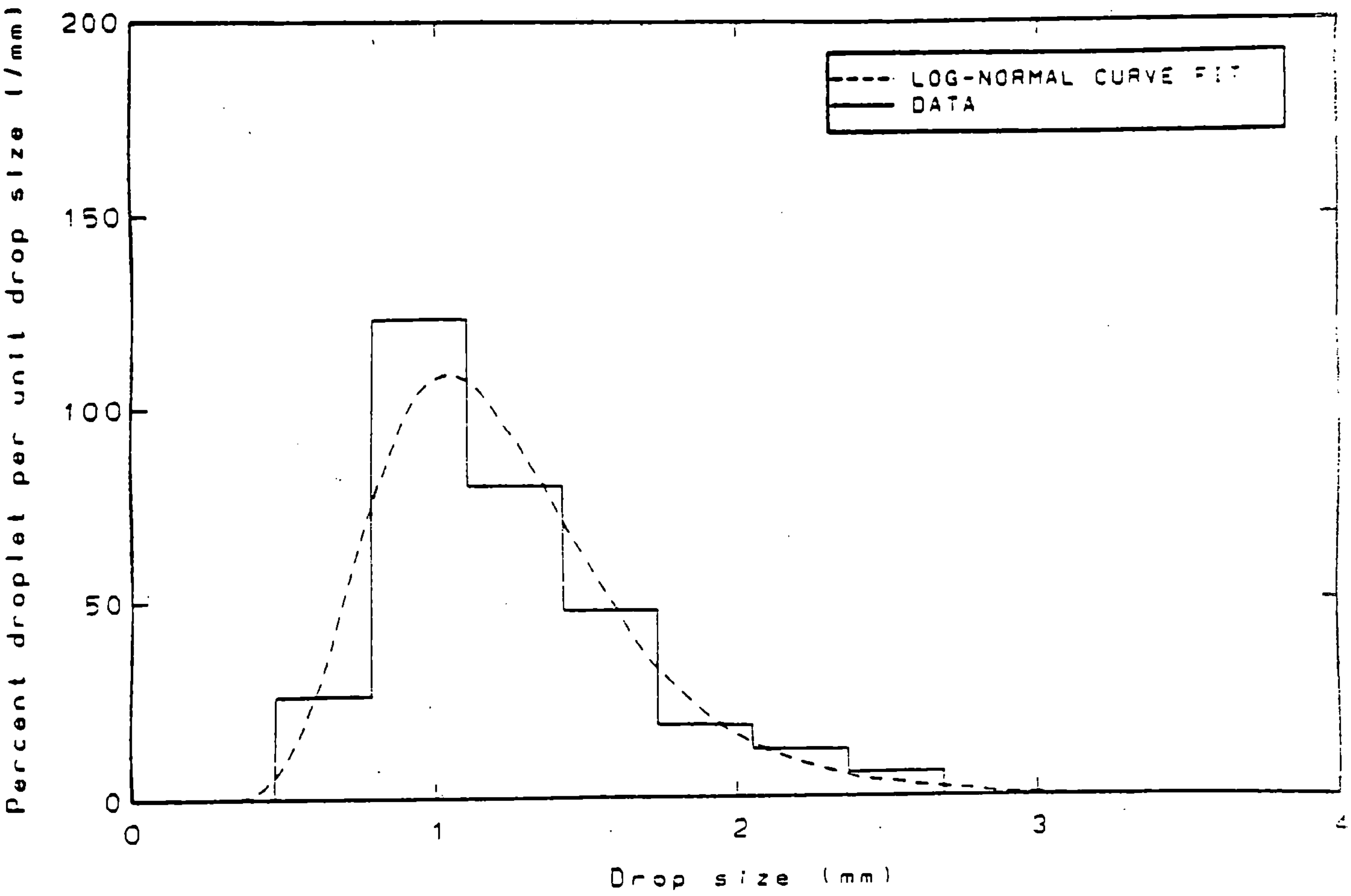

Figure A-26. Droplet diameter frequency distribution fo test 32333 (0.91 m elevation).

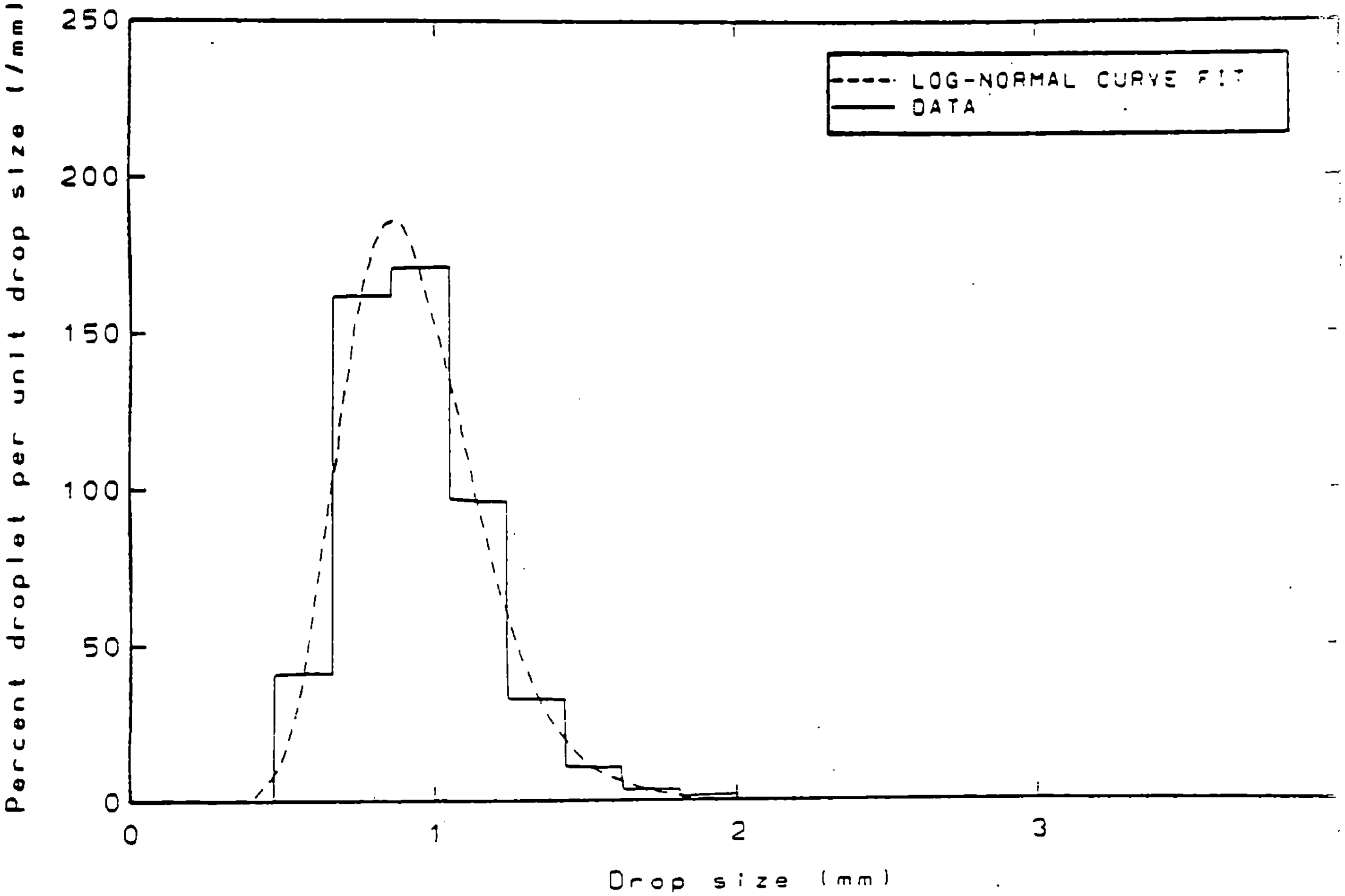

Figure A-27. Droplet diameter frequency distribution fc test 32333 (2.74 m elevation).

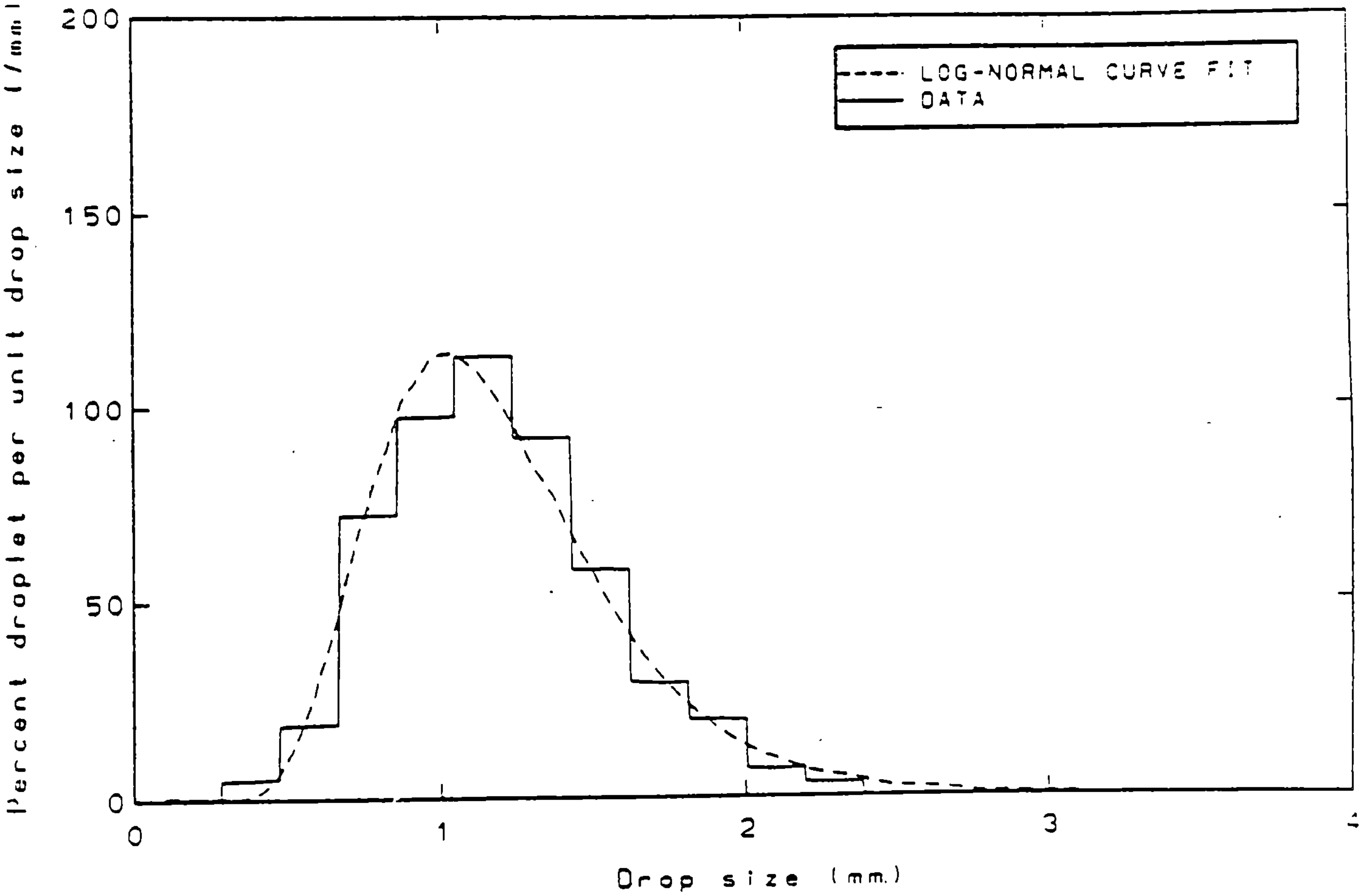

Figure A-28. Droplet diameter frequency distribution for test 34524.

APPENDIX B

HEAT TRANSFER CORRELATION

1.0 INTRODUCTION

In References 5 and 6, a heat transfer correlation has been derived based on the concept that the heat transfer coefficient is primarily a function of the distance from the quench front. The basis of this concept is explained in detail in Reference 5. The correlation of References 5 and 6 predicts the quench time and the heat transfer coefficient quite well for the FLECHT cosine and skewed power tests with 15 x 15 assembly rod bundle. However, the correlation is not in dimensionless form, therefore, it is not general enough to be applicable to other rod bundle geometries such as the FLECHT-SEASET tests which has a 17 x 17 assembly rod bundle.

In the following sections the new FLECHT-SEASET heat transfer correlation is presented. The FLECHT correlation of References 5 and 6 is reformulated in dimensionless form and modified to bring better agreement with the data of the 15 x 15 FLECHT cosine and skewed power tests as well as the 17 x 17 FLECHT-SEASET tests.

As with the correlation of References 5 and 6, the FLECHT-SEASET correlation consists of two sub-correlations:

- Quench correlation, which predicts the quench front elevation as a function of time.
- Heat transfer coefficient correlation, which predicts the heat transfer coefficient as a function of the distance from the quench front, $Z-Z_q$.

The heat transfer coefficient can be computed as a function of time by using the quench correlation which bridges the space variable Z_q and the time variable t.

2.0 QUENCH CORRELATION

The quench correlation of References 5 and 6 has been modified and reformulated in dimensionless form as follows: (whenever confusion is likely to occur, exponentiation is indicated by "**")

$$\frac{t_q V_{in}}{Z_q} = 1 + \left\{\frac{t_{q,\,peak} V_{in}}{Z_q} \left(Q_r + 0.5\, Q_r\, e^{-9 Q_r^2}\right) - 1\right\} \Big/ \left[1 + 50^{**} \left\{\frac{T_{init,q} - T_o}{T_o - T_{sat}}\right\}\right] \qquad \text{(B-1)}$$

where

$$Q_r = \int_0^{Z_q} Q'(Z)\, dZ \Big/ \int_0^{Z_{peak}} Q'(Z)\, dZ \qquad \text{(B-2)}$$

$Q'(Z)$ = linear power at the elevation Z of one rod, kcal/sec-m (Btu/sec-ft)

Z_q = quench elevation, m (ft),

Z_{peak} = peak power elevation, m (ft),

t_q = quench time at elevation Z_q, sec

V_{in} = flooding rate, m/sec (ft/sec)

T_o = 204.3°C (= 400°F)

T_{sat} = saturation temperature, °C (°F)

T_{initq} = $(T_{init} - T_{sat})\, Q'(Z_q)/Q'(Z_{peak}) + T_{sat}$, °C (°F)

T_{init} = cladding temperature at the peak power elevation at the beginning of flood, °C (°F) and $t_{q,peak}$ is the quench time at the peak power elevation which is given by

$$\frac{t_{q,peak}\ V_{in}}{Z_{q\ peak}} = 0.0028\ Re\ (\rho_g/\rho_f)^{-0.262}\ [F_{t1}\ (F_{t2} + F_{t3} + F_{t4}) + F_{t5}]$$

$$(F_{t6} - F_{t7})\ F_{t8} \qquad \text{(B-3)}$$

where

$$F_{t1} = \exp\,[-10.09\ (C_{pf}\Delta T_{sub}/h_{fg})][6.458\ (10^{-5})$$

$$Re^{1.938}/(\rho_g/\rho_f)^{0.5078}(C_Q\ D_{rod}/Z_{peak})\ 1.5]$$

$$-0.7\ \{1-\exp(-0.0000801\ Re/(\rho_g/\rho_f)^{0.262})\}]$$

$$F_{t2} = 1 + 0.5\ \exp\,[-5.6251\ (10^8)\ (\rho_g/\rho_f)^3]$$

$$F_{t3} = 1.3\ \exp\,[-1.652\ (10^{-9})\ Re^2/(\rho_g/\rho_f)^{0.524}]$$

$$F_{t4} = 17.3\ \exp\,[-5.6251\ (10^8)\ (\rho_g/\rho_f)^3]$$

$$\exp\,[-7.293(10^{-9})\ Re^2/(\rho_g/\rho_f)^{0.524}]$$

$$F_{t5} = 66203(\rho_g/\rho_f)^{0.2882}/Re^{1.1}$$

$$-2.8\ \exp\,[-0.000122\ Re/(\rho_g/\rho_f)^{0.262}]F_{t2}$$

$$F_{t6} = 1.01552 + 0.01388\ C_T$$

$$F_{t7} = 1.05\ \exp\,(-0.66 - 0.59\ C_T)\ [1 + 0.5/\{1 + 50^{**}$$

$$(2-8.137\ (10^{-5})\ Re/(\rho_g/\rho_f)^{0.262})\}]$$

$$F_{t8} = F_{t81}\ F_{t82}$$

$$F_{t81} = 0.3 + 0.7 \left[1 - \exp \left\{-10.31(10^{-8})\right.\right.$$

$$\left.\left. Re^2/(\rho_g/\rho_f)^{0.524}\right\}\right]$$

$$-2.9\ (10^{-11})\ Re^3\ (\rho_g/\rho_f)^{0.786}$$

$$\exp \left\{-9.3\ (10^{-8})\ Re^2/(\rho_g/\rho_f)^{0.524}\right\}$$

$$/\left[1 + 50^{**}\left\{-15.75\ (C_{pf}\Delta T_{sub}/h_{fg}) + 1.333\right\}\right]$$

$$F_{t82} = 1-0.16/[1 + 70^{**}\ 1250\ (D_{rod}/Z_{peak})$$

$$-5.45]\ /\ [1 + 80^{**}\ (7.14\ C_Q - 4.93)]$$

and

C_Q = $\int_0^{Z_{peak}} Q(Z)\ dZ/(\rho_f A_f V_{in} h_{fg})$

C_T = $(T_{init} - T_{sat})/(T_{Lei} - T_{sat})$

ρ_f = water density, kg/m^3 (lbm/ft^3)

D_{rod} = rod diameters, m (ft)

A_f = flow area formed by four adjacent rods, m^2 (ft^2)

h_{fg} = latent heat of evaporation, kcal/kg (Btu/lbm)

T_{Lei} = Leidenfrost temperature = 260°C (= 500°F)

ΔT_{sub} = inlet subcooling, °C (°F)

C_{pf} = specific heat of water at saturation temperature, Kcal/Kg (Btu/lbm)

The rationale and the method in deriving Equations (B-1) and (B-3) are as follows. In the early FLECHT correlation the quench time was predicted only for the peak power elevation, which is 1.83 m (6 ft) for cosine power shape. In the present version of the FLECHT-SEASET correlation, since the concept of the heat transfer coefficient, h, being a function of the distance from the quench front Z-Zq was used, it is necessary to have a correlation which is able to predict the quench time for all elevations. Since the old FLECHT correlation predicts the quench time at the peak power elevation quite well, it is used as a base correlation for the later and the present versions (Equation B-3), which is depicted by $t_{q,peak}$, and the quench time of the other elevations is predicted by adjusting $t_{q,peak}$ with the integrand of power Q_r as expressed in Equation (B-1).

In the above correlation, the quench time, t_q, is given as a function of the quench elevation, Z_q. In practice, it is necessary to compute the quench elevation as a function of time. This can be accomplished by (see References 5 and 6) first computing the quench front velocity V_q for a given time t by

$$V_q = \frac{(Z_q + \Delta Z_q) - Z_q}{t_q(Z_q + \Delta Z_q) - t_q(Z_q)} \tag{B-4}$$

where $t_q\ (Z_q + \Delta Z_q)$ and $t_q(Z_q)$ are the quench times computed from Equation (B-1), then compute the quench front elevation at the time $t + \Delta t$ by

$$Z_q(t + \Delta t) = Z_q(t) + V_q\ \Delta t \tag{B-5}$$

This method of computing the quench elevation as function of time is also valid for variable flooding rate. Note that for the case of variable flooding rate the actual time t is different from t_q as explained in References 5 and 6.

It is noted that the power per flow area is preserved in the above correlation through the parameter C_Q. It is also noted that through the use of the dimensionless quench time, $t_q V_{in}/Z_q$, the length effect as noted in the previous reports (f-factor in References 5 and 6) has been automatically taken care of.

3.0 HEAT TRANSFER COEFFICIENT CORRELATION

As with the previous FLECHT correlation, the FLECHT-SEASET heat transfer coefficient h is defined as

$$h = q_{total}/(T_{rod} - T_{sat})$$

where

q_{total} = rod total surface heat flux which includes radiation and convection

T_{rod} = rod surface (cladding) temperature

T_{sat} = saturation temperature.

The FLECHT-SEASET heat transfer coefficient correlation is divided into four parts instead of three parts as in References 5 and 6. These four parts are discussed in the following.

- The Radiative Heat Transfer Period

The radiative heat transfer period exists only for the case of low initial cladding temperature. For low initial cladding temperature there is practically no vapor generation at early time of flood because the rods are cold at the lower elevation. Therefore, the heat transfer during this period is essentially radiative heat transfer.

- The Early Developing Period

This period extends from the end of adiabatic period to the time when the heat transfer reaches a quasi-steady state (Figure B-1). During this developing period the heat transfer mechanism changes from the radiation-dominated pre-reflood condition to the single-phase steam flow. The mecnanism then changes to the dispersed flow when the steam velocity becomes great enough to carry droplets up the bundle.

- The Quasi-Steady Period

During this period the heat transfer is essentially in a quasi-steady state. This means that the heat transfer pattern moves with the quench front, that is, the heat transfer coefficient versus the distance from the quench front is essentially unchanged with time.

- Heat Transfer Coefficient Above the Peak Cladding Temperature Elevation

The situation for the elevation above the peak cladding temperature elevation is different from that below the peak cladding temperature elevation and therefore must be treated separately. Above the peak cladding temperature elevation the steam temperature may be greater than the cladding surface temperature, and the heat may be transferred from the steam to heater rods. The FLECHT definition of heat transfer coefficient (saturation temperature equal to sink temperature) implies that the heat transfer coefficient is negative. Below the peak cladding temperature elevation the steam temperature never becomes greater than the cladding surface temperature. Therefore, the heat transfer coefficient never becomes negative.

The four parts of the heat transfer coefficient correlation are as follows: (the transition between the adiabatic period and the developing period occurs when Z_q is equal to Z_{ad}, and the transition between the developing period and the quasi-steady period occurs when Z_q is equal to

$Z_{ad} + \Delta Z_s$, where Z_{as} and ΔZ_s are defined below):

- Radiative Heat Transfer Period ($Z_q < Z_{ad}$)

$$h \equiv h_1 = C\frac{Q'(Z)}{(\rho\ C_p\ A)_{rod}}\left[1 - \exp\left\{-\frac{T_{initz} - T_{ro}}{\Delta T_r}\right\}\right] \qquad \text{(B-6)}$$

where Z_{ad} is computed from the following dimensionless expression

$$1 = 51\ \frac{(\rho C_p A)_f\ \Delta T_{sub}\ V_{in}}{Q'_{max}\ Z_{ad}}$$

$$-0.234\ \frac{(\rho C_p A)_{rod}\ (T_{init} - T_{sat})\ V_{in}}{Q_{max}\ Z_{ad}} + \frac{Z_o}{Z_{ad}}\ F_h \qquad \text{(B-7)}$$

and

C = 1.89 kcal/C^2/m^2(=0.215 Btu/°F^2/ft^2)

F_h = $1/[1 + 70^{**}\{1-0.0133\ (Z_{peak}/D_{rod})\}]$

$(\rho C_p A)$rod = heat capacity of a rod, kcal/m (Btu/ft)

T_{initz} = $(T_{init} - T_{sat})\ Q'(Z)/Q'(Z_{peak}) + T_{sat}$, °C (°F)

T_{ro} = 371°C (=700°F)

ΔT_r = 224°C (=435°F)

$(\rho C_pA)_f$ = heat capacity of water in a channel formed by four adjacent rods, kcal/m (Btu/ft)

Z_o = 0.3496 m (=1.147 ft)

h = heat transfer coefficient, kcal/sec °C m^2 (Btu/sec °F ft^2).

It is noted that the radiative heat transfer coefficient h_1 given by Equation (B-6) is mainly due to the radiative heat exchange between the rod of interest and its neighboring thimble and rods. Therefore, h_1 depends on the temperature difference between the rods and the neighboring thimbles. The temperature difference depends on the pre-reflood heat-up rate. For example, if the pre-reflood heat-up rate is very slow, then the radial temperature will be essentially uniform and the temperature difference is practically zero so that h_1 is also zero. The faster the heat-up rate the larger the temperature difference and hence the larger the h_1. The heat-up rate is proportional to the local power $Q'(Z)$ and is inversely proportional to the heat capacity $(\rho C_pA)_{rod}$ of the rod. This leads to the expression of Equation (B-6).

- Developing Period ($Z_{ad} < Z_q < Z_{ad} + \Delta Z_s$)

$$Nu = Nu_1 \left[1 - \exp(2.5X - 10)\right] + \left[Nu_2 - Nu_1 \{1 - \exp(2.5X - 10)\}\right]$$

$$\cdot \left[1 - e^{-X} - 0.9 \times e^{-X^2}\right] \qquad \text{(B-8)}$$

Where $Nu = h\, D_{rod}/k_g$. When $Z_q = Z_{ad} + \Delta Z_s$, the heat transfer changes from the developing period to quasi-steady period, where ΔZ_s is computed from

$$\frac{\Delta Z_s}{V_{in}\, \rho_f\, C_{pf}\, D_e^2/k_f} = 6329\, (Re + 4000)^{-1.468}\ F_h. \qquad \text{(B-9)}$$

Other parameters are computed as follows:

$$Nu_2 = Nu_3 + 108 \exp [-1.83 (10^{-5}) Re/(\rho_g/\rho_f)^{0.262}] \exp [-0.0534 (Z - Z_q)/D_e] \qquad (B-10)$$

Nu_1 and Nu_3 are computed by first calculating h_1 and h_3, respectively, then using the definition of Nusselt number as follows

h_1 = from equation (B-6)

$N_{u1} = h_1 D_e/k_g$

$$\frac{h_3(T_{eff,z} - T_{sat}) D_{rod}}{Q'_{eff,z}} = 1.21 [1 - \exp \left\{-305(10^{-5}) Re(\rho_g/\rho_f)^{-0.262}\right\}] [0.714 + 0.286 \left\{1 - \exp (-3.05(10^{-4}) (\rho_g/\rho_f)^{1.524} Re^{-2})\right\}] \qquad (B-11)$$

$Nu_3 = h_3 D_e/k_g$.

The other paramerters in the above correlation are

$\Delta T_{eff} = \Delta T_c/[1 + 60** \left\{1.08\left(T_{init} - T_{sat}\right)/\Delta T_c - 1.26\right\}]$

ΔT_c = 427°C (=800°F)

$T_{eff} = T_{init} + \Delta T_{eff}$

$T_{eff,Z} = T_{sat} + (T_{eff} - T_{sat}) Q'(Z_q)/Q'(Z_{peak})$

$X = 4(Z_q - Z_{ad})/\Delta Z_s$

D_e = hydraulic diameter of the channel formed by four adjacent rods, m (ft)

ρ_f = density of water at saturation temperature, kg/m^3 (lbm/ft^3)

ρ_g = density of steam at saturation temperature, kg/m^3 (lbm/ft^3)

C_{pf} = specific heat of water at saturation temperature, kcal/kg (Btu/lbm)

k_f = conductivity of water at saturation temperature, kcal/sec °C m (Btu/sec °F ft)

Q'_{eff} = 2297 w/m = 2297 joules/sec m (= 0.7 kw/ft)

$Q'_{eff,Z}$ = $Q'_{eff}\ Q'(Z_q)/Q'(Z_{peak})$

k_g = conductivity of steam at saturation temperature, kcal/sec °C m (Btu/sec °F ft)

D_{rod} = rod diameter, m (ft)

Re = $\rho_f\ V_{in}\ D_e/\mu_f$, dimensionless

- Quasi-Steady Period ($Z_q > Z_{ad} + \Delta Z_s$)

$Nu = Nu_2$.

- Above Peak Elevation ($Z > Z_{peak}$)

$$Nu = Nu_4 - 44.2\ [1 - Q'(Z)/Q'(Z_{peak})]\ \exp\ [-0.00304\ (Z - Z_{peak})/D_e]$$

where $Nu_4 = N_{u1}$ for adiabatic period, Nu_4 = Equation (B-8) for developing period, and $Nu_4 = Nu_2$ for quasi-steady period.

Note that in above correlation all expressions are in dimensionless forms except Equation (B-6), which is primarily due to the radiation. Therefore, consistent units must be used.

The range of application for the parameters contained in the correlations discussed are given in Tables B-1 and B-2. Following the tables is a listing of a computer program of the correlations. In case there is any difference between the above correlations and the computer program, the computer program should be considered the correct version.

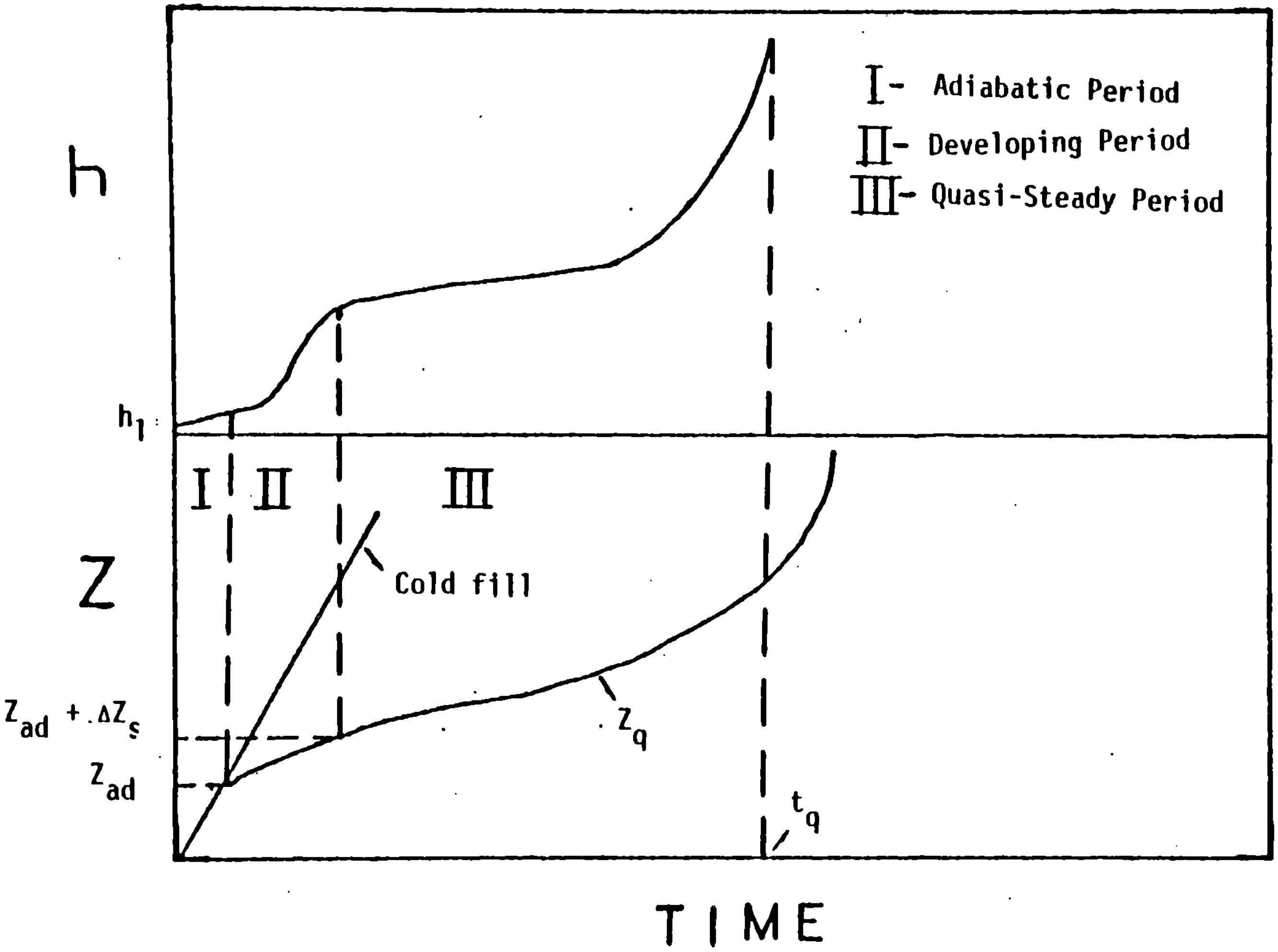

Figure B-1. Definition of heat transfer periods.

TABLE B-1. DIMENSIONAL PARAMETER RANGE

Parameter	Parameter Range
Pressure	103 to 414 KPa (15 to 60 psia)
Inlet subcooling	9 to 78°C (16 to 140°F)
Initial temperature	149 to 1204°C (300 to 2200°F)
Flooding rate	1.02 to 25.4 cm/s (0.4 to 10 in./s)
Equivalent peak power[a]	0.984-6.56 kW/m (0.3-2.0 kW/ft)

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a. The equivalent peak power is the power equivalent to the peak power of the FLECHT cosine power shape when the integrated power is preserved.

TABLE B-2. DIMENSIONLESS PARAMETER RANGE

Parameter	Parameter Range
C_Q	0.204 to 1.14
C_T	0.146 to 6.9
ρ_g/ρ_f	0.000636 to 0.0036
$C_{pg}\ \Delta T_{sub}/h_{fg}$	0.0165 to 0.158
Re $(\rho_f\ V_{in}\ D_e/\mu_f)$	470 to 8620
Z_{peak}/D_{rod}	61 to 284

COMPUTER PROGRAM OF HEAT TRANSFER CORRELATION

```
TYPE YHTDL.F4
C  FLECHT-SEASET UNBLOCKED BUNDLE EVALUATION REPORT
C  REFLOOD HEAT TRANSFER COEFFICIANT CORRELATION IN
C    DIMENSIONLESS FORM DEVELOPED BY YEH.
      REAL KF,KG,NU1,NU2,NU3,NU
      DIMENSION QAXZQ(92),QAXTB(92),FAXTB(93),FAXZ(93)
     1,PDCAY(111),PDCT(111),QAXTBS(99),QAXZQS(99),FAXTBS(99),
     2FAXZS(99),VINTM(111),VINTB(111),QAXZQ4(99),QAXTB4(99),
     3FAXZQ4(99),FAXTB4(99),FTQTBS(99),FTQZQS(99)
     4,QAXZQ3(33),QAXTB3(33),FAXZQ3(33),FAXTB3(33),
     5FTQZQ3(33),FTQTB3(33),ZQTM(55),ZQTB(55)
10    CONTINUE
      TYPE 950
950   FORMAT(' MR=1 FOR FLECHT POWER, MR=2 FOR UNIFORM POWER')
      TYPE 900
900   FORMAT (' M=1 FOR COSINE, M=2 FOR SKEW'/
     1' MBDL=15 FOR 15X15, MBDL=17 FOR 17X17')
      TYPE 1000
1000   FORMAT(' ENTER RUN   DTSUB    P    TINT    QMAX    TSAT
     1  M  MR  Z  ZPEAK  MBDL'/)
      ACCEPT 1002,NRUN,DTSUB,P,TINIT,QMAX,TSAT,M,MR,
     1 Z,ZPEAK,MBDL
1002   FORMAT (11G)
      TYPE 1100
1100  FORMAT(' ENTER VIN TABLE BELOW')
      TYPE 1110
1110  FORMAT(' ENTER NO. OF POINTS'/)
      ACCEPT 1112, NVIN
1112  FORMAT(I)
      TYPE 1102
1102  FORMAT(' ENTER TIME(10/LINE)'/)
      ACCEPT 1104, (VINTM(J),J=1,NVIN)
1104  FORMAT((10G))
      TYPE 1106
1106  FORMAT(' ENTER VIN(10/LINE)'/)
      ACCEPT 1104, (VINTB(J),J=1,NVIN)
      IF (MZQ .NE. 1) GO TO 1300
      TYPE 1200
1200  FORMAT(' ENTER ZQ TABLE BELOW')
      TYPE 1210
1210  FORMAT(' ENTER NO. OF POINTS'/)
      ACCEPT 1112, NZQ
      TYPE 1202
1202  FORMAT(' ENTER TIME (10/LINE)'/)
      ACCEPT 1104, (ZQTM(J),J=1,NZQ)
      TYPE 1206
```

```
1206  FORMAT(' ENTER ZQ (10/LINE)'/)
      ACCEPT 1104, (ZQTB(J),J=1,NZQ)
1300  CONTINUE
C
C  TABLE OF NORMALIZED POWER DECAY
C
      DATA (PDCAY(J),J=1,17)/1., 1.085, 1.153, 1.198, 1.226
     1, 1.244, 1.255, 1.262, 1.27, 1.28, 1.298, 1.311, 1.319
     2, 1.324, 1.327, 1.328, 1.33/
      DATA (PDCT(J),J=1,17)/0., 20., 40., 60., 80.
     1, 100., 120., 140., 160., 200., 280., 360., 440.
     2, 520., 600., 680., 2000./
      IF (M .NE. 1) GO TO 12
C
C  TABLE OF NORMALIZED INTEGRAL OF POWER FOR FLECHT COSINE
C  POWER BUNDLE
C
      DATA (QAXZQ(J),J=1,17)/0., 1.83, 2.34, 3., 3.58,
     1 4.17, 4.83, 5.42, 6., 6.58, 7.17, 7.83, 8.42, 9.,
     2 9.66, 10.17, 12./
      DATA (QAXTB(J),J=1,17)/0., .53, .735, 1.088,
     11.478, 1.935, 2.534, 3.096, 3.6795, 4.263, 4.825,
     2 5.424, 5.881, 6.271, 6.624, 6.829, 7.359/
C
C  TABLE OF AXIAL POWER SHAPE FACTOR FOR FLECHT COSINE
C  PWER BUNDLE
C
      DATA (FAXTB(J),J=1,30)/.289, .289, .41, .41, .53, .53
     1, .669, .669, .783, .783, .898, .898, .964, .964, 1., 1.
     2, .964, .964, .898, .898, .783, .783, .669, .669, .53, .53
     3, .41, .41, .289, .289/
      DATA (FAXZ(J),J=1, 30)/0., 1.83, 1.84, 2.33, 2.34, 3.
     1, 3.01, 3.58, 3.59, 4.17, 4.18, 4.83, 4.84, 5.42, 5.43
     2, 6.58, 6.59, 7.17, 7.18, 7.83, 7.84, 8.42, 8.43
     3, 9., 9.01, 9.67, 9.68, 10.17, 10.18, 12./
      GO TO 16
12    CONTINUE
C
C  TABLE OF NORMALIZED INTEGRAL OF POWER FOR FLECHT SKEWED
C  POWER BUNDLE
C
      IF (M .NE. 2) GO TO 13
      DATA (QAXZQS(J),J=1,14)/0., 1.5, 2.5, 3.5, 4.5, 5.5
     1, 6.5, 7.5, 8.5, 9.25, 10.25, 10.75, 11.25, 12./
      DATA (QAXTBS(J),J=1,14)/0., .722, 1.285, 1.907, 2.589
     1, 3.33, 4.13, 4.989, 5.915, 6.643, 7.643, 8.098
     2, 8.494, 8.845/
C
C  TABLE OF AXIAL POWER SHAPE FACTOR FOR FLECHT SKEWED POWER
C  BUNDLE
C
```

```
      DATA (FAXZS(J),J=1,26)/0., 1.5, 1.51, 2.5, 2.51, 3.5
     1, 3.51, 4.5, 4.51, 5.5, 5.51, 6.5, 6.51, 7.5, 7.51
     2, 8.5, 8.51, 9.25, 9.26, 10.25, 10.26, 10.75, 10.76
     3, 11.25, 11.26, 12./
      DATA (FAXTBS(J),J=1,26)/.4815, .4815, .563, .563, .622
     1, .622, .681, .681, .741, .741, .8, .8, .859, .859
     2, .926, .926, .97, .97, 1., 1., .911, .911, .793, .793
     3, .5259, .5259/
      GO TO 16
13    CONTINUE
16    CONTINUE
      TYPE 2100
2100   FORMAT (3X,4HTIME,8X,1HH,4X,6HZQ(FT)
     1,4X,5HH(SI),1X,5HZQ(M))
       IX=30
       IF(M.EQ.1)CALL INTERP(FAXZ,FAXTB,IX,Z,FAX,FAXVZQ)
       IX=26
       IF(M.EQ.2)CALL INTERP(FAXZS,FAXTBS,IX,Z,FAX,FAXVZQ)
       TINITZ=(TINIT-TSAT)*FAX+TSAT
      RCPA=.05562
      IF (MBDL .EQ. 17) RCPA=.03851
      H1=.215*QMAX*.9481*FAX/RCPA*(1.-EXP(-(TINITZ-700.)/435.
      IF (TINITZ .LT. 700.) H1=0.
C
C  STEAM PROPERTIES---THE FOLLOWING ARE WESTINGHOUSE STEAM
C    TABLE FUNCTIONS.  THEY MAY BE REPLACED BY APPROPRIATE
C    FUNCTIONS OR GIVEN AS INPUTS.
C
      HG=HSV(P,TSAT,S,VOLG)
C  THIS FUNCTION PERFORMS  H,T,S,V=F(P)
C  WHERE ENTROPY S IS NOT USED.
      VOLF=VCL(P,TSAT)
      CPF=CPL(P,TSAT)
      HF=HSL(TSAT)
      VISF=VISL(P,TSAT)
      KF=CONDL(P,TSAT)/3600.
      KG=CONDV(P,TSAT)/3600.
C
      A=.00123
      IF (MBDL .EQ. 17) A=.0009455
      RHOG=1./VOLG
      RHOF=1./VOLF
      RHOGF=RHOG/RHOF
      CT=(TINIT-TSAT)/(500.-TSAT)
      HFG=HG-HF
      DR=.422/12.
      DE=.04451
      IF (MBDL .EQ. 15) RCPAF=.00123
      IF (MBDL .EQ. 15) RCPAR=.05562
      IF (MBDL .EQ. 17) RCPAF=.0009455
      IF (MBDL .EQ. 17) RCPAR=.0385
```

```
      IF (MBDL .EQ. 17) DE=.03863
      IF (MBDL .EQ. 17) DR=.374/12.
      H=H1
      HSI=H*5.67826
       T=0.
       ZQ=0.
       DZQ=.005
       CALL INTERP(VINTM,VINTB,NVIN,0.,VIN,VINSL)
       JTYPE=0
       JSTYPE=0
       J=1
   15  CONTINUE
   19 CONTINUE
C
C  COMPUTE QUENCH FRONT ELEVATION
C
      ZQ=ZQ+DZQ
   60 CONTINUE
      DO 40 IVQ=1,2
      IF (IVQ .EQ. 1) ZQ=ZQ-.0005
      IF (IVQ .EQ. 2) ZQ=ZQ+.0005
      IX=17
      IF (M .EQ. 1) CALL INTERP(QAXZQ,QAXTB,IX,ZQ,QAX,QAXSLP)
      IX=14
      IF (M .EQ. 2) CALL INTERP(QAXZQS,QAXTBS,IX,ZQ,QAX,QAXSLP)
      QEQ1=QMAX
      IF (MR .EQ. 2) QEQ1=QEQ1*1.1
      IX=30
      IF (M .EQ. 1) CALL INTERP(FAXZ,FAXTB,IX,ZQ,FAX,FAXVZQ)
      IX=26
      IF (M .EQ. 2) CALL INTERP(FAXZS,FAXTBS,IX,ZQ,FAX,FAXVZQ)
      QEQ=QEQ1
      TINITE=(TINIT-TSAT)*FAX+TSAT
      DTC=800.
      DTE=DTC/(1.+60.**(1.08*(TINIT-TSAT)/DTC-1.26))
      TE=TINIT+DTE
      TEZ=TSAT+(TE-TSAT)*FAX
      QEFFZ=.7*FAX*.9481
      CALL INTERP(VINTM,VINTB,NVIN,T,VIN,VINSL)
      RE=VIN/12.*RHOF*DE/VISF
      FH=1./(1.+70.**(1.-.0133*(ZPEAK/DR)))
      ZS=6329.*(RE+4000.)**(-1.468)*VIN/12.*RHOF
     1*CPF*DE*DE/KF*FH
      ZAD=51.*RCPAF*DTSUB*VIN/12./QMAX/.9481-.234*RCPAR
     1*(TINIT-TSAT)*VIN/12./QMAX/.9481+1.147*FH
      IF (ZAD .LE. 0.) ZAD=0.
      FDTSUB=EXP(-10.09*(CPF*DTSUB/HFG))
      FVIN1=1.-EXP(-.00008137*RE/RHOGF**.262)
      FVIN2=1.3*EXP(-1.652E-9*RE*RE/RHOGF**.524)
      FVIN3=EXP(-7.293E-9*RE*RE/RHOGF**.524)
      FVIN4=66203.*RHOGF**.2882/RE**1.1-2.8*EXP(-.000122*
```

```
     1RE/RHOGF**.262)
      FVIN5=1.+.5/(1.+50**(2.-.00008137*RE/RHOGF**.262))
      FP1=1.+.5*EXP(-5.6251E+08*RHOGF*RHOGF*RHOGF)
      FP2=17.3*EXP(-5.6251E+08*RHOGF*RHOGF*RHOGF)
      FP3=FP1
      FP4=1.+.32/(1.+50.**(5.-2520.*RHOGF))
      CT=(TINITE-TSAT)/(500.-TSAT)
      FT1=1.01552+.01388*CT
      FT2=1.05*EXP(-.66-.59*CT)
      FT=FT1+FT2
      FVSUB=.3+.7*(1.-EXP(-10.31E-8*RE*RE/RHOGF**.524
     1))-2.9E-11*RE*RE*RE/RHOGF**.786*EXP(-9.3E-8*RE*RE
     2/RHOGF**.524)/(1.+50.**(-15.75*(CPF*DTSUB/HFG)+1.333)
      DO 20 K=1,3
      IF (M.EQ.1) QDLS=.9481*3.6795/RHOF/A/VIN*12./HFG
      IF (M.EQ.2) QDLS=.9481*7.393/RHOF/A/VIN*12./HFG
      CQ=QEQ*QDLS
      FVQ1=-.7*(1.-EXP(-.0000801*RE/RHOGF**.262))
      FVQ2=6.458E-5*RE**1.938/RHOGF**.5078*(CQ*DR/ZPEAK)**1.
      FVQ=FVQ1+FVQ2
      FQ=1.-.16/(1.+70.**(1250.*(DR/ZPEAK)-5.45))
     1/(1.+80.**(7.14*CQ-4.93))
      TQ=(FDTSUB*FVQ*(FP1+FVIN2+FP2*FVIN3)
     1+FVIN4*FP3)*(FT1-FT2*FVIN5*FP4)*FVSUB*FQ
      TQ=ZPEAK/VIN*.00228*RE*RHOGF**(-.262)*TQ
      FR1=.5
      FR2=9.
      IF (M .EQ. 1) QR=QAX/3.6795
      IF (M .EQ. 2) QR=QAX/7.393
      FQ=QR+FR1*QR*EXP(-FR2*QR*QR)
      TQ=TQ*FQ
      TQ=ZQ/VIN*12.+(TQ-ZQ/VIN*12.)/(1.+50.**
     1(-(TINITE-400.)/(400.-TSAT)))
      IX=16
      CALL INTERP(PDCT,PDCAY,IX,TQ,PDECAY,PDCP)
      QEQ=QEQ1*PDECAY
20    CONTINUE
C      TYPE 3000, NS,T,TQ,HSI,ZQM
      IF (IVQ .EQ. 1) ZQ1=ZQ
      IF (IVQ .EQ. 1) TQ1=TQ
      IF (IVQ .EQ. 2) ZQ2=ZQ
      IF (IVQ .EQ. 2) TQ2=TQ
40    CONTINUE
      VQ=(ZQ2-ZQ1)/(TQ2-TQ1)
      VQINCH=VQ*12.
C
C  COMPUTE HEAT TRANSFER COEFFICIENT
C
70    CONTINUE
      ZQM=ZQ*.3048
C      TYPE 3000, NS,T,TQ,HSI,ZQM
```

```
      IF(J.EQ.1) TYPE 2200,T,H,ZQ,HSI,ZQM
      T=T+DZQ/VQ
      X=4.*(ZQ-ZAD)/ZS
      NU1=H1/3600.*DE/KG
      H3=QEFFZ/(TEZ-TSAT)/DR*1.21*(1.-EXP(-.0000305*RE/RHOGF
     1**.262))
     2*(.714+.286*(1.-EXP(-3.05E-4*RHOGF**1.524/RE/RE)))
      NU3=H3*DE/KG
      NU2=NU3+108.*EXP(-.0000183*RE/RHOGF**.262)*
     1EXP(-.0534*(Z-ZQ)/DE)
      IF (ZQ .LE. ZAD) NU=NU1
      IF (ZQ .LT. (ZS+ZAD) .AND. ZQ .GT. ZAD) NU=NU1*
     1(1.-EXP(2.5*X-10.))+(NU2-NU1*(1.-EXP(2.5*X-10.)))
     2*(1.-EXP(-X)-.9*X*EXP(-X*X))
      IF (ZQ .GE. (ZS+ZAD)) NU=NU2
      IF (Z .LE. ZPEAK) GO TO 27
      IF (M .EQ. 1) CALL INTERP(FAXZ,FAXTB,30,Z,FAX,FAXV)
      IF (M .EQ. 2) CALL INTERP(FAXZS,FAXTBS,26,Z,FAX,FAXV)
27    CONTINUE
      IF (Z .GT. ZPEAK) NU=NU-44.2*(1.-FAX)*EXP(-.00304
     1*(Z-ZPEAK)/DE)
      JTYPE=JTYPE+1
      JSTYPE=JSTYPE+1
      H=NU*KG*3600./DE
      HSI=H*5.67826
      IF(ZQ.LE.ZS.AND.JSTYPE.EQ.40.AND.JTYPE.NE.100)
     1 TYPE 2200,T,H,ZQ,HSI,ZQM
      ZMZQ=Z-ZQ
      IF(JTYPE.EQ.100)TYPE 2200,T,H,ZQ,HSI,ZQM
2200  FORMAT(F7.0,F11.2,F7.1,F9.0,F6.2)
      IF(JSTYPE.EQ.40)JSTYPE=0
      IF (JTYPE .EQ. 100) JTYPE=0
      IF (ZQ .GE. 12.) GO TO 30
      J=J+1
      GO TO 15
30    CONTINUE
      STOP
      END
      SUBROUTINE INTERP(X,Y,L,X1,Y1,SLOPE)
      DIMENSION X(100),Y(100)
      DO 100 K=1,L
      K1=K
      IF (X(K1)-X1) 100,100,200
100   CONTINUE
200   Y1=Y(K1-1)+((X1-X(K1-1))/(X(K1)-X(K1-1)))
     1*(Y(K1)-Y(K1-1))
      SLOPE=(Y(K1)-Y(K1-1))/(X(K1)-X(K1-1))
      RETURN
      END
```

EXAMPLES OF CALCULATION

```
 RUN YHTDL

MR=1 FOR FLECHT POWER, MR=2 FOR UNIFORM POWER
M=1 FOR COSINE, M=2 FOR SKEW
MBDL=15 FOR 15X15, MBDL=17 FOR 17X17
ENTER RUN    DTSUB   P   TINT    QMAX    TSAT  M  MR  Z  ZPEAK  MBDL
     31805, 140.,  40., 1600.,   .7,    267., 1, 2,  6., 6.,     17

ENTER VIN TABLE BELOW
ENTER NO. OF POINTS
2

ENTER TIME(10/LINE)
0., 1000.

ENTER VIN(10/LINE)
.8, .8

  TIME          H     ZQ(FT)     H(SI) ZQ(M)
    0.        3.24    0.0        18.  0.00
    5.        3.24    0.2        18.  0.06
   10.        3.24    0.4        18.  0.12
   13.        3.24    0.5        18.  0.15
   15.        3.24    0.6        18.  0.18
   20.        3.55    0.8        20.  0.24
   25.        5.27    1.0        30.  0.30
   30.        6.71    1.2        38.  0.37
   37.        7.33    1.5        42.  0.46
   54.        7.68    2.0        44.  0.61
   75.        7.84    2.5        45.  0.76
   93.        8.16    3.0        46.  0.91
  117.        8.79    3.5        50.  1.07
  142.       10.07    4.0        57.  1.22
  174.       12.61    4.5        72.  1.37
  209.       17.68    5.0       100.  1.52
  247.       27.81    5.5       158.  1.68
  287.       48.01    6.0       273.  1.83
  326.       88.35    6.5       502.  1.98
  362.      168.86    7.0       959.  2.13
  394.      329.58    7.5      1871.  2.29
  419.      650.36    8.0      3693.  2.44
  435.     1290.67    8.5      7329.  2.59
  460.     2568.77    9.0     14586.  2.74
  456.     5119.91    9.5     29072.  2.90
  442.    10212.13   10.0     57987.  3.05
  410.    20376.46   10.5    115703.  3.20
  418.    40665.03   11.0    230907.  3.35
  427.    81162.08   11.5    460859.  3.51
  436.   161996.38   12.0    919858.  3.66
```

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

RES Files
Subject File No. R-2112
NUREG/CR 1532
NUREG/CR 1533
NUREG/CR 2256
Task No.
Research Request No.
FIN No. B 6204
NUREG NO.
NRC CONTRACT 04-77-127
Rulemaking No.
Other RIL 135
NRC PDR
Return NRC-318 to RES, Yes [✓ No]

SEP 13 1983

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NO. 135, "HEAT TRANSFER AND HYDRAULICS IN FULL LENGTH 17 x 17 ROD FUEL BUNDLE DURING REFLOOD PHASE OF PWR LOCA

References:
(1) Letter from B. C. Rusche to S. Levine, "Extension of the PWR FLECHT Program" February 9, 1977
(2) Research Information Letter No. 67, "Reflooding of Simulated PWR Cores at Low Flow Rates," November 6, 1979
(3) L. E. Hochreiter, et al., "PWR FLECHT-SEASET Unblocked Bundle, Forced and Gravity Reflood Task: Data Report, NRC/EPRI/Westinghouse Report No. 7," NUREG/CR-1532, June 1980
(4) S. Wong and L. E. Hochreiter, "Analysis of the FLECHT-SEASET Unblocked Bundle Steam Cooling and Boiloff Tests," NRC/EPRI/Westinghouse Report No. 8, NUREG/CR-1533, January 1981
(5) N. Lee, et al., "PWR FLECHT-SEASET Unblocked Unbundle Forced and Gravity Reflood Task, Data Evaluation and Analysis Report," NRC/EPRI/Westinghouse Report No. 10, NUREG/CR-2256, November 1981

This memorandum transmits the results of a completed research task investigating the heat transfer and hydraulic in a full length 17 x 17 rod fuel bundle during the reflood phase of a pressurized water reactor (PWR) large-break loss-of-coolant accident (LOCA). This research was conducted as part of the Full-Length Emergency Core Heat Transfer-Separate Effects and System Effects Tests (FLECHT-SEASET). It is jointly sponsored by the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute and Westinghouse Electric Corporation. This 7-year research program is conducted by Westinghouse under the direction of the Program Management Group (PMG) from the three sponsoring parties.

Part of the request of Reference 1 is that reflood experiments be conducted on the 17 x 17 rod design because the present nonproprietary data base is limited

Contact:
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42-74260

to the Westinghouse 15 x 15 rod design. The goals of the FLECHT-SEASET 17 x 17 Rod Unblocked Bundle Task were:

A. Provide an expanded reflood data base that will be useful in the development or verification of computational methods to predict the reflood thermal-hydraulic behavior of the new 17 x 17 core rod geometries.

B. Establish a baseline for comparison with the future FLECHT-SEASET 21-rod and 17 x 17 rod flow blockage tasks.

C. Evaluate the effects of bundle geometry on reflood heat transfer when compared to previous FLECHT 15 x 15 unblocked tests.

These goals were accomplished and the significant results can be summarized as follows:

A. Compared with the FLECHT (15 x 15) data, both bundle geometries produce approximately the same parametric effects for flooding rate, pressure, subcooling, initial cladding temperature, and peak power, if the integrated power per unit bundle flow area is preserved.

B. The existing PWR reflood data base has been expanded to include the new 17 x 17 rod experiments. A new and more general correlation has been developed which can predict the new data as well as the old 15 x 15 data.

C. The data supports the conclusion of RIL 67 that substantial heat transfer is available for reflood rate below 1 inch/second. This is due to the significant dispersed flow heat transfer observed for low flooding rates.

D. An improved data-based steam cooling correlation for low Reynolds number has been developed.

We recommend that these results be used to update the existing evaluation method and incorporated into any substantial revision to Appendix K to 10 CFR 50. The blockage task is expected to be completed in FY 1984 and a RIL to address the blockage issue will then be issued.

Original signed by:
ROBERT B. MINOGUE

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosure: FLECHT-SEASET 17 x 17 Unblocked
Bundle Reflood Heat Transfer
Experiment Results

RES:DD
DFRoss
8/26/83

RES:D
RBMinogue
9/2/83