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PREDICTABILITY OF BURN DEPTH: DATA ANALYSIS AND MATHEMATICAL MODELING BASED ON USAARL'S EXPERIMENTAL PORCINE BURN DATA

FINAL REPORT

BY

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This report summarizes the work accomplished during the contract period 1 July 1975 through 30 September 1978. The working hypothesis of this study was: given the output of physical thermal sensors and the actual burns experienced by pigs, it should be possible to develop a mathematical model which can convert the output of the sensors to predicted burn depths in reasonable agreement with the observed burn depths. The specific objectives accomplished are as follows: 1) the previously collected data base was reviewed for error both in coding and

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) in content; 2) the biopsy specimens were re-read using a new set of standards so that corrections for thermally induced tissue shrinkage could be calculated; 3) graphical representations of the data contained in the revised data base were made as a help in understanding the relationships embodied in the data; 4) an empirical, multidiscriminant model was written which predicts either gross (clinical) grade or histopathologic grade given parameters such as heat flux, exposure time, skin temperature, and the like; 5) an analytical model was developed to circumvent the problems associated with the multidiscriminant model regarding the inability to use a flux-time profile; 6) optimization of the analytical model was accomplished using data in the data base, intraskin time-temperature profiles and such data as could be found in the literature, e.g. University of Rochester, Moritz and Henriques and Stoll, as performance criteria. Abstracts of 10 additional reports covering various aspects of the project in more detail and a listing of BRNSIM, the analytical model are appended. Conclusions and Recommendations include:

1) The USAARL Porcine Burn Data Base is ready for release.
2) Data handling and graphing programs are available to facilitate further study.
3) BRNSIM, which predicts burn depths over a wide range with reasonable accuracy, should be tested against the Aerotherm manikin model.
4) Skin cooling by blood and tissue water boiling should be further studied.
5) BRNSIM should be tested using Stoll's extensive human burn data base.

PREFACE

Research discussed in this report was accomplished between 1 July 1975 and 30 September 1978 by the author under USAARL Contract DABT01-75-C-0257 (1 July 1975 through 30 September 1976) and USAMRDC Contract No. DAMD17-77-C-7004 (1 October 1976 through 30 September 1978). The original data was collected at the U. S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama between June 1972 and January 1973.

In the data collection phase of this project the animals used were procurred, maintained and used in accordance with the Animal Welfare Act of 1970 and AR 70-18. The investigators adherred to the "Guide for Laboratory Animal Facilities and Care", as promulgated by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences, National Research Council.

The vivarium of the United States Army Aeromedical Research Laboratory (USAARL) is fully accredited by the American Association for Accreditation of Laboratory Animal Care.

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TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	10
	1.1. Experimental Rationale	10
	1.2. Data Collection	10
	1.3. Analysis by IITRI	11
	1.4. Working Hypothesis	11
	1.5. Objectives	11
	1.6. Summary	12
2.0	DATA BASE VALIDATION	13
	2.1. Eliminate Keypunch/Transcription Errors	13
	2.2. Re-Read Biopsy Material to Allow for Shrinkage Correction	13
	2.3. Corrections to Original Data	16
	2.3.1. Shutter Dynamics	16
	2.3.2. Initial Skin Temperature	16
	2.3.3. Hair Removal	16
	2.4. Data Management Computer Programs	16
3.0	GRAPHIC PRESENTATION OF THE DATA BASE	18
4.0	EMPIRICAL MODEL	32
5.0	ANALYTICAL MODEL	32
6.0	SOLUTION OF MATHEMATICAL MODEL	35
7.0	THERMAL PROPERTIES OF SKIN	38
8.0	INTRASKIN TEMPERATURES	39
9.0	PREDICTIONS FROM SENSOR DATA	40

TABLE OF CONTENTS

		Page
10.0	COMPARISON WITH WEAVER AND STOLL (7)	62
11.0	UNANALYZED SENSOR DATA	62
12.0	DISCUSSION	68
13.0	CONCLUSIONS AND RECOMMENDATIONS	68
14.0	REFERENCES	70

LIST OF APPENDIXES

		Page
APPENDIX A:	Bibliography - Thermal Project	72
APPENDIX B:	Bibliography - Thermal Analysis Program: Abstracts of Reports and Papers in Preparation	76
APPENDIX C:	BRNSIM 3 - Listing of the Interactive Analytical Model BRNSIM	83

LIST OF FIGURES

Figure		Page
1	Schematic Diagram of Porcine Skin Showing Location of Measurements A through E Recorded for Each Biopsy Specimen	14
2	Gross Grade vs. Normalized Burn Depth	20
3	Gross Grade vs. Corrected Burn Depth	21
4	New Micro Grade vs. Normalized Burn Depth	22
5	New Micro Grade vs. Corrected Burn Depth	23
6	New Micro Grade vs. Total Flux	24
7	Gross Grade vs. Total Flux	25
8	Gross Grade vs. New Micro Grade	26
9	Log Exposure Time vs. Log Flux Paramaterized by New Micro Grade 4	27
10	Log Exposure Time vs. Log Flux Parameterized by New Micro Grade 6	28
11	Log Exposure Time vs. Log Flux Parameterized by New Micro Grade 9	29
12	Normalized Burn Depth vs. Total Flux Parameterized by Exposure Time	30
13	Gridwork for Numerical Analysis	36
14	One Page Summary Report from a Simulation of the Exposure of Pig 294RF	41
15	Photographs of Intraskin Thermocouple Before and After Burn	42
16	Observed Temperature Profile #27 Overlayed on the Calculated Temperature Profile	43
17	Observed Temperature Profile #28 Overlayed on the Calculated Temperature Profile	44

LIST OF FIGURES (Continued)

Figure		Page
18	Observed Temperature Profile #29 Overlayed on the Calculated Temperature Profile	45
19	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off	46
20	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off vs. Observed Profile #27	47
21	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off vs. Observed Profile #28	48
22	Simulation in Which Intraskin Temperature Gradient, Cooling by Blood and Water Boiling are Turned Off vs. Observed Profile #29	49
23	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On	50
24	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On vs. Observed Profile #27	51
25	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On vs. Observed Profile #28	52
26	Simulation of BRNSIM 3 vs. M12VB0120 in Which Temperature Gradient, Cooling by Blood and Water Boiling are Turned On vs. Observed Profile #29	53
27	Simulation of Pig 296RF in 8.2 Seconds at 2.36 $cal/cm^2/sec$	56
28	Temperature Plot of Simulation (Fig. 27) Showing Model Instability Due to Recalculation of Thermal Properties	57
29	Simulation Which Results in a Prompt Cooling of the Skin Following Shutter Closure when Recalculation of Thermal Properties is Inhibited	58

LIST OF FIGURES (Continued)

Figure		Page
30	Simulation Which Results in a Prompt Cooling of the Skin Following Shutter Closure when Recalculation of Thermal Properties is Inhibited	59
31	Results of a Simulation of Aerotherm Thermoman Sensor in Contact with Fabric	61
32	Results of a Comparison of Predictions of BRNSIM (M12VB0120) with Weaver and Stoll's Measured Surface Temperature	64
33	Results of a Comparison of Predictions of BRNSIM (M12VB0120) with Weaver and Stoll's Measured Surface Temperature	65
34	Results of a Comparison of Predictions of BRNSIM (M12VB3745) in Which Blood Cooling Starts at 37 Seconds Postburn with Weaver and Stoll's Measured Surface Temperature	66
35	Results of a Comparison of Predictions of BRNSIM (M12VB3745) in Which Blood Cooling Starts at 37 Seconds Postburn with Weaver and Stoll's Measured Surface Temperature	67

LIST OF TABLES

Table		Page
I	Histopathological and Burn Depth Grading Definitions	15
II	Regression Analysis of Pig Skin Temperatures	17
III	One Page Sample Listing of the Primary Data Base	19
IV	Results of Applying an Empirical Model to Predict Gross Burn Grade	33
V	Model Parameters Changeable Interactively	37
VI	Comparison of Burns Observed in Bioassay Test with Predictions of Model 3	54
VII	Effect of Normalized Depth in Reducing RMS Error in Data Summarized in Table VI	55
VIII	Summary of Twenty Simulations of Fabric Covered Sensors Comparing Predicted Depths with Both Normalized and Corrected Depths	60
IX	Effect of Normalized Depth in Reducing RMS Error in Sensor Data Summarized in Table VIII	63

1.0 INTRODUCTION

This is the final report of a data analysis and model development study based on information collected in USAARL's Thermal Analysis Program. (1, 2)

The overall technical objective was to provide managers with a clinically valid algorithm for evaluating thermally protective fabrics with potential for military use. The basic question which managers need answered is whether a particular fabric will, when exposed to an accurate simulation of a post-crash fire, reduce thermal transfer to clinically safe levels, and, if so, for how long? Colateral to this basic question is whether the fabric itself adds hazard by becoming a secondary thermal source. If a particular fabric becomes a secondary source, it is then important to know the degree to which it increases the hazard.

In order to answer these questions, a logical approach would be to expose fabrics to a controlled thermal source which accurately simulates a post-crash fire and to measure the thermal transfer through the fabrics with skin simulants or heat flux transducers. This approach, if carefully carried out, would provide accurate, reproducible engineering data on thermal transfer through the fabrics. However, it would not, by itself, provide clinically meaningful data. Calories per second transferred is not biologically significant information. What is significant is the resulting tissue damage. It is this thermally induced damage and not the heat transfer *per se* which incapacitates or kills the army aviator.

1.1 EXPERIMENTAL RATIONALE

The original Thermal Analysis Program (1, 2) was set up to determine the relationships which exist between thermal transfer and injury production. The experimental rationale was as follows: Heat flux transducers and the skin of pigs, as a human skin analog, were exposed to the same accurately simulated post-crash fire produced by a specially designed shuttered furnace burning JP-4 fuel (3). Both sensors and skin were exposed either bare, or while covered by layers of test fabric. Thus the sensors gave an accurate indication of heat flux as a function of time with direct exposure or as modified by fabric layers. The skin tissue samples gave a valid measurement of clinical damage.

1.2 DATA COLLECTION

From July, 1972 to January, 1973 a large body of experimental data was collected using the USAARL porcine bioassay technique (1, 2, 3) relating thermal flux and exposure time to burn depth. Physical thermal sensors were also exposed to the simulated post-crash fires in hopes of establishing a correlation between their output and the burns received by the pigs.

1.3 ANALYSIS BY IITRI

During the collection period and shortly thereafter, IIT Research Institute, under contract, analyzed the data that was being collected and developed a mathematical model for predicting burn injury (4) based on earlier work by Henriques (5), Stoll and Greene (6), Weaver and Stoll (7), Mehta and Wong (8) and Morse et al (9). IITRI's model could accept either a constant heat flux as an input parameter or a table of heat fluxes as would be generated from the heat flux sensor either in a laboratory test or as part of an instrumented manikin used in "fire pit" testing. But, during the data collection and model building, both IITRI and USAARL personnel observed that the data was noisy and that the model could be improved. There were also some items of data either not available during this period or not utilized by IITRI such as: 1) intraskin temperature recordings; 2) heat flux values derived from analog output of the heat flux sensors which had been recorded on FM magnetic tape; 3) burn depth readings which allowed for corrections to be made accounting for the shrinkage observed to occur in the more severely burned tissues; 4) additional measurements of tissue water and density.

1.4 WORKING HYPOTHESIS

The hypothesis of this study was: given the output of physical thermal sensors and the actual burns experienced by pigs, it should be possible to develop a mathematical model which can convert the output of the sensors to predicted burn depths in reasonable agreement with the observed burn depths. To the extent that this were possible, it would be reasonable to use such a physical thermal sensor and the mathematical model thus derived as part of a screening methodology for thermally protective fabrics.

1.5 OBJECTIVES

The specific objectives accomplished toward developing a clinically valid fabric screening method are as follows: 1) the previously collected data base was reviewed for error both in coding and in content; 2) the biopsy specimens were re-read using a new set of standards so that corrections for thermally induced tissue shrinkage could be calculated; 3) graphical representations of the data contained in the revised data base were made as a help in understanding the relationships embodied in the data; 4) an empirical, multi-discriminant, model was written which predicts either gross (clinical) grade or histopathologic grade given parameters such as heat flux, exposure time, skin temperature, and the like. However, since this model required either a constant input flux or the use of total flux, its use is limited, making the model incapable of using the thermal exposures experienced at the "fire pit" test facility of Natick labs; 5) an analytical model was developed to circumvent the problems associated with the multidiscriminate model regarding the inability to use a flux-time profile; 6) optimization of the analytical model was accomplished using data in the data base, intraskin time-temperature profiles and such data as could be found in the literature, e.g. University of Rochester, Moritz and Henriques and Stoll, as performance criteria.

1.6 SUMMARY

In summary then, the objectives were to validate the data base collected by the staff at USAARL, to look at the data in graphic presentation, to ascertain functional relationships and problems with the data and to develop, ultimately, a model which would take the output from heat flux sensors and accurately predict the burn depth which would have occurred had the sensor itself been replaced by living skin. The remainder of the report will deal with the work accomplished to meet each of these objectives taken in the order just presented.

2.0 DATA BASE VALIDATION

Data from the thermal project were recorded in three forms: 1) handwritten records, e.g. gross (clinical) grading sheets; 2) stripchart recordings of temperature, heat flux and shutter system state as a function of time; 3) analog voltages representing temperature and heat flux recorded on FM magnetic tape. At the start of this contract the written records had been coded on computer oriented record forms and key-punched on computer cards. These cards were read into data files which then became the data base. None of the data on FM magnetic tape had been utilized although it had been digitized and stored on digital magnetic tape as part of the contract performed by IITRI (4).

In order to form a data base containing pertinent information from all sources, which was reasonably free of error, the following tasks were accomplished.

2.1 ELIMINATE KEYPUNCH/TRANSCRIPTION ERRORS

The entire data base was read item by item and compared with the original data records (clinical grading forms, pathology reports, etc.). Errors were eliminated and those observations which did not match, e.g. a gross grade of 15 with a burn depth of 200µm, were further checked against the photographic records and biopsy material to resolve the mismatch.

2.2 RE-READ BIOPSY MATERIAL TO ALLOW FOR SHRINKAGE CORRECTION

It became apparent late in the data collection period (10) that biopsies from deep dermal burns showed a marked thermally induced shrinkage while more superficial burns showed some edema and swelling. The edema and swelling was slight, approximately 3-5%, and not as dramatic as seen in human burns (11). The shrinkage, on the other hand, was at least 40% and went as high as 216%. Clearly correction for such a large distortion of measured burn depth would enhance the chances of a model's ability to predict burn depth.

With this in mind, the entire set of more than 1600 biopsy slides was re-read using descriptive criteria as before (1) but adding several new depth measurements as shown in Figure 1. By recording both normal skin thickness, (A + B), and burned skin thickness, (E), as well as "depth of burn" C it was possible to calculate a "corrected burn depth" as follows: $(A + B) - C\,[(A+B)/E] = C.B.D.$

Measurements A, B, C, D, E and the corrected burn depth were added to the data base[1]. The histopathological grading definitions along with mean experimentally observed burn depths are found in Table I. A second transformation was made to the burn depths as follows: $[\text{Corrected BD}/(A+B)] * 2000 = N.B.D.$ This

[1] A more detailed discussion of the histopathology grading system can be found in USAARL Report 78-11, June, 78. Abstract App. B.

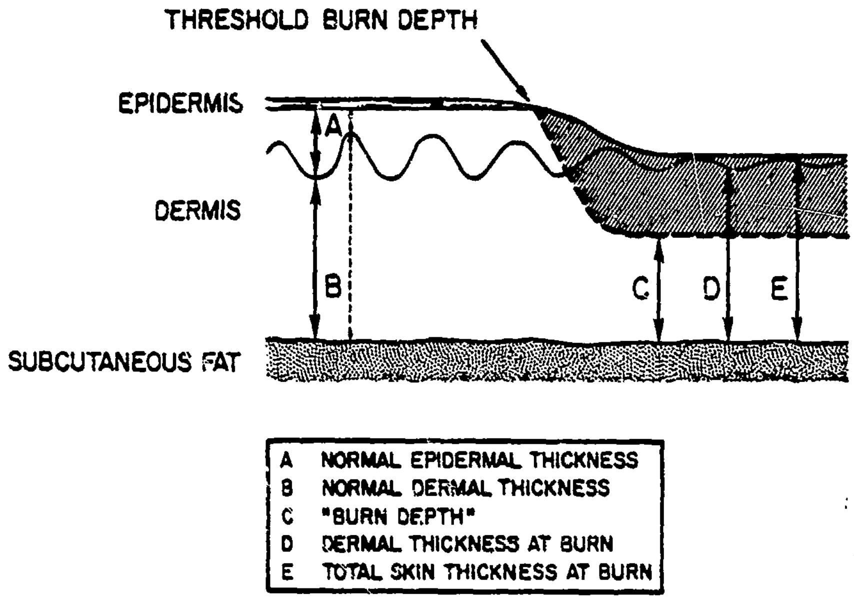


Figure 1. Schematic Diagram of Porcine Skin Showing Location of Measurements A through E recorded for each biopsy specimen.

TABLE 1

HISTOPATHOLOGICAL AND BURN DEPTH GRADING DEFINITIONS

Grade	Description	Approximate Depth (μm) Nominal Range	Mid-Range	Mean Normalized	Mean Corrected
0	No thermal damage	0	0	----	----
1	Cell damage without acidophilism	1-20	10	----	----
2	Partial epidermis acidophilism	20-50	37.5	----	----
3	Complete epidermal acidophilism	50-100	75	70	86
4	Partial dermal-epidermal separation	100-150	125	73	90
5	Complete dermal-epidermal separation	150-250	200	62	75
6	Superficial dermal	250-500	400	416	467
7	Mid-dermal	500-1000	800	894	1037
8	Deep dermal	1000-1500	1300	1400	1547
9	Complete dermal to adipose border	1500-2000	1800	2000	2160
10	Adipose	<2000	2000	2000	2375

"normalized burn depth" corrected for the large variability in total skin thickness (A+B). Normalized burn depth was added to the data base.

2.3 CORRECTIONS TO ORIGINAL DATA

2.3.1 Shutter Dynamics.

There were four different shutter propulsion systems employed during this study. In a study of the fire simulator/shutter system (see Abstract, Appendix B) correction factors were derived for each shutter system and each burn site location. These correction factors were applied to each exposure time in the data base so that the time represents the best estimate of actual exposure time ignoring complicating factors such as day to day variations in exposure time caused by changes in the rolling/sliding friction of the shutter.

2.3.2 Initial Skin Temperature.

Initial skin temperature has been shown to be an important factor in determining the energy requirements for a given level of burn damage (12). Skin temperatures were recorded at one of the burn sites for each exposure beginning 5 September 1972. No such recording was made prior to that date. A multiple linear regression analysis (see Table II) was used to derive a relationship between environmental factors (order of burn, time of day, temperature at Carins AAF, % humidity, wind velocity and % cloud cover) and measured skin temperature for pigs burned subsequent to 5 Sept 1972. This relationship was then used to calculate a predicted skin temperature for those pigs burned during July and August. This temperature was inserted into the data base.

2.3.3 Hair Removal.

Two different hair removal procedures were used during the course of the experiment and this resulted in mean hair length of 3.2mm for pigs burned in July and August and 1.75mm for the remaining pigs. In the first case, only about 93.75% of the incident radiation gets to the skin while in the latter case, 96.5% does so (4). Hair length for each pig is in the data base to aid in correcting the incident heat flux.

2.4 DATA MANAGEMENT COMPUTER PROGRAMS

In order to edit, retrieve, sort, list and otherwise manage the data in the data base, and to retrieve and format data from digitized tapes, e.g. records of sensor output digitized from FM magnetic tape recordings, some 12 programs were written, primarily in FORTRAN IV. Their complete description including source listings and sample output may be found in a report entitled "Thermal Analysis

TABLE II

REGRESSION ANALYSIS OF PIG SKIN TEMPERATURES

FILE NAME: SKTSHRT.DAT ALL PIGS FOR SEPTEMPER AND OCTOBER 1972

MEANS	Order	Time	Temp.Cairns	% Hum.	Wind Vel.	% Cloud	Obs.Skin Temp.
	2.50	1165.34	79.34	53.44	4.54	55.57	90.44
STD. DEVIATIONS	1.12	159.45	10.21	8.35	2.94	30.72	4.82

CORRELATION MATRIX

	1	2	3	4	5	6	
1	1.000	0.053	0.041	-0.111	-0.037	-0.004	0.123
2	0.053	1.000	0.281	-0.540	0.102	0.113	0.471
3	0.041	0.281	1.000	-0.364	-0.236	-0.319	0.913
4	-0.111	-0.540	-0.364	1.000	0.446	-0.009	-0.410
5	-0.037	0.102	-0.236	0.446	1.000	0.231	-0.021
6	-0.004	0.113	-0.319	-0.009	0.231	1.000	-0.150

MULTIPLE R 0.901

MULTIPLE R SQUARE 0.912

STD.ERROR ESTIMATE 2.141

F VALUE OF REGRESSION 83.650

DF 6. 116.

PREDICTOR	REG. COEF	ST. COEF	T VALUE
1	0.371	0.175	2.121
2	0.003	0.002	1.526
3	0.442	0.825	17.387
4	-0.066	0.033	-1.981
5	0.400	0.036	4.662
6	0.038	0.008	4.753

INTERCEPT 51.088

OBSERVED	PREDICTED	RESIDUAL
96.30	94.62	-1.68
94.60	92.30	-2.30
94.60	91.43	-3.17
96.80	96.11	-0.69
95.60	93.39	-2.21
97.30	94.56	-2.74
98.80	96.11	-2.69
95.80	95.53	-0.27
90.00	93.73	3.73
90.20	92.32	2.32
90.00	95.12	5.12
90.00	94.62	4.62
92.00	94.99	2.99
92.00	94.79	2.79
93.00	95.53	2.53
93.00	95.33	2.33
89.00	88.33	-0.67
89.00	88.52	-0.48
94.30	91.86	-2.44
94.00	91.00	-3.00
93.00	92.61	-0.39
93.00	92.22	-0.78

Program: Computer Programs for Data Base Manipulation" (see Appendix B for an abstract). A one page sample listing of the primary data base is shown as Table III. The group (GRP) number in the last column is a quality control rating from 1 to 9. A rating of 4 indicates prime quality data which was collected during the summer months when the experimental protocol was undergoing considerable development. For a complete listing of the data base which includes a discussion of all the quality scores, see a report entitled "Experimental porcine burn injury data base: listings and graphic representation." (see abstract in Appendix B).

3.0 GRAPHIC PRESENTATION OF THE DATA BASE

A computer graphing program, PLOTS, allows the user to plot any two variables on arithmetic or log axes parameterized by a third variable if desired. The following examples give an indication of complexities and the basic variability inherent in the data. Verticle bars indicate sample means and the individual data points are indicated with a symbol instead of a bar for ±1 standard deviation or ±1 standard error of the mean. The first four plots show gross (clinical) and micro (histopathologic) grades versus normalized and corrected burn depth. In all cases there is a logical progression, though not linear, from low grades and shallow depth to high grades and deep burn depths.

Both systems apparently lack precision in distinguishing degrees of shallow, i.e. epidermal burn. It turns out that this is mostly a function of the burn depth measurement scheme in which C (see Figure 1) is measured from fat/dermal border up to epidermal border and stops there. Thus there is no really accurate, quantitative depth measurement when damage is limited to some fraction of the epidermis. For more discussion of this and other "Pitfalls in the use of the USAARL Histopathology Grading System", see abstract in Appendix B.

The next two plots relate burn grade to total heat flux. Again there is a logical progression with more severe burns requiring more energy to produce them. Neither of these representations reveals the difference between the burns resulting from one second at 8 $cal/cm^2 \cdot sec^{-1}$ versus 8 seconds at 1 $cal/cm^2/sec$. Since reciprocity has been shown not to hold (13), there is reason to believe that the picture is more complex. Moreover, none of these plots takes into account such uncontrolled variables as initial skin temperature, length of time anesthetized, length of hair, etc. All these other variables have, most probably, contributed to the noisiness of the data.

The next plot compares the gross and micro grading systems. The correlation between them is quite good (r^2 = .99) from gross grade 6 through 16 and micro grade 4.5 to 10. There are so few data points below this level that it is not possible to draw any conclusion regarding the relationship between gross and micro grades.

The next four plots are an attempt to explore the relationship among three variables, flux, exposure time, and burn grade or depth. The log exposure time

TABLE III

PIG	HOLE	SMOKE	TIMLT		TIME	FLUX	WALL T (C)	SKIN T	FAB	COND	GROSS	MIC	EPI	DERM	BURN	NORM. BD	DATE	TIME	N MIC	EPI	DERM	BURN	T BURN	SKIN	COR BD	GRP
177LF	1	1	1	1	1.02	1.44	809.	32.6	0	0	9	9	90.	2980.	2980.	1677.	728	851	8	75.	2925.	500.	2875.	3100.	2516.	4
177LF	2	2	1	1	1.08	1.44	809.	32.6	0	0	10	6	110.	2480.	520.	431.	728	851	6	75.	2500.	2000.	2500.	2550.	555.	4
177LF	3	3	1	1	1.12	1.44	809.	32.6	0	0	8	6	80.	2850.	350.	230.	728	851	6	75.	3000.	2500.	2750.	2825.	354.	4
177LF	4	4	1	1	1.03	1.44	809.	32.6	0	0	9	6	70.	2380.	450.	140.	728	851	4	50.	2500.	2000.	2100.	2150.	170.	4
177LF	5	5	1	1	1.08	1.44	809	32.6	0	0	9	6	100.	2230.	450.	125.	728	851	4	50.	1875.	1875.	1950.	2000.	120.	4
177LF	6	6	1	1	1.12	1.44	809.	32.6	0	0	8	6	70.	2630.	300.	125.	728	851	4	50.	2500.	2625.	2750.	2800.	159.	4
177RR	1	21	1	1	4.16	1.44	852.	35.2	0	0	15	6	110.	2360.	500.	289.	728	900	6	75.	2250.	1500.	1625.	1675.	243.	4
177RR	2	22	1	1	4.22	1.44	852.	35.2	0	0	15	7	110.	2480.	590.	831.	728	900	6	75.	2250.	1125.	1875.	1925.	966.	4
177RR	3	23	1	1	4.26	1.44	852.	35.2	0	0	13	6	90.	2600.	550.	293.	728	900	6	50.	2500.	1750.	2000.	2050.	373.	4
177RR	4	24	1	1	4.17	1.44	852.	35.2	0	0	14	6	80.	2950.	740.	400.	728	900	6	50.	3250.	2500.	3950.	3125.	660.	4
177RR	5	25	1	1	4.22	1.44	852.	35.2	0	0	14	6	60.	2850.	790.	462.	728	900	6	50.	3000.	2250.	2875.	2925.	704.	4
177RR	6	26	1	1	4.26	1.44	852.	35.2	0	0	13	6	70.	2850.	990.	470.	728	900	6	50.	2500.	1750.	2250.	2300.	610.	4
21GRF	1	27	1	1	8.00	1.44	840.	33.2	0	0	15	9	80.	2030.	1450.	1077.	728	928	7	100.	2125.	750.	1625.	1625.	1190.	4
21GRF	2	28	1	1	8.06	1.44	840.	33.2	0	0	14	9	80.	2360.	1490.	1500.	728	928	8	75.	2375.	250.	1000.	1000.	1838.	4
21GRF	3	29	1	1	8.10	1.44	840.	33.2	0	0	16	9	100.	1980.	1460.	1600.	728	928	8	75.	2000.	250.	1250.	1250.	1663.	4
21GRF	4	30	1	1	8.01	1.44	840.	33.2	0	0	15	9	80.	1740.	1610.	1800.	728	928	7	75.	1750.	750.	1500.	1500.	913.	4
21GRF	5	31	1	1	8.06	1.44	840.	33.2	0	0	15	9	70.	1590.	1360.	1030.	728	928	7	50.	1500.	625.	1250.	1300.	805.	4
21GRF	6	32	1	1	8.10	1.44	840.	33.2	0	0	15	9	60.	1740.	1540.	2000.	728	928	9	75.	1750.	0.	1125.	1125.	1025.	4
21GRR	1	21	1	1	4.07	1.44	840.	35.5	0	0	13	7	80.	1690.	740.	571.	728	928	6	75.	1625.	1250.	1750.	1750.	486.	4
21GRR	2	22	1	1	4.13	1.44	840.	35.5	0	0	13	7	80.	2360.	1240.	471.	728	928	6	100.	2125.	1625.	2125.	2125.	524.	4
21GRR	3	23	1	1	4.17	1.44	840.	35.5	0	0	14	9	80.	2430.	920.	714.	728	928	6	75.	2125.	1125.	1750.	1750.	786.	4
21GRR	4	24	1	1	4.03	1.44	840.	35.5	0	0	13	7	70.	2480.	720.	444.	728	928	6	75.	2250.	1750.	2250.	2250.	517.	4
21GRR	5	25	1	1	4.13	1.44	840.	35.5	0	0	13	8	50.	2810.	780.	1000.	728	928	7	75.	2125.	625.	1250.	1250.	1100.	4
21GRR	6	26	1	1	4.17	1.44	840.	35.5	0	0	13	8	70.	2080.	840.	1000.	728	928	7	75.	2000.	750.	1500.	1500.	1038.	4
21GLF	1	1	1	1	2.05	1.44	862.	35.5	0	0	10	7	80.	1240.	640.	68.	728	928	3	75.	1750.	2125.	2125.	2200.	62.	4
21GLF	2	2	1	1	2.11	1.44	862.	35.5	0	0	10	7	100.	1610.	740.	68.	728	928	4	75.	2000.	2125.	2125.	2200.	71.	4
21GLF	3	3	1	1	2.15	1.44	862.	35.5	0	0	10	7	70.	1980.	540.	52.	728	928	4	100.	1750.	1875.	1875.	1925.	40.	4
21GLF	4	4	1	1	2.06	1.44	862.	35.5	0	0	12	7	70.	1740.	790.	143.	728	928	6	75.	1750.	1625.	1750.	1750.	130.	4
21GLF	5	5	1	1	2.11	1.44	862.	35.5	0	0	11	6	70.	1860.	690.	43.	728	928	5	75.	1750.	2250.	2250.	2300.	40.	4
21GLF	6	6	1	1	2.15	1.44	862.	35.5	0	0	10	6	60.	1490.	730.	52.	728	928	4	100.	1625.	1875.	1875.	1925.	45.	4
21GLR	1	7	1	1	1.00	1.44	869.	35.5	0	0	9	6	70.	1880.	130.	68.	728	928	3	100.	2000.	2125.	2125.	2200.	72.	4
21GLR	2	8	1	1	1.06	1.44	869.	35.5	0	0	8	6	80.	2180.	100.	41.	728	928	4	75.	2375.	2375.	2375.	2425.	51.	4
21GLR	3	9	1	1	1.10	1.44	869.	35.5	0	0	4	6	90.	2430.	110.	39.	728	928	4	100.	2250.	2500.	2500.	2550.	46.	4
21GLR	4	10	1	1	1.01	1.44	869.	35.5	0	0	9	6	60.	1660.	270.	52.	728	928	4	75.	1875.	1875.	1875.	1925.	51.	4
21GLR	5	11	1	1	1.06	1.44	869.	35.5	0	0	9	6	100.	2330.	220.	52.	729	928	4	100.	2125.	1875.	1075.	1925.	50.	4
21GLR	6	12	1	1	1.10	1.44	869.	35.5	0	0	6	6	70.	2430.	150.	65.	728	928	4	75.	2375.	2250.	2250.	2325.	79.	4
21OLF	1	1	1	1	1.00	1.44	872.	32.8	0	0	9	5	100.	2360.	0.	65.	728	955	3	75.	2500.	2250.	2250.	2325.	83.	5
21OLF	2	2	1	1	1.06	1.44	872.	32.8	0	0	9	6	110.	1660.	200.	68.	728	955	5	75.	2500.	2125.	2125.	2200.	80.	4
21OLF	3	3	1	1	1.10	1.44	872.	32.8	0	0	8	6	90.	2730.	100.	58.	728	955	4	75.	2500.	2500.	2500.	2575.	75.	4
21OLF	4	4	1	1	1.01	1.44	872.	32.8	0	0	9	6	80.	1860.	200.	95.	728	955	5	75.	2125.	1500.	1500.	1575.	105.	4
21OLF	5	5	1	1	1.06	1.44	872.	32.8	0	0	9	6	90.	2360.	150.	52.	728	955	5	75.	2000.	1875.	1875.	1925.	54.	4
21OLF	6	6	1	1	1.10	1.44	872.	32.8	0	0	9	6	120.	2600.	100.	36.	728	955	4	75.	2250.	2750.	2750.	2800.	42.	4
21ORF	1	27	1	1	4.02	1.44	858.	33.2	0	0	13	7	90.	2550.	890.	767.	728	928	6	75.	2500.	1125.	1825.	1825.	980.	4
21ORF	2	28	1	1	4.08	1.44	858.	33.2	0	0	14	9	70.	2360.	690.	1000.	728	928	7	50.	2625.	500.	1000.	1000.	1330.	4
21ORF	3	29	1	1	4.12	1.44	858.	33.2	0	0	13	8	70.	2110.	1310.	714.	728	928	6	75.	2000.	1125.	1750.	1750.	741.	4
21ORF	4	30	1	1	4.03	1.44	858.	33.2	0	0	10	8	90.	1660.	1490.	857.	728	928	7	75.	1750.	1000.	1750.	1750.	702.	4
21ORF	5	31	1	1	4.08	1.44	858.	33.2	0	0	14	6	80.	2230.	1240.	857.	728	928	6	75.	2500.	1000.	1750.	1750.	1104.	4
21ORF	6	32	1	1	4.12	1.44	858.	33.2	0	0	15	8	60.	2060.	820.	727.	728	928	6	75.	2125.	875.	1375.	1375.	800.	4
21ORR	1	21	1	1	2.00	1.44	855.	32.9	0	0	10	6	80.	-9.	-9.	39.	728	928	4	50.	2375.	2500.	2500.	2550.	40.	5
21ORR	2	22	1	1	2.06	1.44	855.	32.9	0	0	10	6	70.	-9.	-9.	61.	728	928	4	75.	2500.	2375.	2375.	2450.	79.	5

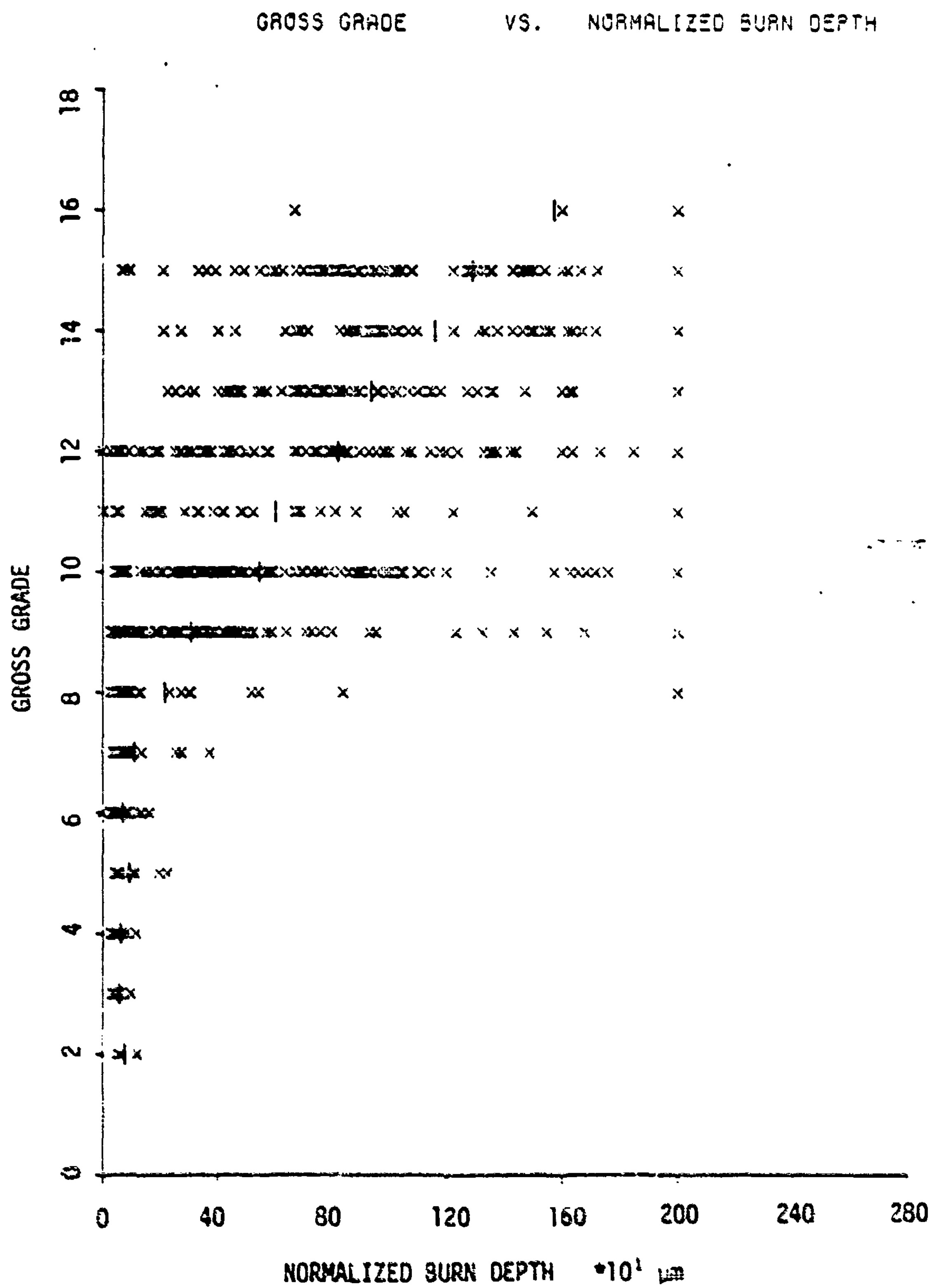

GROSS GRADE VS. NORMALIZED BURN DEPTH
GROSS GRADE
0
2
4
6
8
10
12
14
16
18
0
40
80
120
160
200
240
280
NORMALIZED BURN DEPTH *10¹ µm

Figure 2.

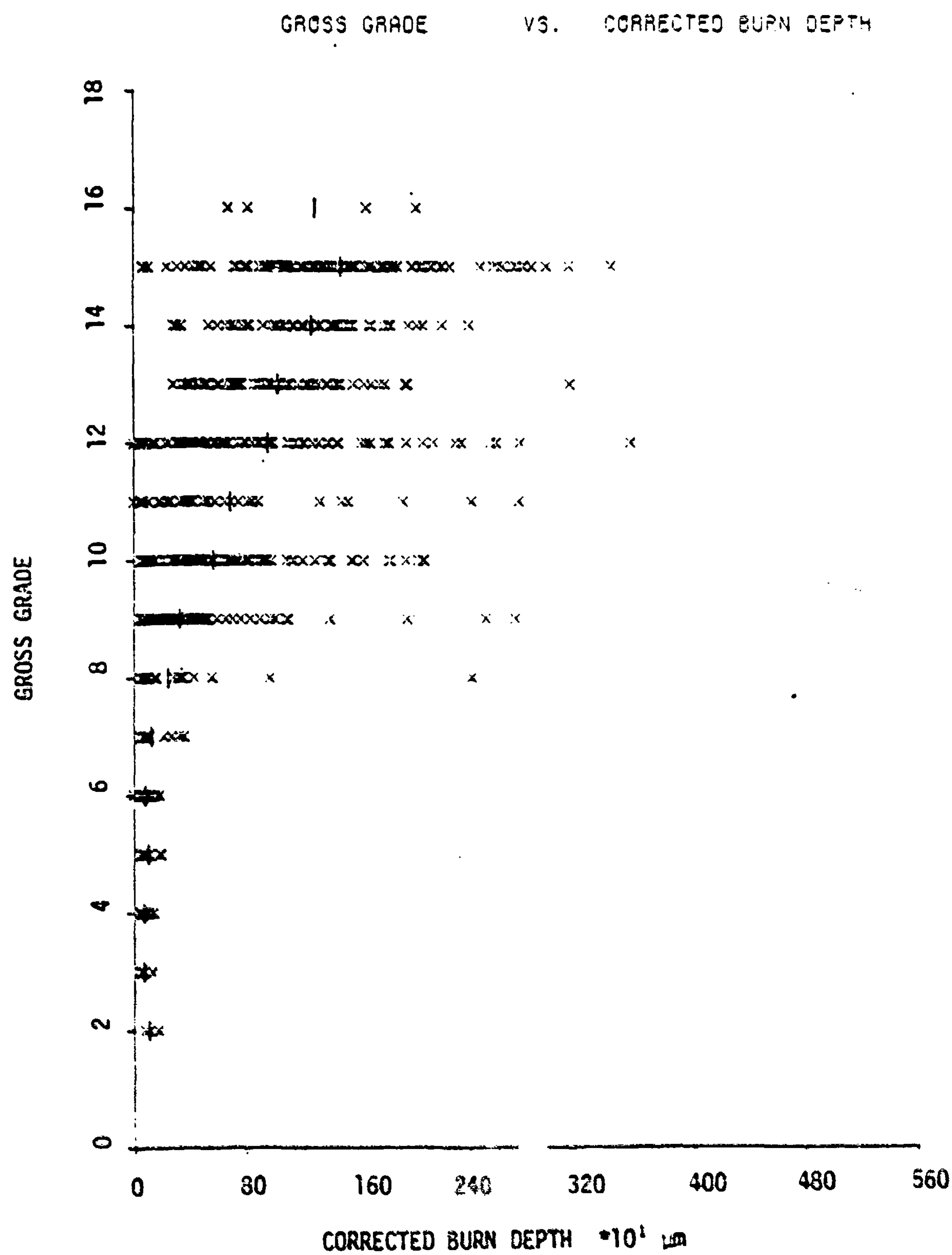

GROSS GRADE VS. CORRECTED BURN DEPTH
GROSS GRADE
0
2
4
6
8
10
12
14
16
18
0
80
160
240
320
400
480
560
CORRECTED BURN DEPTH *10¹ µm

Figure 3.

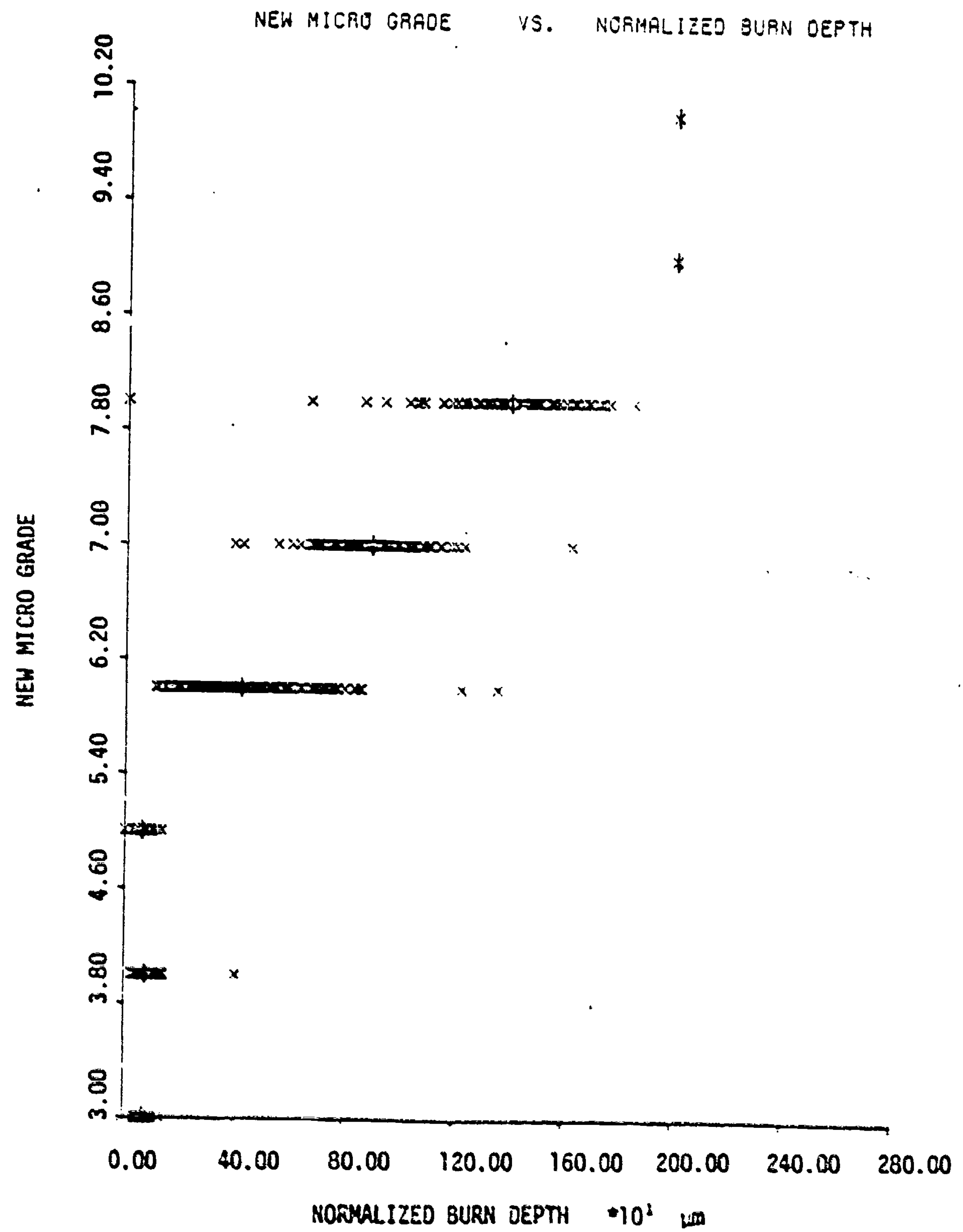

NEW MICRO GRADE VS. NORMALIZED BURN DEPTH
NEW MICRO GRADE
10.20
9.40
8.60
7.80
7.00
6.20
5.40
4.60
3.80
3.00
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
NORMALIZED BURN DEPTH *10¹ µm

Figure 4.

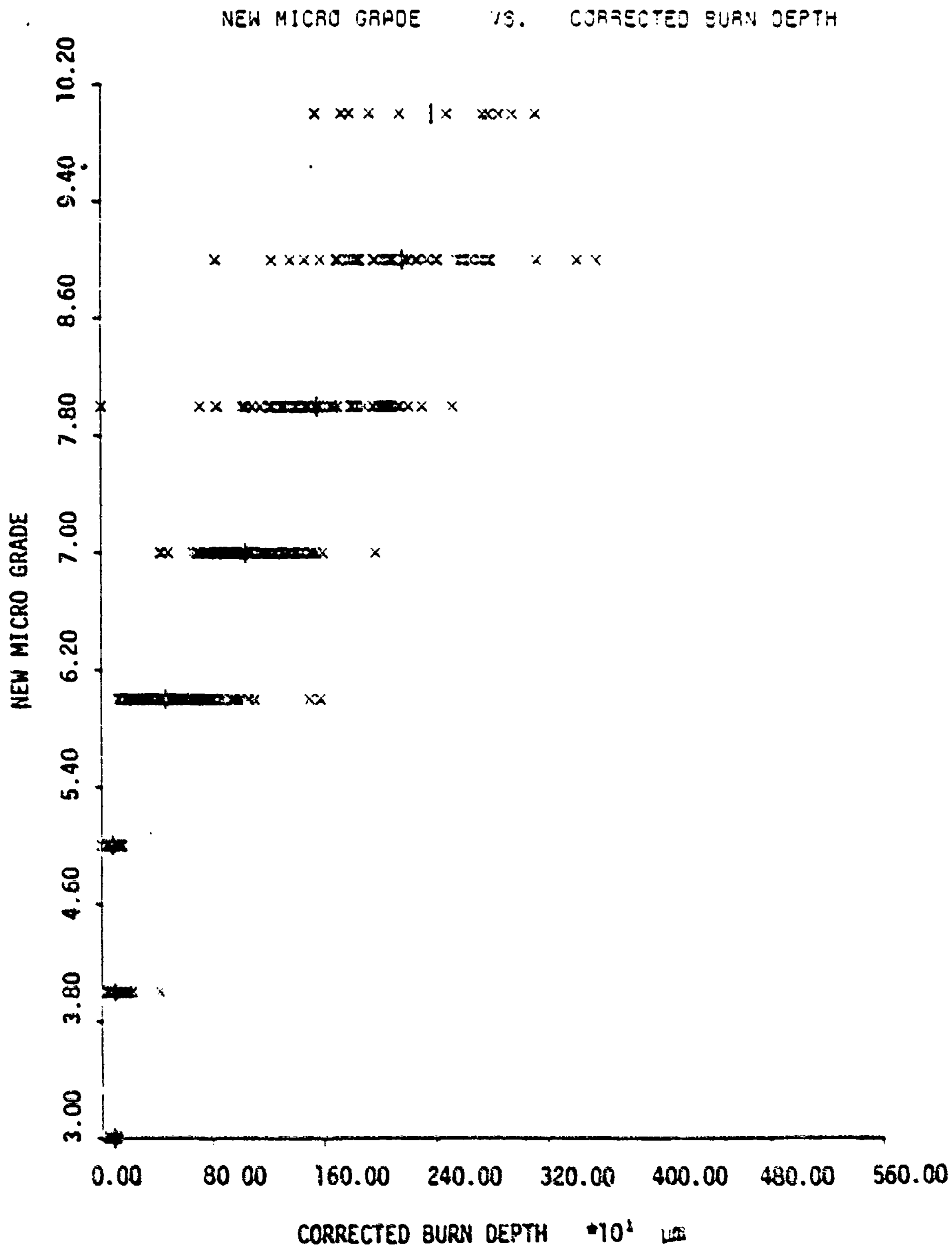

NEW MICRO GRADE VS. CORRECTED BURN DEPTH
NEW MICRO GRADE
10.20
9.40
8.60
7.80
7.00
6.20
5.40
4.60
3.80
3.00
0.00
80 00
160.00
240.00
320.00
400.00
480.00
560.00
CORRECTED BURN DEPTH *10¹ µm

Figure 5.

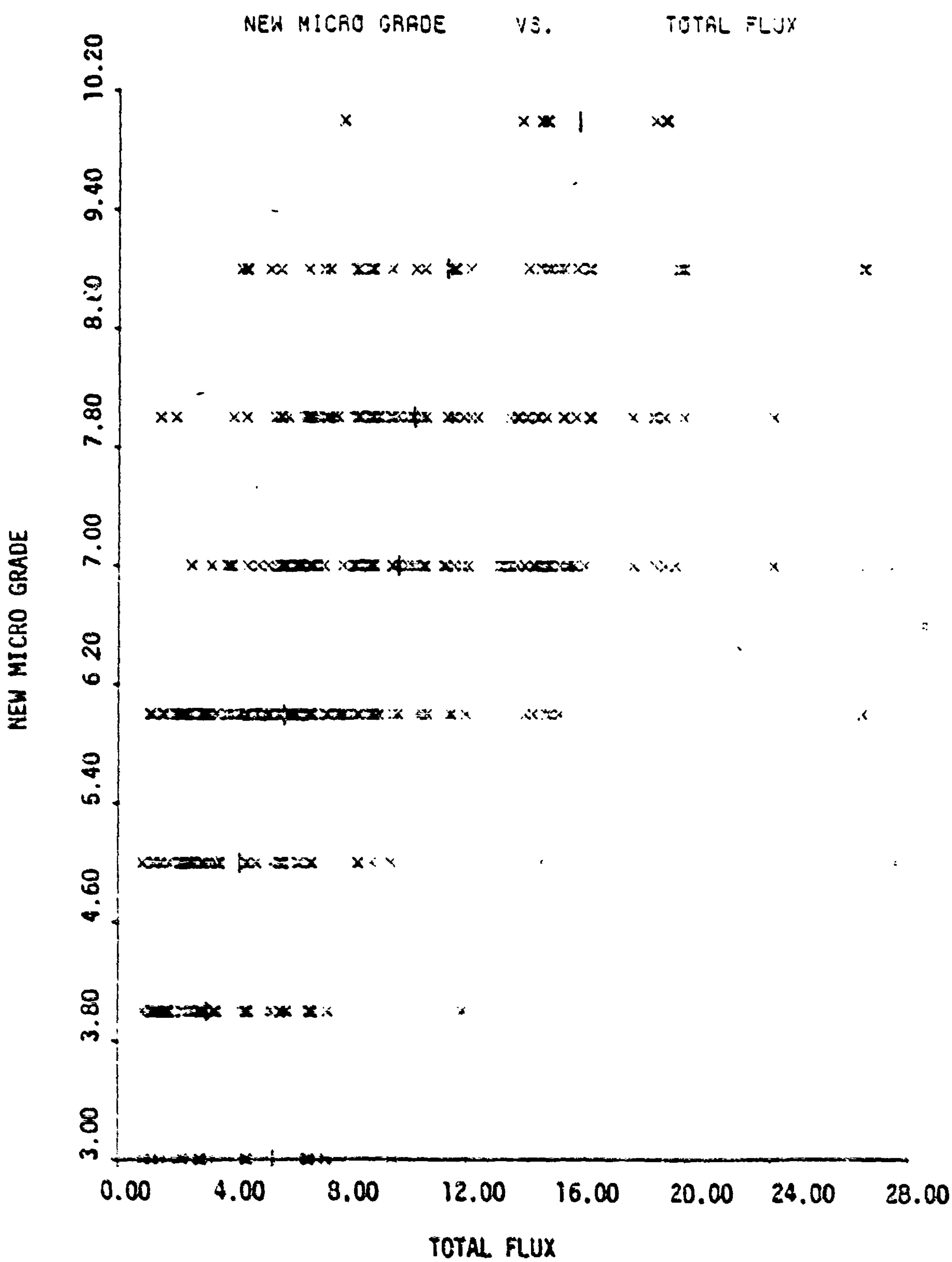

NEW MICRO GRADE VS. TOTAL FLUX
NEW MICRO GRADE
TOTAL FLUX
10.20
9.40
7.80
7.00
6.20
5.40
4.60
3.80
3.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00

Figure 6.

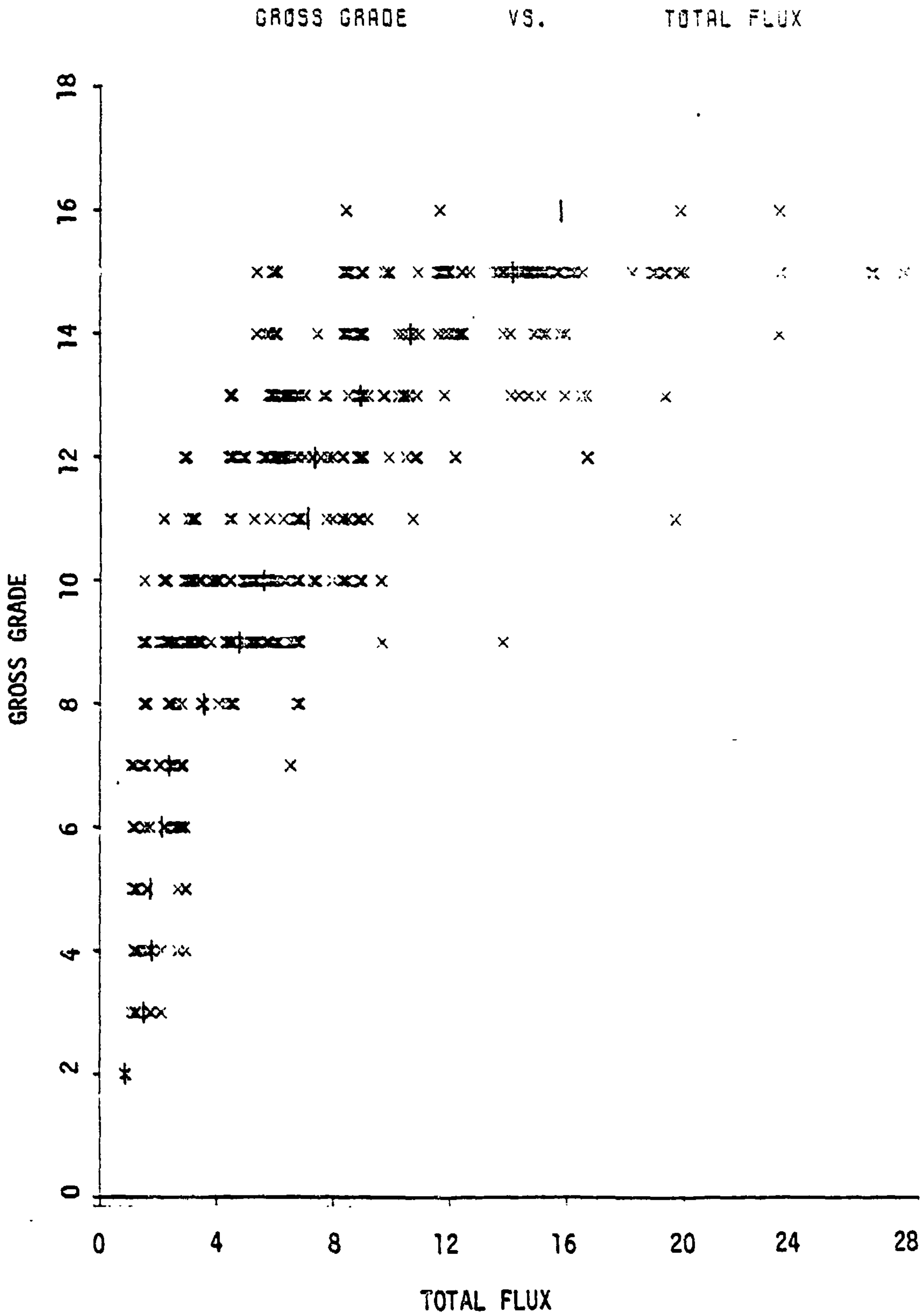

GROSS GRADE VS. TOTAL FLUX
GROSS GRADE
TOTAL FLUX
0
2
4
6
8
10
12
14
16
18
20
24
28

Figure 7.

GRØSS GRADE VS. NEW MICRO GRADE

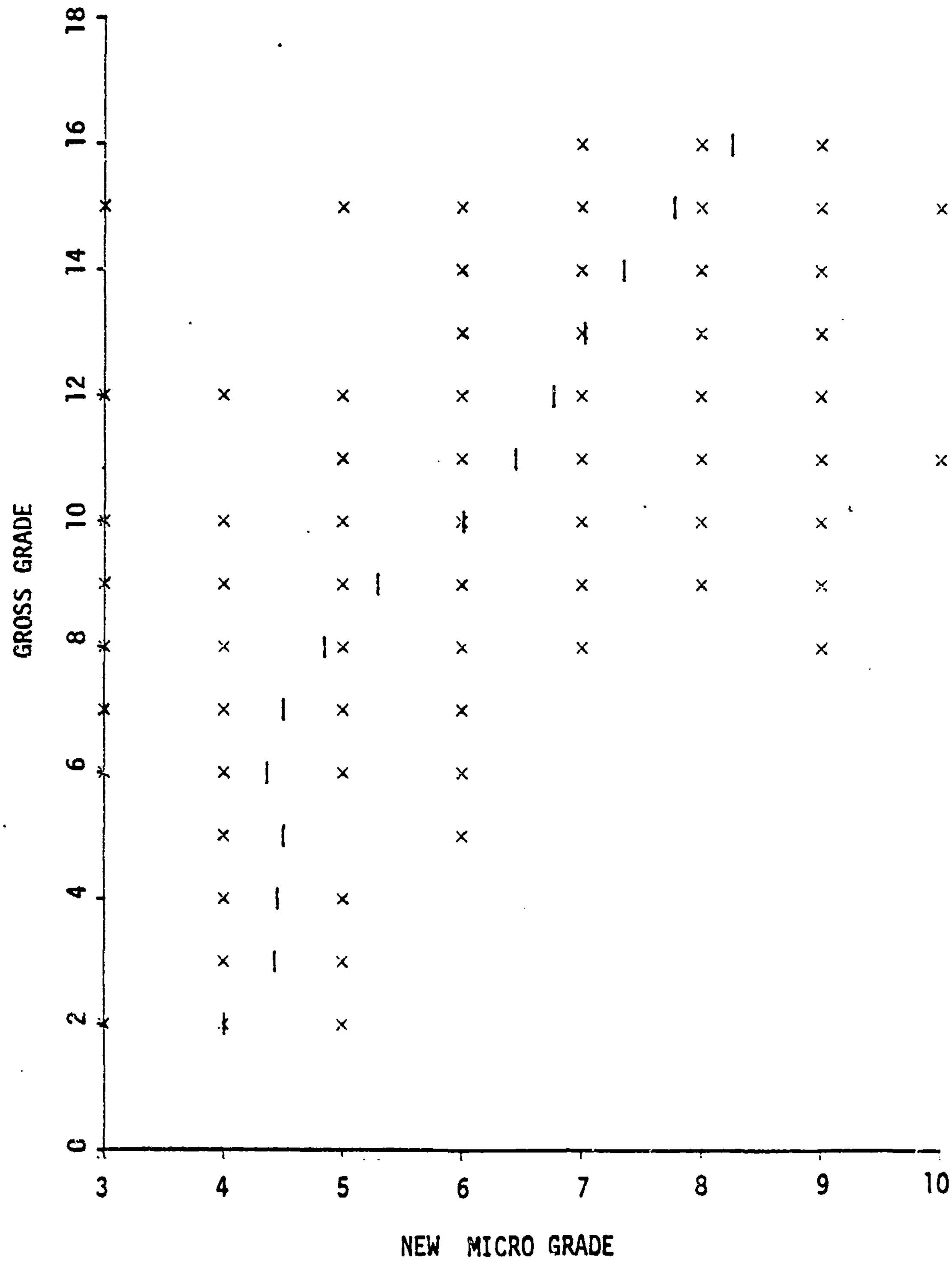
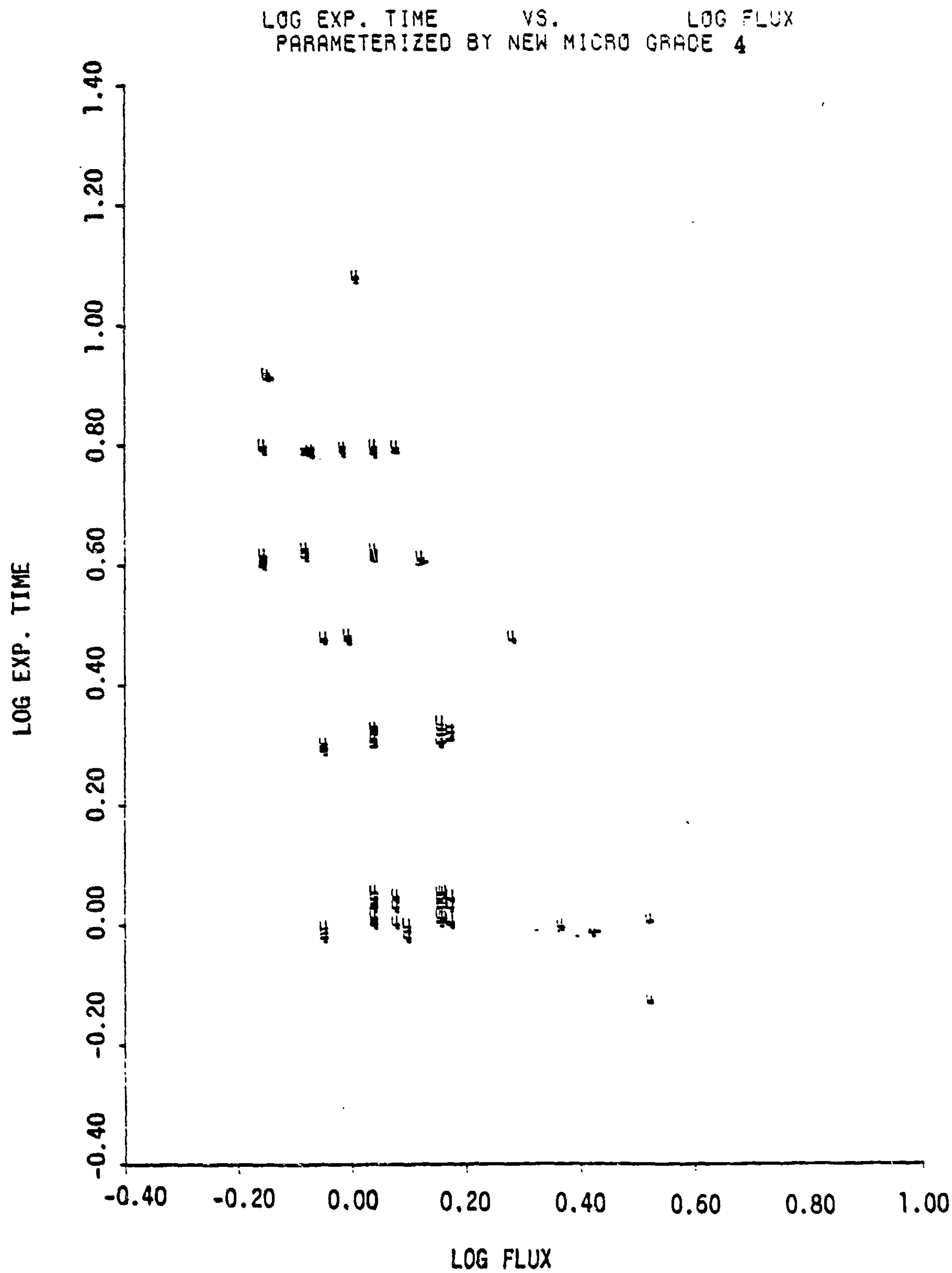


Figure 8.



LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 4
LOG EXP. TIME
LOG FLUX
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40

Figure 9.

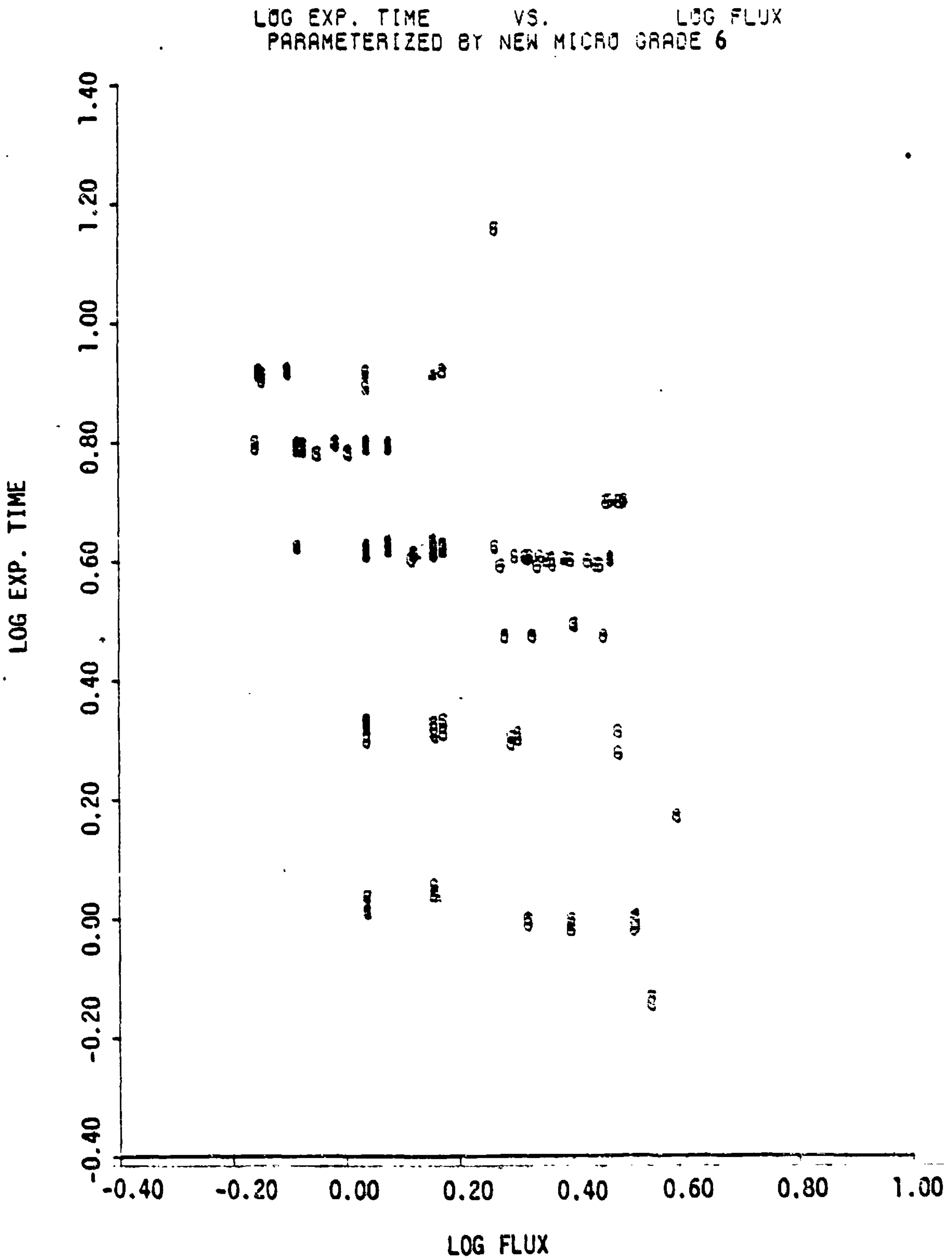

LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 6
LOG EXP. TIME
LOG FLUX
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00

Figure 10.

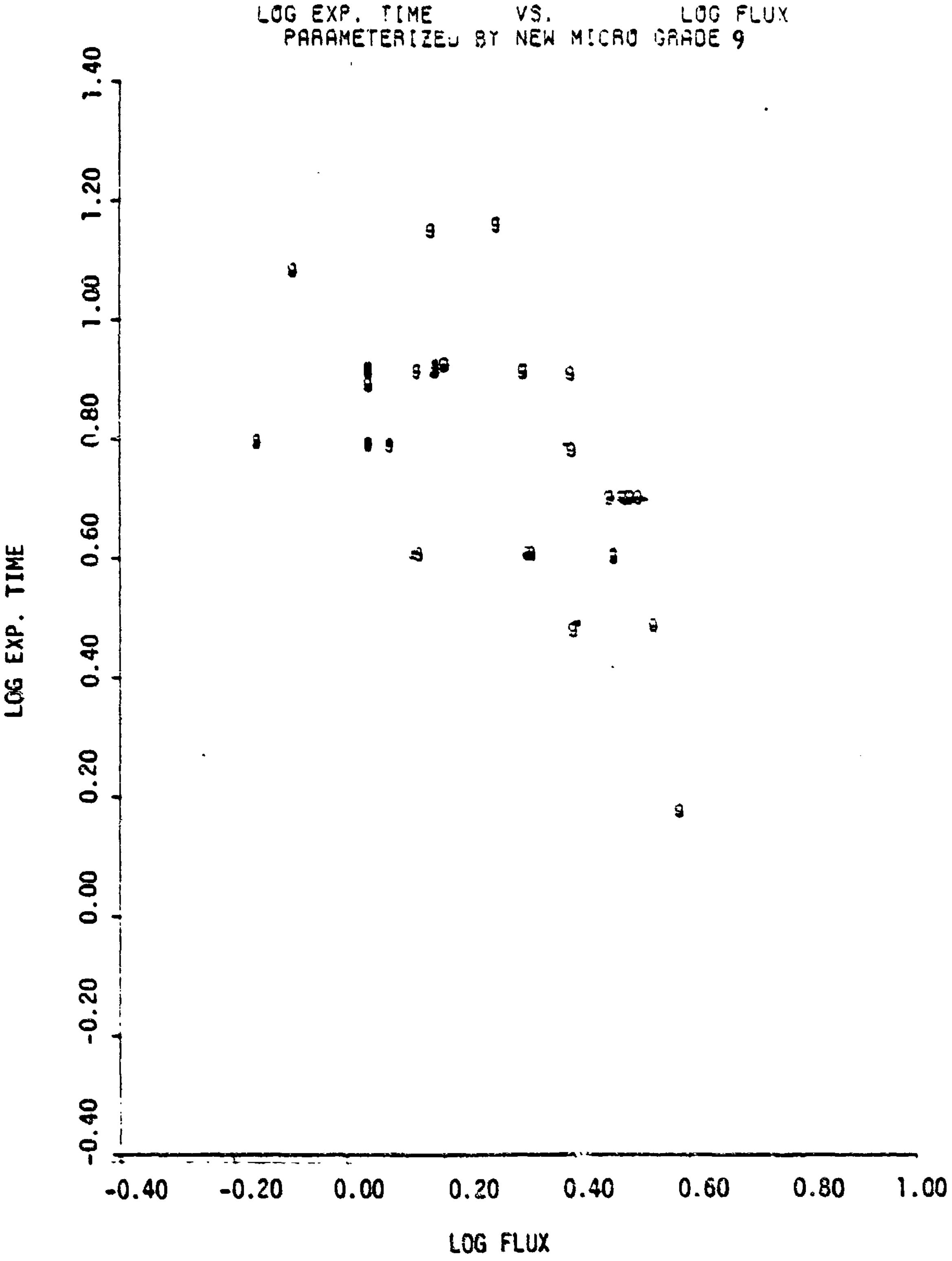

LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 9
LOG EXP. TIME
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
LOG FLUX

Figure 11.

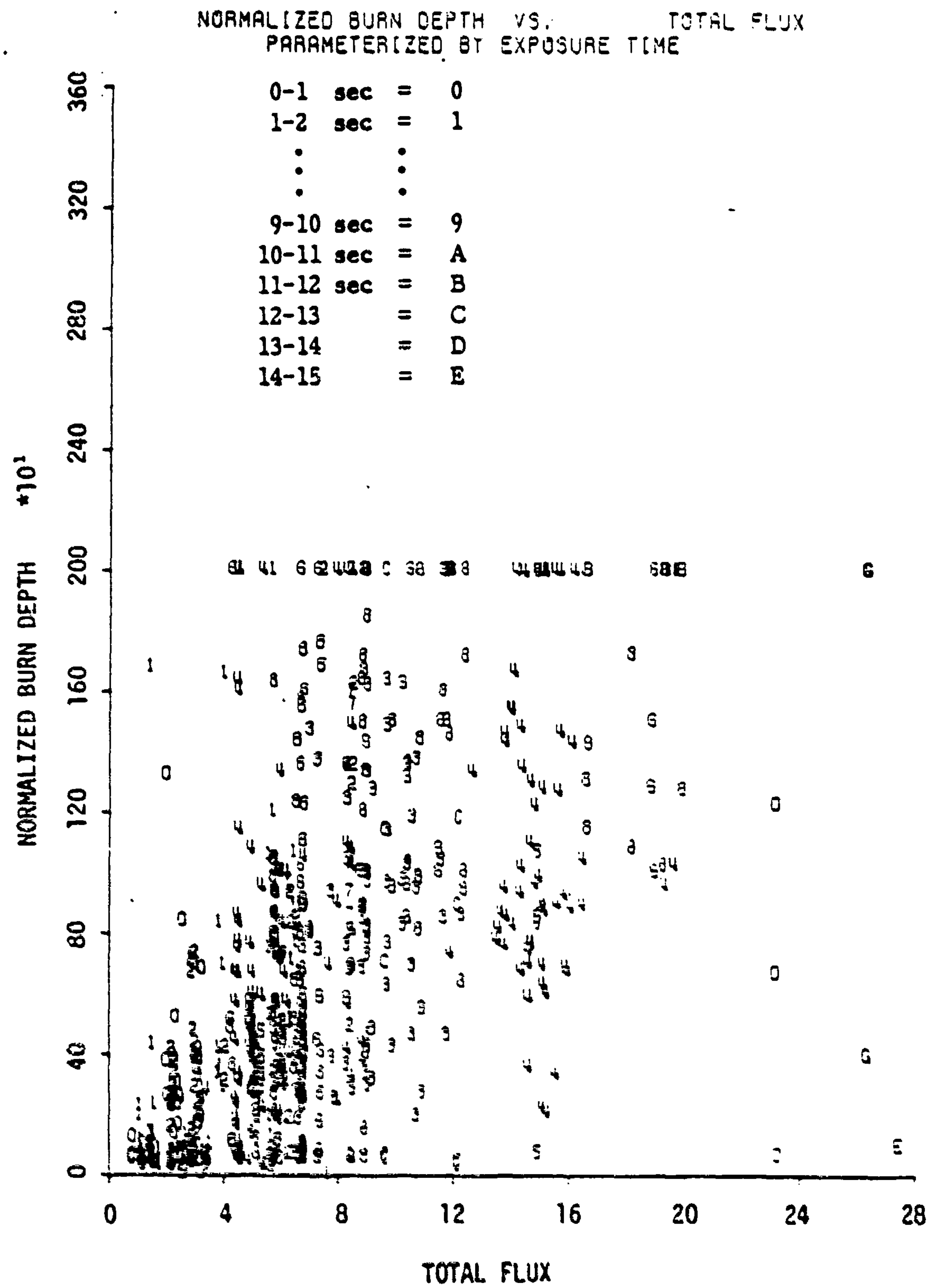

NORMALIZED BURN DEPTH VS. TOTAL FLUX
PARAMETERIZED BY EXPOSURE TIME
0-1 sec = 0
1-2 sec = 1
9-10 sec = 9
10-11 sec = A
11-12 sec = B
12-13 = C
13-14 = D
14-15 = E
NORMALIZED BURN DEPTH *10¹
TOTAL FLUX
0
40
80
120
160
200
240
280
320
360
0
4
8
12
16
20
24
28

Figure 12.

vs. log flux parameterized by burn grade plots were suggested by Alice Stoll (14) based on her experience with pain thresholds and threshold blister burns. In her plots these two parameters form straight lines which are essentially parallel. The USAARL data suggests a shift to the upper right as a function of burn depth as might be expected but there also appears to be a slight change in slope of the "best" (drawn by eye) straight line from one burn level to the next.

The last plot (figure 12) is a different view of the same data, namely: normalized depth versus total flux parameterized by exposure time. While there is a progression to the data, it is largely obscured by the internal variability.

4.0 EMPIRICAL MODEL

The lack of really clear cut relationships in the foregoing graphical analysis, prompted the development of a multidiscriminant model which takes into account not only time, flux, total flux and burn grade, but includes furnace wall temperature, skin temperature and skin color as well. The results of applying this model to predict gross burn grade is shown in Table IV. The generalized Mahalanobis D-square, the equivalent of a Chi square for this sort of analysis, is highly significant showing that it is possible to predict with reasonable certainty the gross burn grade knowing exposure time, flux, furnace wall temperature, total flux, initial skin temperature, and skin color.

Multidiscriminant analysis was also applied to predict micro grades with a somewhat lower D-square but generally similar results. Both models were used to flag outlying data points for further checking against original records. However, neither model lends itself to use with an instrumented manikin and fire pit testing where the time-heat flux profiles recorded by the data acquisition system are not constant but change as the overlying fabrics react to the fire which is itself variable. In this case an analytical model is more suitable.

5.0 ANALYTICAL MODEL

Several years ago Weaver and Stoll (7) proposed an extension of Stoll's earlier model (6) to heat fluxes higher than used in obtaining the experimental data upon which the earlier model had been based. They also found that the effective conductivity changed during the exposure and subsequent cooldown period. Takata (15), using preliminary data from USAARL's Thermal Project (the uncorrected version of the current data base), formulated a model which not only predicted threshold burns but deep burns and tissue water boiling as well. Building on the work of Henriques (5), Stoll and Greene (6), Weaver and Stoll (7), Mehta and Wong (8) and Takata (15) we formulated an analytical model as follows:

For thermal exposures of interest, skin is essentially opaque to thermal radiation and can be considered to transfer energy internally by conduction only, since exposure durations are no longer than the minimum response times reported for increased thermoregulatory system activity (16). Consequently, thermal energy transfer in skin can be described by the heat conduction or Fourier equation. In rectangular coordinates, the Fourier equation may be written as follows:

$$p \; Cp \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x}\right) + q \qquad (1)$$

where,

p = density, gm/cm^3

Cp = heat capacity, cal/gm/°C

K = thermal conductivity, cal/cm-sec.°C

TABLE IV

DISCRIMINANT ANALYSIS...GROSS BURN GRADE

NUMBER OF GROUPS - 5

NUMBER OF VARIABLES - 6

Sample Size.. Group	
1	25
2	34
3	61
4	121
5	143

GROUP MEANS	TIME	FLUX	WALL T.	T.°F.	SKIN T.	SKIN COLOR
1	0.087	1.012	1128.000	0.000	90.100	0.640
2	1.509	2.014	1676.177	2.009	89.021	0.613
3	3.030	2.023	2039.288	5.571	85.210	0.194
4	4.035	2.470	2734.777	8.091	91.058	0.108
5	6.065	2.709	1022.181	15.262	89.726	0.133

GENERALIZED MAHALANOBIS D-SQ[illegible]RE 1281.51285

DISCRIMINANT FUNCTION 1

CONSTANT + COEFFICIENTS

-247.001	+	0.002	-61.851	0.155	1.034	5.052	16.250

DISCRIMINANT FUNCTION 2

CONSTANT + COEFFICIENTS

-334.130	+	1.126	-62.027	0.104	0.016	5.020	15.261

DISCRIMINANT FUNCTION 3

CONSTANT + COEFFICIENTS

-381.055	+	3.046	-55.352	0.106	0.080	6.074	14.372

DISCRIMINANT FUNCTION 4

CON[illegible]ANT + COEFFICIENTS

-400.00[illegible]	+	5.759	-54.005	6.157	1.072	6.236	14.262

DISCRIMINANT FUNCTION 5

CONSTANT + COEFFICIENTS

-480.052	+	5.257	-55.453	0.193	1.763	6.255	14.305

EVALUATION OF CLASSIFICATION FUNCTIONS FOR EACH OBSERVATION

OBSERVATION	PROBABILITY ASSOCIATED WITH LARGEST DISCRIMINANT FUNCTION	LARGEST FUNCTION NO.
Group 1		
1	0.001	5
2	0.002	2
.		
.		
23	0.404	3
24	0.042	1
25	0.045	3
Group 2		
1	0.827	1
2	0.849	1
.		
.		
33	0.681	3
34	0.677	3
Group 3		
1	0.440	3
2	0.457	3
.		
.		
60	0.600	3
61	0.565	3
Group 4		
1	0.706	4
2	0.645	4
.		
.		
120	0.533	3
121	0.500	5
Group 5		
1	0.525	4
2	0.525	4
.		
.		
142	0.901	5
143	0.901	5

T = temperature, °C

x = distance, cm

q = energy source, for the first nodal volume, cal/cm³/sec

Since skin is considered to be opaque to radiant energy, and since the source term is due only to radiant energy[1], equation (1) applies only to the surface of the skin. For all conditions in which $x > 0$, equation (1) reduces to the following:

$$p\, C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x}\right) \qquad (2)$$

Solution of equations (1) and (2) requires two boundary conditions for x, preferably at $x = 0$ and $x = L$, and initial conditions at $t = 0$ for all positions $0 \leq X \leq L$. If one assumes that there is no backward flux of thermal energy at $x = 0$ (all conduction is into the skin), then the energy flux at $x = 0$ is zero and, consequently, $\partial T/\partial X = 0$. Similarly, if the problem assumes that an adiabatic backwell condition prevails at $X = L$, the fatty tissue, then the net flux out of the system at $X = L$ is 0, or $\partial T/\partial X = 0$. These two boundary conditions indicate that the system is closed and that all thermal energy added to the system, $0 \leq X \leq L$, is distributed within the system and cannot escape.

Initial conditions are established by specifying a uniform temperature for all locations, $0 \leq X \leq L$, at time, $t = 0$.

Consequently, the system may be defined by the following mathematical model:

$$p\, C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x}\right) + q \qquad @\ x = 0$$

$$p\, C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x}\right) \qquad @\ 0 \leq X \geq L \qquad (3)$$

$T = T_o, \quad 0 \leq X \geq L, \ t = 0$ Initial conditions

$\frac{\partial T}{\partial x} = 0, \ x = 0, \quad 0 \leq t \geq x$ Boundary conditions 1

$\frac{\partial T}{\partial x} = 0, \ x = L, \quad 0 \leq t \geq x$ Boundary conditions 2

[1] A simplifying assumption based on the predominance of the radiate mode of heating. May be less valid with fabrics. In actuality a correction is made to q to account for convective heating, surface absorptivity, and attenuation of radiant heating by hair.

6.0 SOLUTION OF MATHEMATICAL MODEL

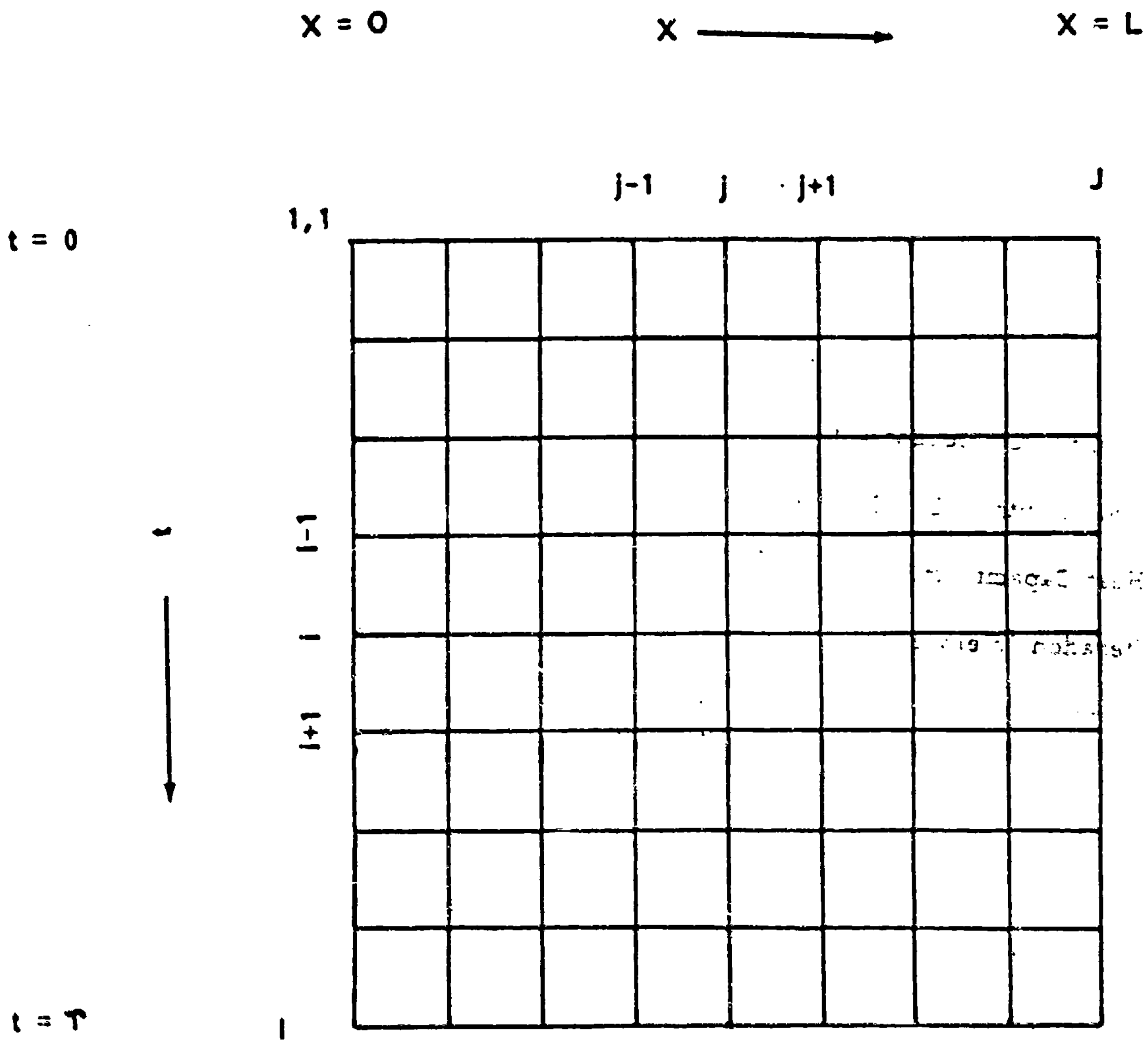
An analytical solution to equation set (3) was not considered feasible due to the variable nature of q, Cp and K; so explicit differencing methods of numerical analysis were employed to solve the equations. Several investigators working with linear systems have found that the Crank-Nicholson six point implicit differencing method provided an excellent numerical solution (17). For the solution of equation set (3), the mathematical model, it was decided to apply the Crank-Nicholson method to the second order partial derivatives and corresponding explicit methods to the first order partials.

The grid work in Figure 13 is a representation of the differenced system from X = 0 to X = L (J's) and t = 0 to t = y (i's).

The Crank-Nicholson technique involves averaging the value of the dependent variable over the i and i + 1 row at a constant j position. The second order derivative is then evaluated at the (j, i + 1/2) position. A forward difference formulation is applied to the $\partial T/\partial t$ term to match the same position.

The above described implicit differencing method is noted for the characteristics of stability and convergence. Correct increment sizes yield reliable convergence. The model was implemented in FORTRAN IV using solution techniques of Thomas as described by Bruce et al (18).

This initial model was revised to allow energy flux across the surface, x = 0, during heating, convective heat loss at the skin surface during cooling and heat transfer into deep tissues including conduction into fat, convective cooling via the blood, tissue water boiling, a temperature gradient from surface to fat and a gradient of thermal properties based on measured tissue water. For a complete description of the model including source listings, sample output and users manual, see a USAARL report entitled "BRNSIM - An Analytical Model for Predicting Thermal Cutaneous Injury", abstracted in Appendix B. The model, BRNSIM, is run interactively with the following variables changeable for each run:



GRIDWORK FOR NUMERICAL ANALYSIS

Figure 13.

TABLE V

MODEL PARAMETERS CHANGEABLE INTERACTIVELY

Initial Surface Temperature (TEMPIØ)

Density (ρ)

Thermal Conductivity for each Node ($BK_{(i)}$)

Node Depth (BL = 0.22 cm)

Heat Capacity for each Node ($Cp_{(i)}$)

Iteration Interval (AK = 0.01 sec)

Number of Nodes (JINC = 12)

Exposure Time (ETIME)

Total Time (ITIME)

Water Boiling Temperature (°C)

Blood - Control Factor for Convective Tissue Cooling by Blood

TEMP B - Difference Between Backwall Tissue Temperature and TEMPIØ

Absorptivity of Surface

Incident Flux, Q, ($cal/cm^2/sec$)

Nxtra Nodes - Number of Interpolated Nodes Between Surface and Node 2 - Used for superficial burns.

Damage Rate Constants PL1, PLN1, PL2, PLN2, DE1, DE2

From the relationship for first order kinetics assumed to apply in damaging tissue protein we have: (5)

$$\text{damage rate} = \frac{d\Omega}{dt} = Pe^{-\Delta E/RT}; \quad \text{total damage} = \int_0^{ETIME} d\Omega/dt + \int_{ETIME}^{ITIME} d\Omega/dt$$

if $P = N \times 10^y$ and $\Delta E/R = DE$

$$\text{then} \quad \ln\frac{dw}{dt} = \ln N + y\ln 10 - \frac{\Delta E}{R}\cdot\frac{1}{T} = PL + PLN - DE\cdot\frac{1}{(T+273)}$$

Thus for damage calculations the following constants are entered: (15)

PL_1 (44°C - 50°C) = 1.46	PL_2 (50°C - 100°C) = 2.24
PLN_1 (44°C - 50°C) = 147.37	PLN_2 (50°C - 100°C) = 239.47
DE_1 (44°C - 50°C) = 50,000	DE_2 (50°C - 100°C) = 80,000

The program outputs $d\Omega/dt$, for each node at each time step, total is damage for each node and a threshold depth, where $\Omega = 1$. This depth, found using inverse interpolation on two or three Ω's nearest 1 using either y or log(y).

Since its first presentations (19, 20) BRNSIM has undergone further development.

7.0 THERMAL PROPERTIES OF SKIN

Measurements of the water content of pig skin as a function of thickness were made on split thickness skin samples from several pigs.

Given a table of measured values of water content as a function of skin thickness, a least-squares cubic polynomial was fit to the data and water content as a function of depth was computed from the formula:

$$w(T-d) = \frac{T}{d}(W_T - W_{T-d}) + W_{T-d}$$

where T is the total thickness of a slab, W_T is the fraction of water computed from the cubic equation, d is the thickness of a thin slab at a depth T-d, and W_{T-d} is the fraction of water above the thin slab.

Thermal properties of the tissue were computed from the equations: (21)

1) density: $\gamma = \left(\frac{W_w}{\gamma w} + \frac{W_f}{\gamma f} + \frac{W_p}{\gamma p} \right)^{-1}$

2) heat capacity: $Cp = W_w\, Cp_w + W_f\, Cp_f + W_p\, Cp_p$

3) thermal conductivity: $K = \gamma \left(\frac{k_w\, W_w}{\gamma w} + \frac{k_f\, W_f}{\gamma f} + \frac{k_p\, W_p}{\gamma p} \right)$

where the subscripts w, f, and p refer to water, fat, and protein, respectively. W_n is the mass fraction, γn the density, Cp_n the heat capacity, and k_n the thermal conductivity of the respective components. Values of the various terms used were:

$\gamma w = 1$ gm/cc	$Cp_w = 1$ cal/gm-°C	$k_w = 1.5\times10^{-3}$ cal/cm-sec-°C
$\gamma f = 0.815$ gm/cc	$Cp_f = 0.55$ cal/gm-°C	$k_f = 4.5\times10^{-4}$ cal/cm-sec-°C
$\gamma p = 1.54$ gm/cc	$Cp_p = 0.26$ cal/gm-°C	$k_p = 4.3\times10^{-4}$ cal/cm-sec-°C

Fat and protein were assumed to be present in equal amounts so that:

$$W_f = W_p = \tfrac{1}{2}(1 - W_w),$$

and the resultant equations were:

$$\gamma = (6.18277\times10^{-2}\, W_w + .938172)^{-1}$$
$$K = \gamma(1.08432\times10^{-3}\, W_w + 4.15684\times10^{-4})$$
$$Cp = .595\, W_w + .405$$

Using the equations above, the profile of thermal properties was calculated for skin depths of from 81 to 2290μm. A linear extrapolation of tissue water content from a depth of 81μm to the skin surface was made using a stratum corneum water content calculated from Rushmer et al (22) and the ambient % humidity during the experimental phase of the project. This calculated water profile was used to complete the calculation of thermal properties profile from 81μm to the skin surface. These new thermal properties replaced those chosen by Morse et al (9) and used during previously reported simulations (19, 20). See the report entitled "Thermal Properties Calculated from Measured Water Content as a Function of Depth in Porcine Skin" as abstracted in Appendix B for additional details.

8.0 INTRASKIN TEMPERATURES

In earlier simulations (19, 20) it became apparent that unless the temperature calculations reasonably represented what actually occurred in the skin, adjustment of the values for PL, PLN and DE in the damage equation to match a few data points would not be likely to res... in a model which works well for all cases. Fortunately eleven intraskin temperature profiles were recorded on FM magnetic tape. These voltage records were digitized and converted to tables of temperatures at 100 samples per second. Figure 14 presents the one page summary report from a simulation of the exposure of Pig 294RF to a 3.47 cal cm^{-2} sec^{-1} fire for 3.02 seconds. Note that boiling occurred (confirmed by blister formation, Figure 15) and that the surface reached a maximum of 128.724°C. Predicted threshold depth was 1520µm. Three observed temperature profiles are overlayed on the calculated temperature profiles (for nodal depths of 0, 220, 440....2200µm) in Figures 16, 17 18. The oscillations in the observed temperature profile are most probably due to a "hunting" in the autoregulation of tissue perfusion by blood. The frequency, for example, is similar to that seen in studies of microcirculation (23).

The next series of figures, 19-22, shows a simulation in which the intraskin temperature gradient, cooling by blood and water boiling are turned off. This time the temperature profile does not fit. The threshold depth is similar only because the heat flux is higher. (The comparable simulation with gradient, blood and boiling turned on had a Max. Temp. = 130.945, Threshold depth = 1585 and a final time of 100). The next simulation (BRNSIM 3 vs M12VB0120, see Figures 23-26) is identical with the previous except that gradient, blood and boiling are turned on and the recalculation of skin thermal properties subsequent to water boiling is inhibited. Note that this simulation does not fit well either. Thus, only the complete model reasonably simulates the temperature profile.

Table VI presents a comparison on burns observed in the bioassay test with predictions of Model 3 (BRNSIM). This table is an updated version of one previously published (20) and includes normalized burn depth in addition to corrected burn depth. The effect of normalized burn depth in reducing the RMS Error can be seen in Table VII. One problem with Model 3 was noted in running case 296RF. The normal version of the model, labelled M12VB0120 or Model 3, includes a recalculation of thermal properties subsequent to boiling. This is done percepitiously following the cessation of boiling and in cases of high heat flux and moderate or longer exposure times; it acts as a pulse of heat flux causing an instability as can be seen in the temperature plot in Figures 27 and 28. A run with BRNSIM 3, which is Model 3 with the recalculation routine inhibited, results in a prompt, but perhaps too rapid, cooling of the skin following shutter closure (see Figures 29 and 30). This is not a problem in those cases when boiling does not occur. It can be fixed by redesigning the recalculation algorithm.

9.0 PREDICTIONS FROM SENSOR DATA

The next set of simulations used the digitized and converted output from Aerotherm Thermoman Sensors, a file of flux values as a function of time, to drive the model. Table VIII summarizes twenty simulations and compares the predicted depths with both normalized and corrected depths and Figure 31 shows the results of one simulation. Data produced by the older version, Model II, from Knox et al (20), is also included. As noted, columns III_A and III_B were run at slightly

```
MODEL NAME OR DESCRIPTION: MODEL 3 PIG 294RF DB VALUES ABS=.613 * INCIDENT FLUX  6 APR 79

                                          SKIN DIFFUSION DATA
                                          INPUT PARAMETER LIST

                                          TEMP10=   34.9700
                                          DENS=   1.00000
                                          Q1=   3.47000
                                          BL=  0.220000
                                          AK=  0.100000E-01
                                          JINC=     12
                                          TEMPB=  3.3600
                                          ABSORB=  0.613000
                                          BOIL=   100.150

                                          PL2=       2.24
                                          PLN2=    239.42
                                          PL1=       1.46
                                          PLN1=    147.37
                                          DE2=  80000.00
                                          DE1=  50000.00
                                          ETIME=     3.02
                                          ITIME=   100.00
                                          NXTRA=  8
                                          BLOOD=    0.0000

EXTRA NODES:  22.2  44.4  66.7  88.9 111.1 133.3 155.6 177.8
FLUX FILE I.D.=          0.01  2
FLUXT(I)=
      3.470     2   3.420
W=           0.39972E+01
W=           0.40754E+00
W=           0.45306E-01

D=           0.72442E+01
D=           0.73778E+01
D=           0.74955E+01

W =          0.19755E+19    AT DEPTH (IN MICRONS)=        0.112535E-06
W =          0.82484E+12    AT DEPTH (IN MICRONS)=         200.000
W =          0.26534E+09    AT DEPTH (IN MICRONS)=         400.000
W =          0.57726E+05    AT DEPTH (IN MICRONS)=         600.000
W =          0.84809E+04    AT DEPTH (IN MICRONS)=         800.000
W =          0.44495E+03    AT DEPTH (IN MICRONS)=         1000.00
W =          0.39339E+02    AT DEPTH (IN MICRONS)=         1200.00
W =          0.39972E+01    AT DEPTH (IN MICRONS)=         1400.00
W =          0.40754E+00    AT DEPTH (IN MICRONS)=         1600.00
W =          0.45306E-01    AT DEPTH (IN MICRONS)=         1800.00
W =          0.89937E-02    AT DEPTH (IN MICRONS)=         2000.00
W =          0.00000E+00    AT DEPTH (IN MICRONS)=         2200.00

MAXIMUM TEMPERATURE =  120.724

THRESHOLD DEPTH =              1520.

FINAL TIME =  100.00
```

Figure 14.

Figure 15. Intraskin thermocouple (0.003", "located superficially") shown prior to burn (left) and subsequent to exposure to 3.47 $cal \cdot cm^{-1} \cdot sec^{-1}$ for 3.02 seconds (right).

Gross grade = 13 New Micro grade = 8 Threshold depth = 1465μm

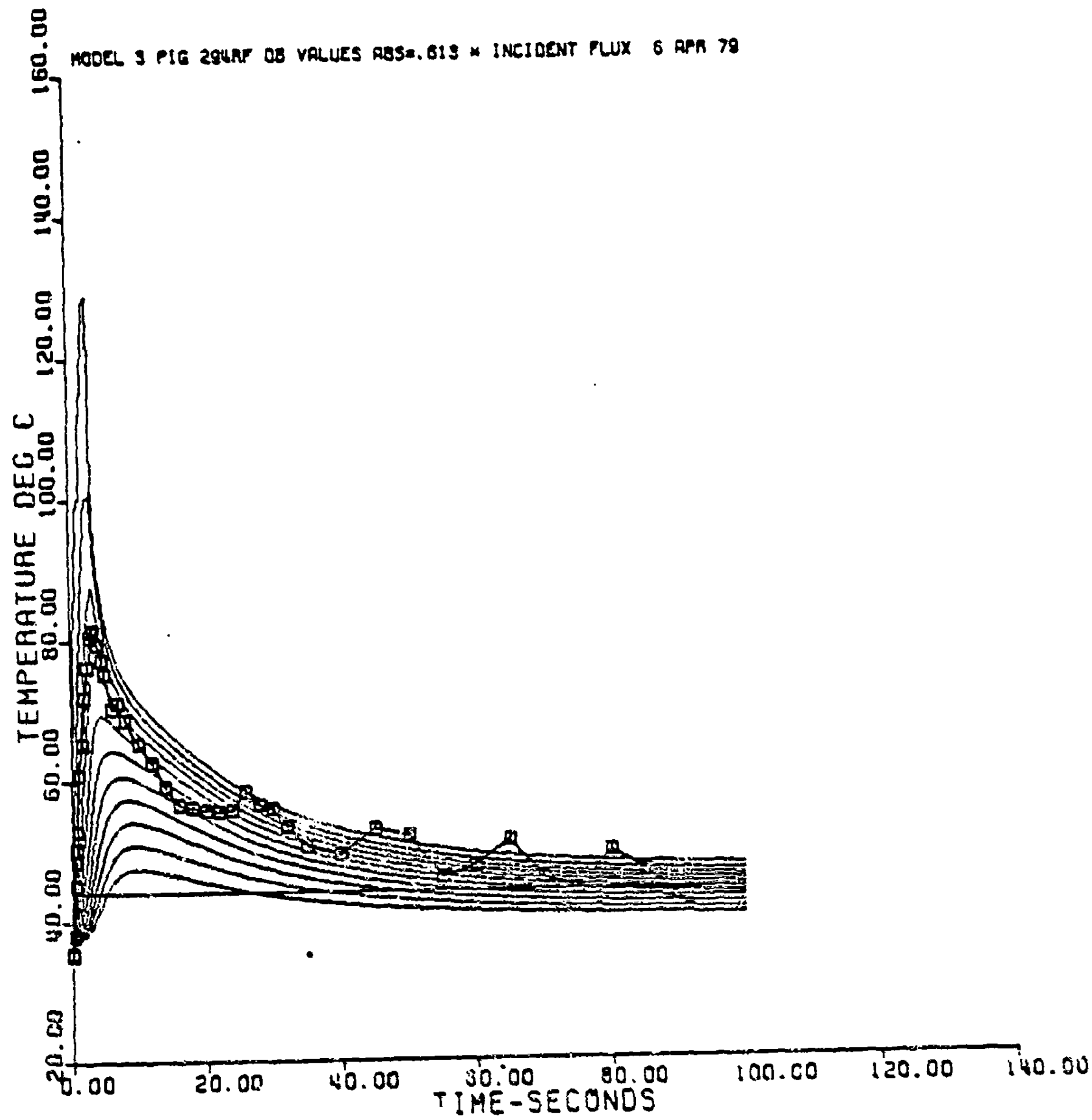

MODEL 3 PIG 294RF 08 VALUES ABS=.613 * INCIDENT FLUX 6 APR 79
TEMPERATURE DEG C
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
TIME-SECONDS

Figure 16.

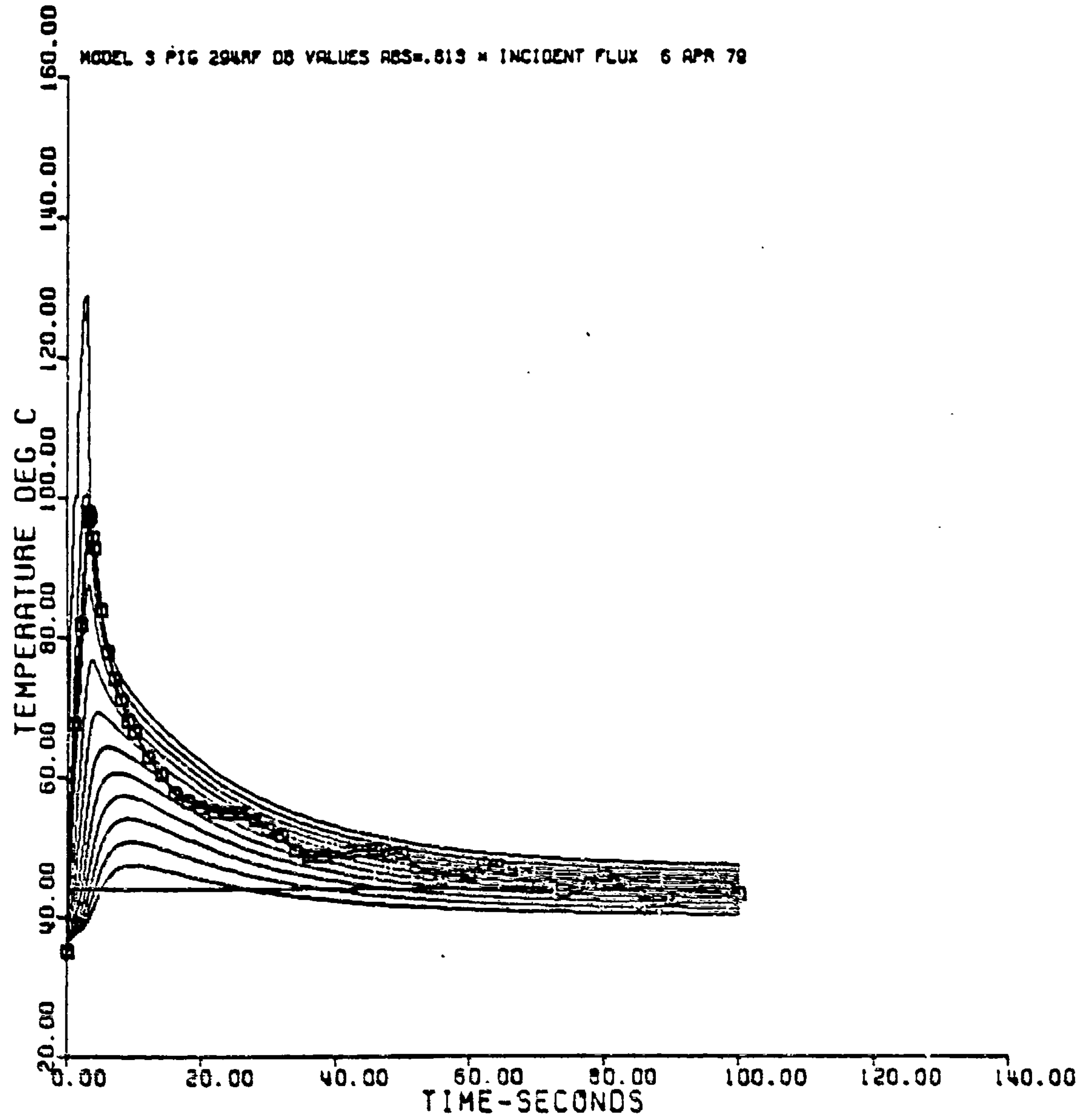
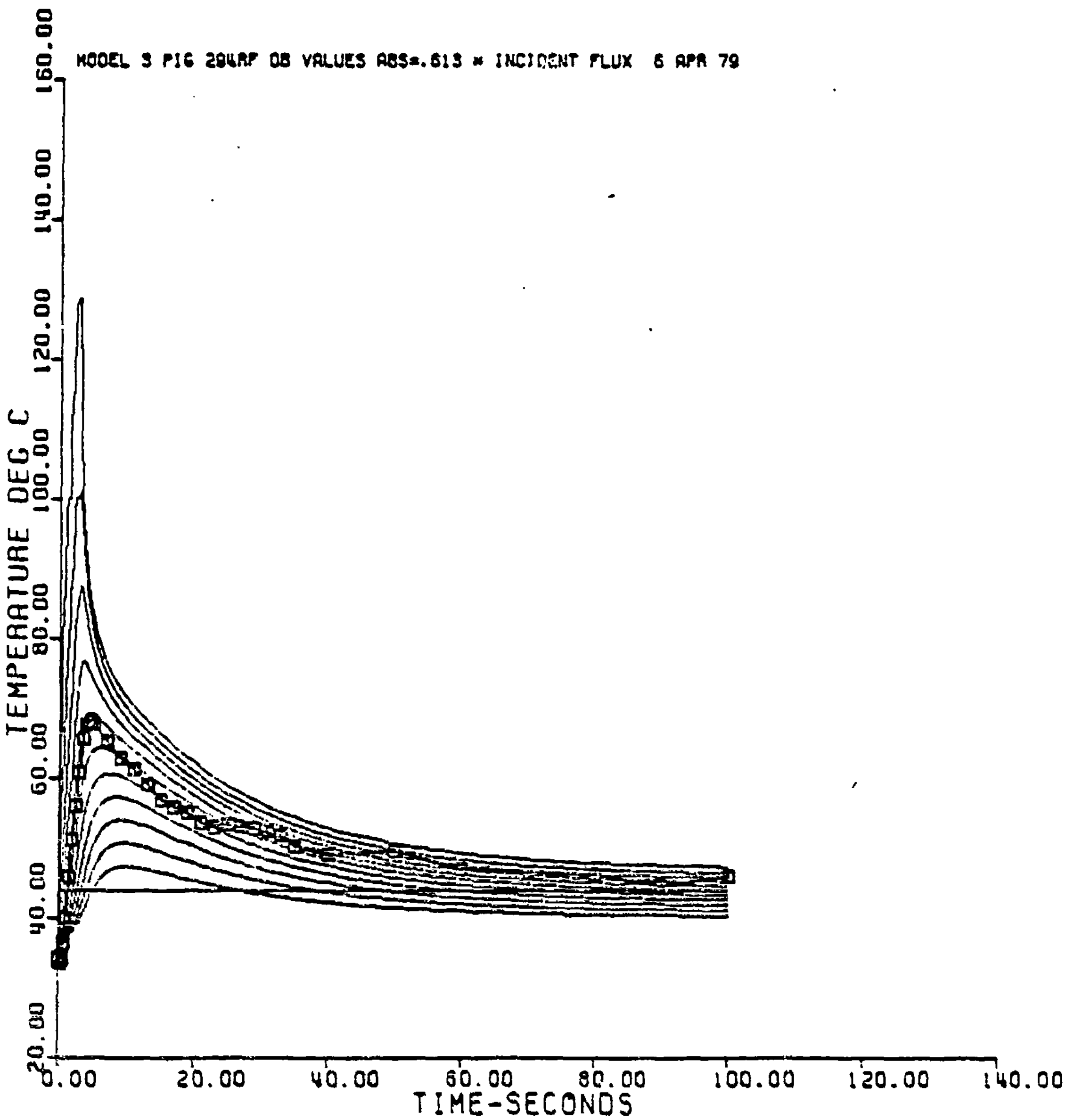

MODEL 3 PIG 294AF DB VALUES ABS=.813 × INCIDENT FLUX 6 APR 78
TEMPERATURE DEG C
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
TIME-SECONDS

Figure 17.



MODEL 3 PIG 294RF OB VALUES ABS=.613 * INCIDENT FLUX 6 APR 79
TEMPERATURE DEG C
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
TIME-SECONDS

Figure 18.

```
MODEL NAME OR DESCRIPTION: M12V80120 PIG 294 #27,28,29 WITH TEMPB,BLOOD=0 AND BOIL=250 4 APR 79

                                                   SKIN DIFFUSION DATA
                                                   INPUT PARAMETER LIST

                                                   TEMPI0=   34.9700
                                                   DENS=   1.00000
                                                   QI=   3.74000
                                                   BL=  0.220000
                                                   AK=  0.100000E-01
                                                   JINC=    12
                                                   TEMPB=  0.0000
                                                   ABSORB=  0.613000
                                                   BOIL=   250.000

                                                   PL2=       2.24
                                                   PLN2=    239.47
                                                   PL1=       1.46
                                                   PLN1=    147.37
                                                   DE2=  80000.00
                                                   DE1=  50000.00
                                                   ETIME=      3.02
                                                   ITIME=    100.00
                                                   NXTRA=   0
                                                   BLOOD=    0.0000

FLUX FILE I.D.:             0.00   2

FLUX(I)=
    1   3.740    2   3.740

W=         0.89104E+01
W=         0.46214E+00
W=         0.26098E-01

D=         0.72442E+01
D=         0.73770E+01
D=         0.74955E+01

W =         0.36075E+22    AT DEPTH (IN MICRONS)=        0.112535E-06
W =         0.20134E+17    AT DEPTH (IN MICRONS)=         200.000
W =         0.41976E+12    AT DEPTH (IN MICRONS)=         400.000
W =         0.11413E+09    AT DEPTH (IN MICRONS)=         600.000
W =         0.32822E+06    AT DEPTH (IN MICRONS)=         800.000
W =         0.50035E+04    AT DEPTH (IN MICRONS)=         1000.00
W =         0.18057E+03    AT DEPTH (IN MICRONS)=         1200.00
W =         0.89104E+01    AT DEPTH (IN MICRONS)=         1400.00
W =         0.46214E+00    AT DEPTH (IN MICRONS)=         1600.00
W =         0.26098E-01    AT DEPTH (IN MICRONS)=         1800.00
W =         0.31424E-02    AT DEPTH (IN MICRONS)=         2000.00
W =         0.00000E+00    AT DEPTH (IN MICRONS)=         2200.00

MAXIMUM TEMPERATURE =  150.245

THRESHOLD DEPTH =            1547.

FINAL TIME =   30.12
```

Figure 19.

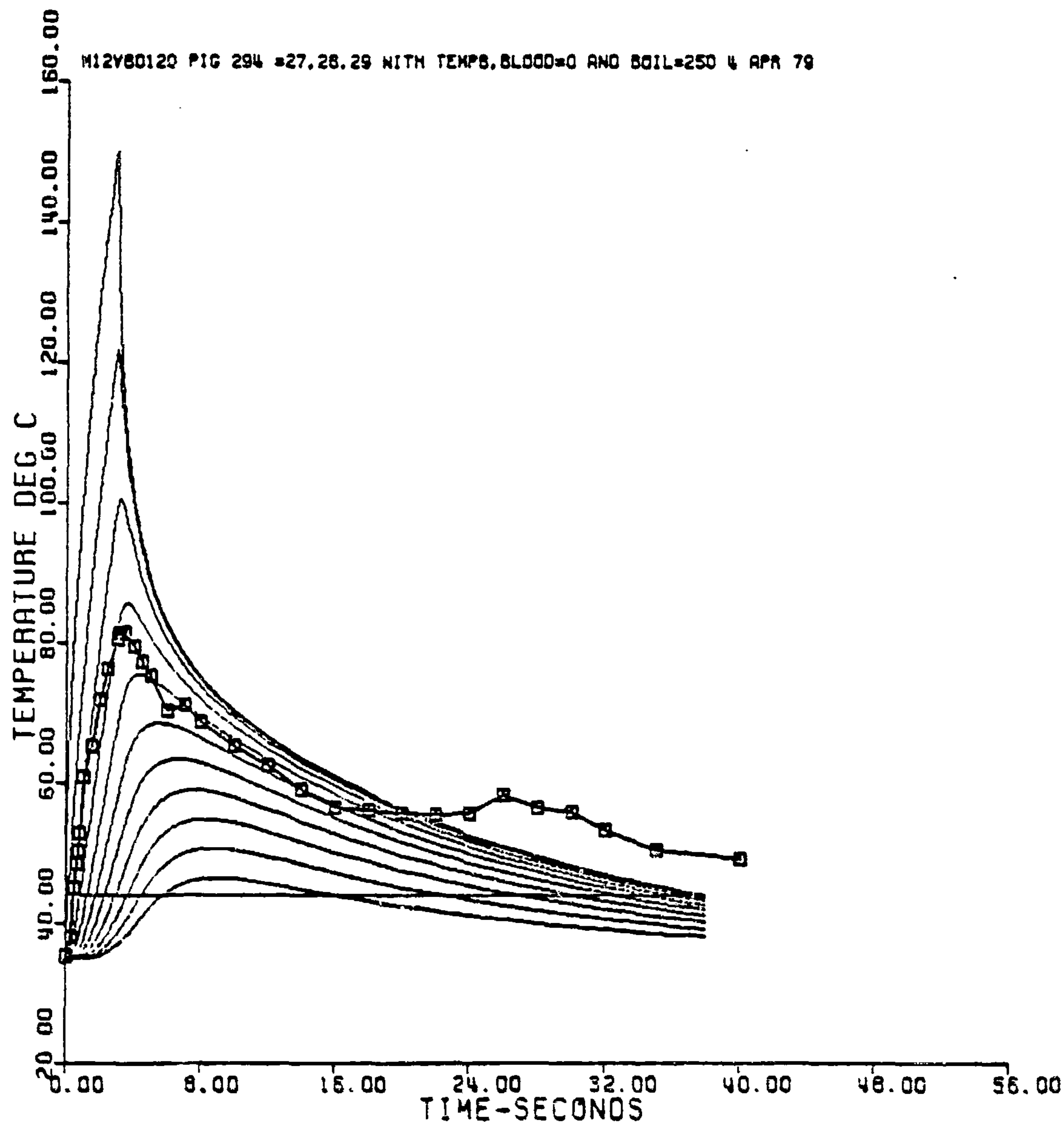

M12V80120 PIG 294 =27,28,29 WITH TEMPS,BLOOD=0 AND BOIL=250 4 APR 79
TEMPERATURE DEG C
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
TIME-SECONDS

Figure 20.

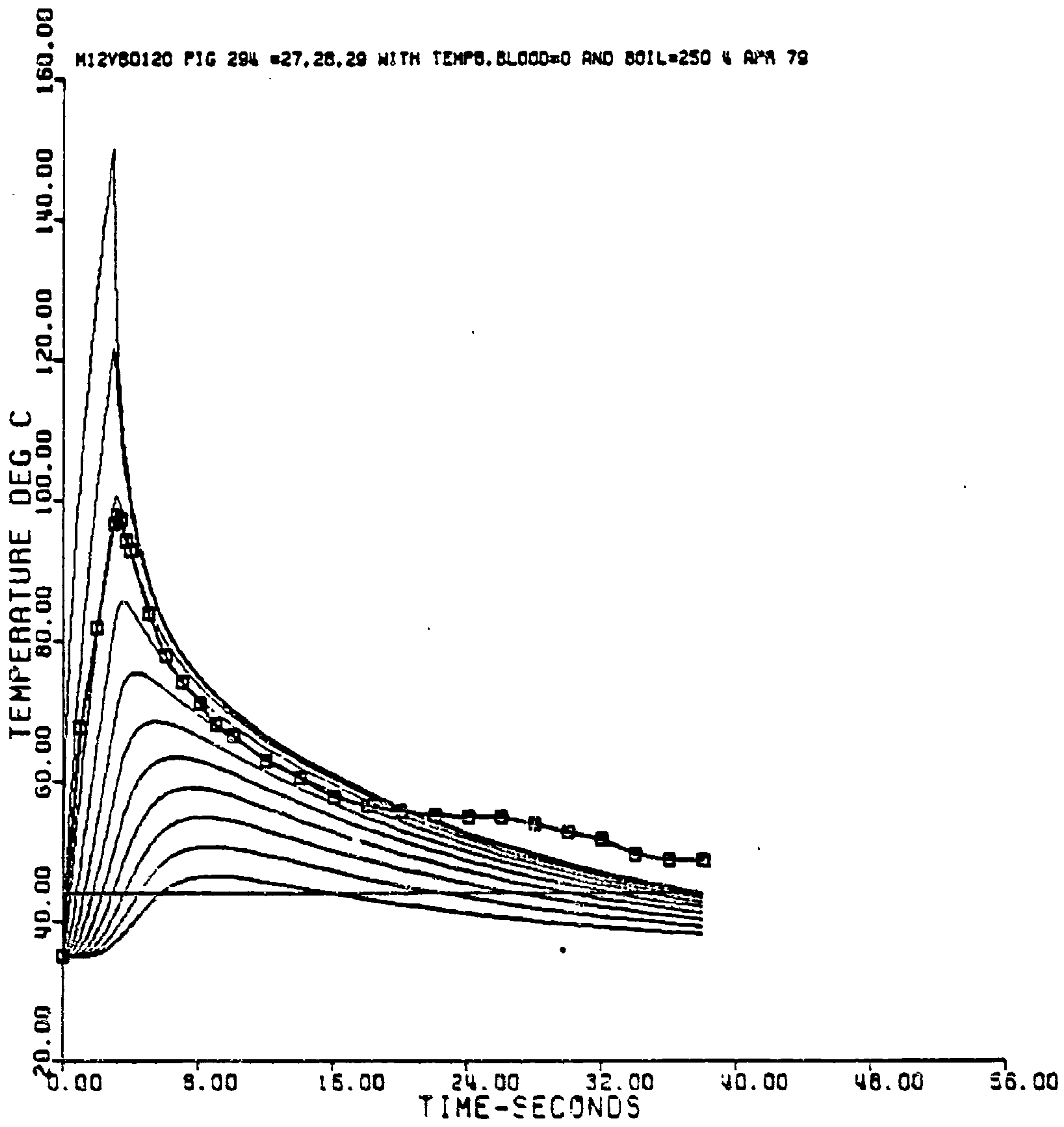
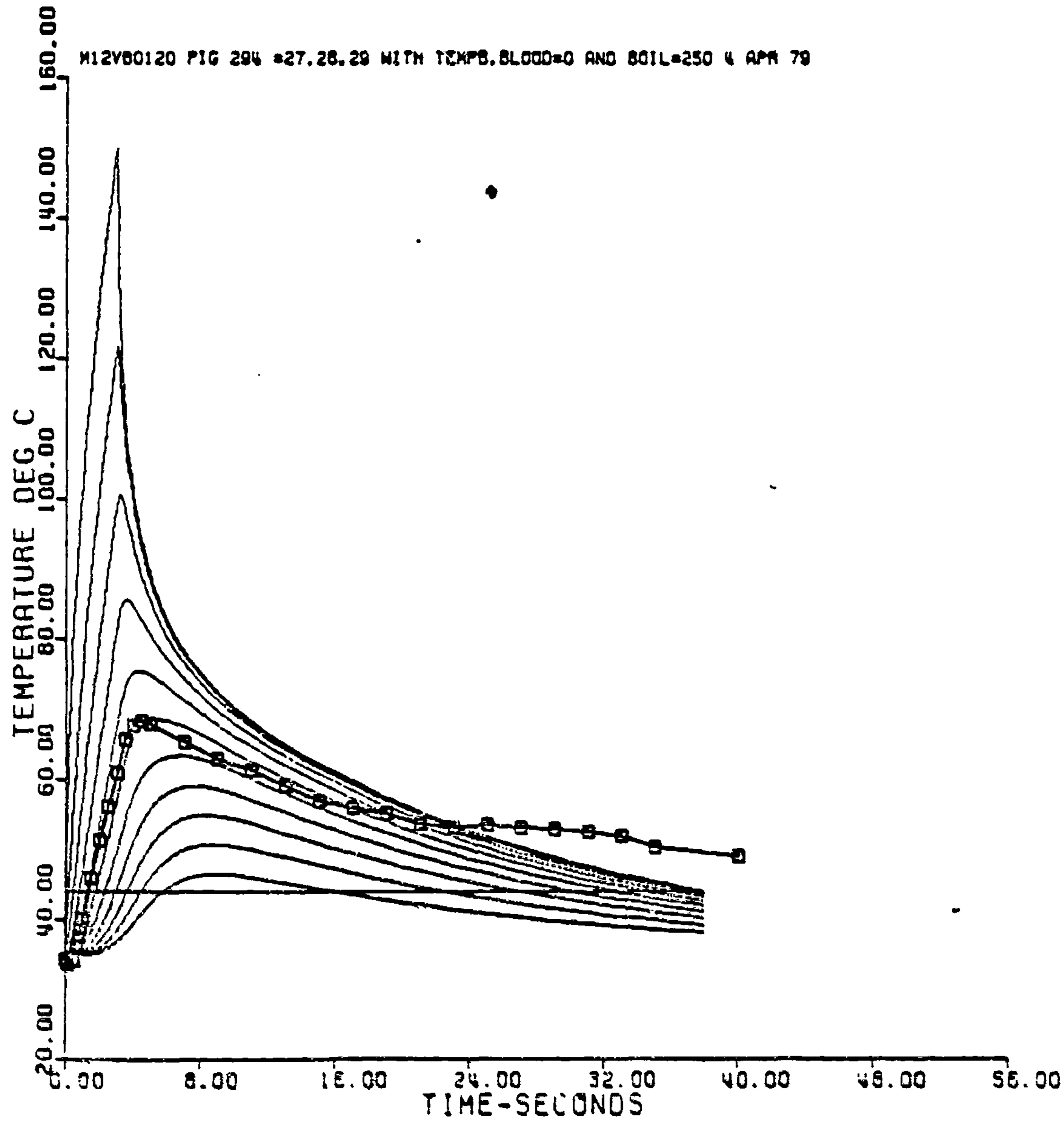

M12V80120 FIG 29A =27,28,29 WITH TEMPB.BLOOD=0 AND BOIL=250 4 APR 79
TEMPERATURE DEG C
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
TIME-SECONDS

Figure 21.



M12V80120 FIG 294 =27,28,29 WITH TEMPB.BLOOD=0 AND BOIL=250 4 APR 79
TEMPERATURE DEG C
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
TIME-SECONDS

Figure 22.

```
MODEL NAME OR DESCRIPTION: BRNSIM3 PIG 294 #27.28.29 DB CORRECTED VALUES ABS=.613 VS M12V80128 5 APR
                                                          SKIN DIFFUSION DATA
                                                         INPUT PARAMETER LIST

                                                         TEMPI0=   34.9700
                                                         DENS=   1.00000
                                                         QI=   3.74000
                                                         BL=  0.220000
                                                         AK=  0.100000E-01
                                                         JINC=     12
                                                         TEMPB=  3.3600
                                                         ABSORB=  0.613000
                                                         BOIL=   100.158

                                                         PL2=       2.24
                                                         PLN2=    239.47
                                                         PL1=       1.46
                                                         PLN1=    147.37
                                                         DE2=  80000.00
                                                         DE1=  50000.00
                                                         ETIME=      3.02
                                                         ITIME=    100.00
                                                         NXTRA=   0
                                                         BLOOD=    0.0010
FLUX FILE I.D.:             0.00   2

FLUX(I)=
    1   3.740    2   3.740

W=          0.18514E+01
W=          0.19398E+00
W=          0.23789E-01

D=          0.72442E+01
D=          0.73778E+01
D=          0.74955E+01

W =          0.74177E+19    AT DEPTH (IN MICRONS)=        0.112535E-06
W =          0.10368E+13    AT DEPTH (IN MICRONS)=        200.000
W =          0.36775E+09    AT DEPTH (IN MICRONS)=        400.000
W =          0.69685E+06    AT DEPTH (IN MICRONS)=        600.000
W =          0.70257E+04    AT DEPTH (IN MICRONS)=        800.000
W =          0.25842E+03    AT DEPTH (IN MICRONS)=        1000.00
W =          0.19083E+02    AT DEPTH (IN MICRONS)=        1200.00
W =          0.18514E+01    AT DEPTH (IN MICRONS)=        1400.00
W =          0.19398E+00    AT DEPTH (IN MICRONS)=        1600.00
W =          0.23789E-01    AT DEPTH (IN MICRONS)=        1800.00
W =          0.52324E-02    AT DEPTH (IN MICRONS)=        2000.00
W =          0.00000E+00    AT DEPTH (IN MICRONS)=        2200.00

MAXIMUM TEMPERATURE =  130.837

THRESHOLD DEPTH =            1453.

FINAL TIME =   33.93
```

Figure 23.

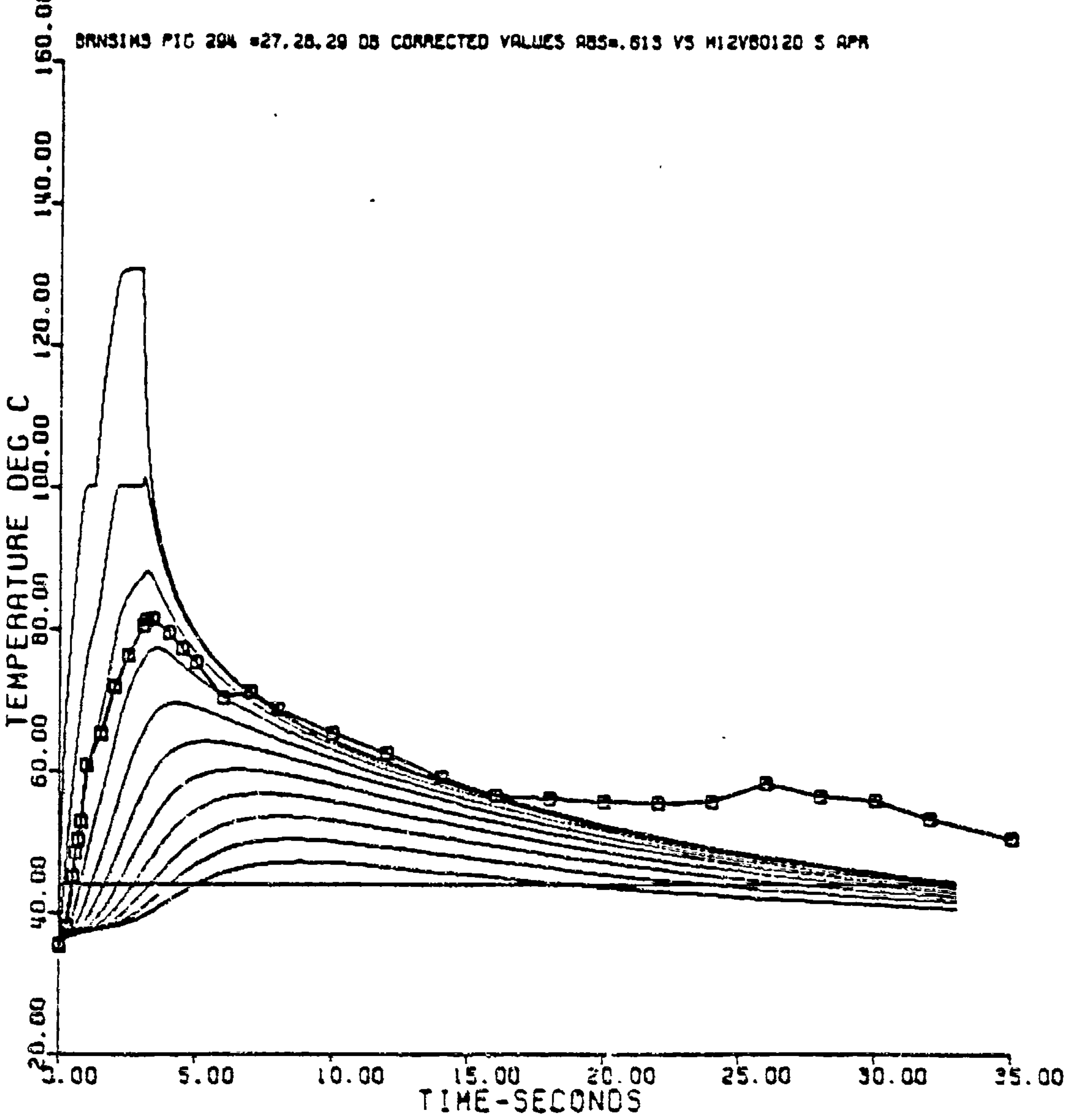

BRNSIM3 PIG 294 =27.28.29 DB CORRECTED VALUES ABS=.613 VS M12V80120 S APR
TEMPERATURE DEG C
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
TIME-SECONDS

Figure 24.

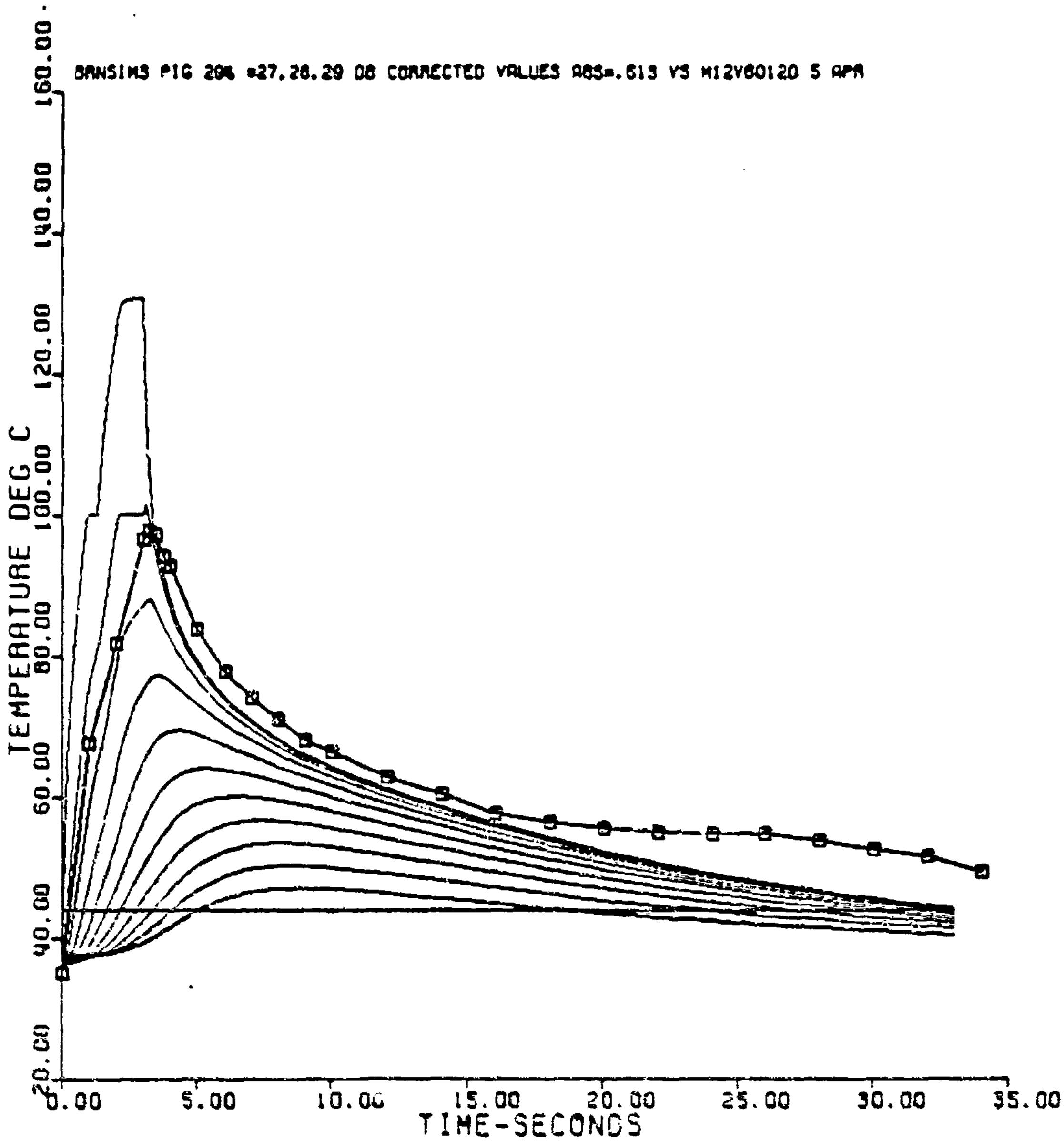

BANSIM3 PIG 20% =27,28,29 08 CORRECTED VALUES ABS=.613 VS M12V60120 5 APR
TEMPERATURE DEG C
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
TIME-SECONDS

Figure 25.

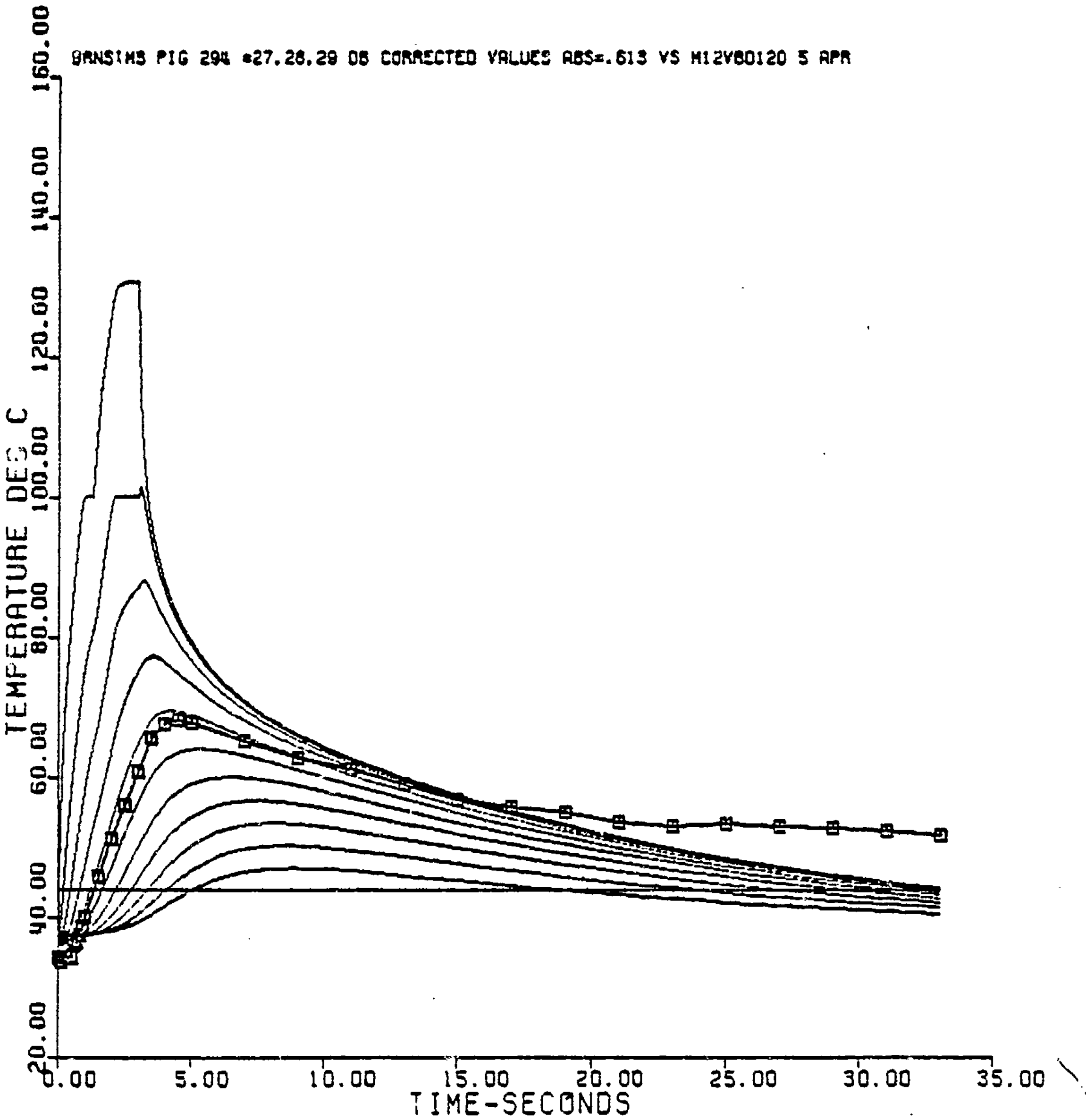

BRNSIMS PIG 294 *27,28,29 OB CORRECTED VALUES ABS=.613 VS M12V80120 5 APR
TEMPERATURE DEG C
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
TIME-SECONDS

Figure 26.

TABLE VI. Comparison of burns observed in bioassay test with predictions of Model 3.

Pig	Exposure Time (s)+	Incident Flux (cal cm^{-2} s^{-1})	Observed Burn Depth Normalized (10^{-4} cm)+	Observed Burn Depth Corrected (10^{-4} cm)+	N	Skin Surface Temp. (°C)	Core Temp. (°C)	Surface Absorptivity	Predicted Depth (10^{-4} cm)	Calculated Surface Temp. (°C)max.	Total Time (s)	Recorded Temp. (°C)# Max.
296LF	3.07±.02	2.55	523±362	611±414	3	28.1	38.0	.613	960	105.57	24.68	----
296LR	0.99±.02	2.64	71±7*	72±7	5	26.1	38.0	.613	151	75.57	3.2	----
296RF	8.2±.02	2.36	1804±437	2411±748	5	27.8	38.0	.613	1775***	119.52	38.10	----
296RR	1.51±.02	2.34	72±30**	73±32	5	26.9	38.0	.613	247	80.76	7.54	----
294LF	0.98±.02	3.27	222±77	257±90	5	30.0(34.3)†	38.33	.613	364	93.13	13.43	49.9
294LR	0.73±.02	3.49	334±298	396±342	5	31.7(37.9)	38.33	.613	318	96.60	13.70	69.9
294RF	3.02±.02	3.47	1680±452	2827±795	2	29.4(34.97)	38.33	.613	1520	128.72	100	98.2
294RR	1.47±.02	3.86	1040±661	910±769	5	30.6(33.9)	38.33	.613	720	111.80	23.22	97.9

† Intraskin temperature at time 0.

+ Mean ± 1 s.d.

Approximate depth of recording = 100–200μm.

* From micro grade depth = 150–250μm.

** From old micro grade depth = 250–400μm; new micro grade depth = 150–250μm.

*** For this simulation the routine to recompute thermal properties subsequent to water boiling was turned off (see text for discussion).

TABLE VII. EFFECT OF NORMALIZED DEPTH IN REDUCING RMS ERROR

RMS ERROR	Model 3	
Normalized Depth	217	208*
Corrected Depth	539	535*

*Using 200μm instead of 71μm for 296 LR and 300μm instead of 72μm for 296 RR.

```
MODEL NAME OR DESCRIPTION: MOPEL. 3 FIG 29ARF DB VALUES ABS=.613 *INCIDENT FLUX  6 APR 79
                                                        SKIN DIFFUSION DATA
                                                       INPUT PARAMETER LIST

                                                      TEMPI0=   27.8000
                                                      DENS=   1.00000
                                                      QI=   2.36000
                                                      BL=  0.220000
                                                      AK=  0.100000E-01
                                                      JINC=     12
                                                      TEMPB= 10.2000
                                                      ABSORB=  0.613000
                                                      BOIL=   100.150

                                                      PL2=       2.24
                                                      PLN2=    239.47
                                                      PL1=       1.46
                                                      PLN1=    147.37
                                                      DE2=  80000.00
                                                      DE1=  50000.00
                                                      ETIME=       0.20
                                                      ITIME=     80.00
                                                      NXTRA=    8
                                                      BLOOD=     0.0010

EXTRA NODES:   22.2  44.4  66.7  88.9 111.1 133.3 155.6 177.8

FLUX FILE I.D.:            0.01   2

FLUX(I)=
   1   2.360    2   2.360

W=          0.95406E+02
W=          0.16466E+01
W=          0.28409E-01

D=          0.74955E+01
D=          0.75809E+01
D=          0.76962E+01

W =          0.11325E+18     AT DEPTH (IN MICRONS)=        0.112535E-06
W =          0.11508E+14     AT DEPTH (IN MICRONS)=         200.000
W =          0.43975E+12     AT DEPTH (IN MICRONS)=         400.000
W =          0.23339E+11     AT DEPTH (IN MICRONS)=         600.000
W =          0.18591E+10     AT DEPTH (IN MICRONS)=         800.000
W =          0.10182E+09     AT DEPTH (IN MICRONS)=         1000.00
W =          0.45823E+07     AT DEPTH (IN MICRONS)=         1200.00
W =          0.16297E+06     AT DEPTH (IN MICRONS)=         1400.00
W =          0.44780E+04     AT DEPTH (IN MICRONS)=         1600.00
W =          0.95406E+02     AT DEPTH (IN MICRONS)=         1800.00
W =          0.16466E+01     AT DEPTH (IN MICRONS)=         2000.00
W =          0.28409E-01     AT DEPTH (IN MICRONS)=         2200.00

MAXIMUM TEMPERATURE =  119.613

THRESHOLD DEPTH =            2025.

FINAL TIME =   80.00
```

Figure 27.

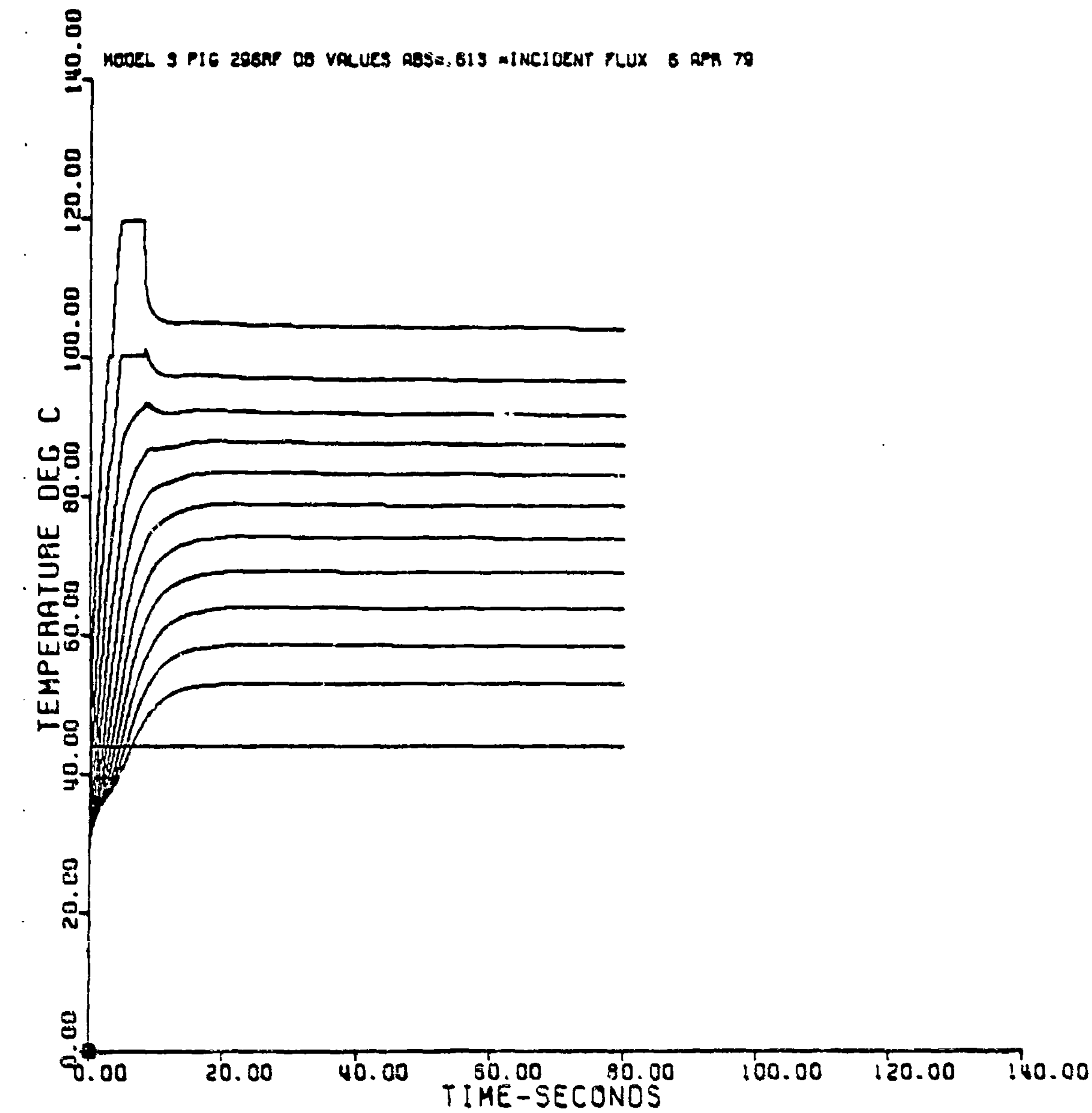
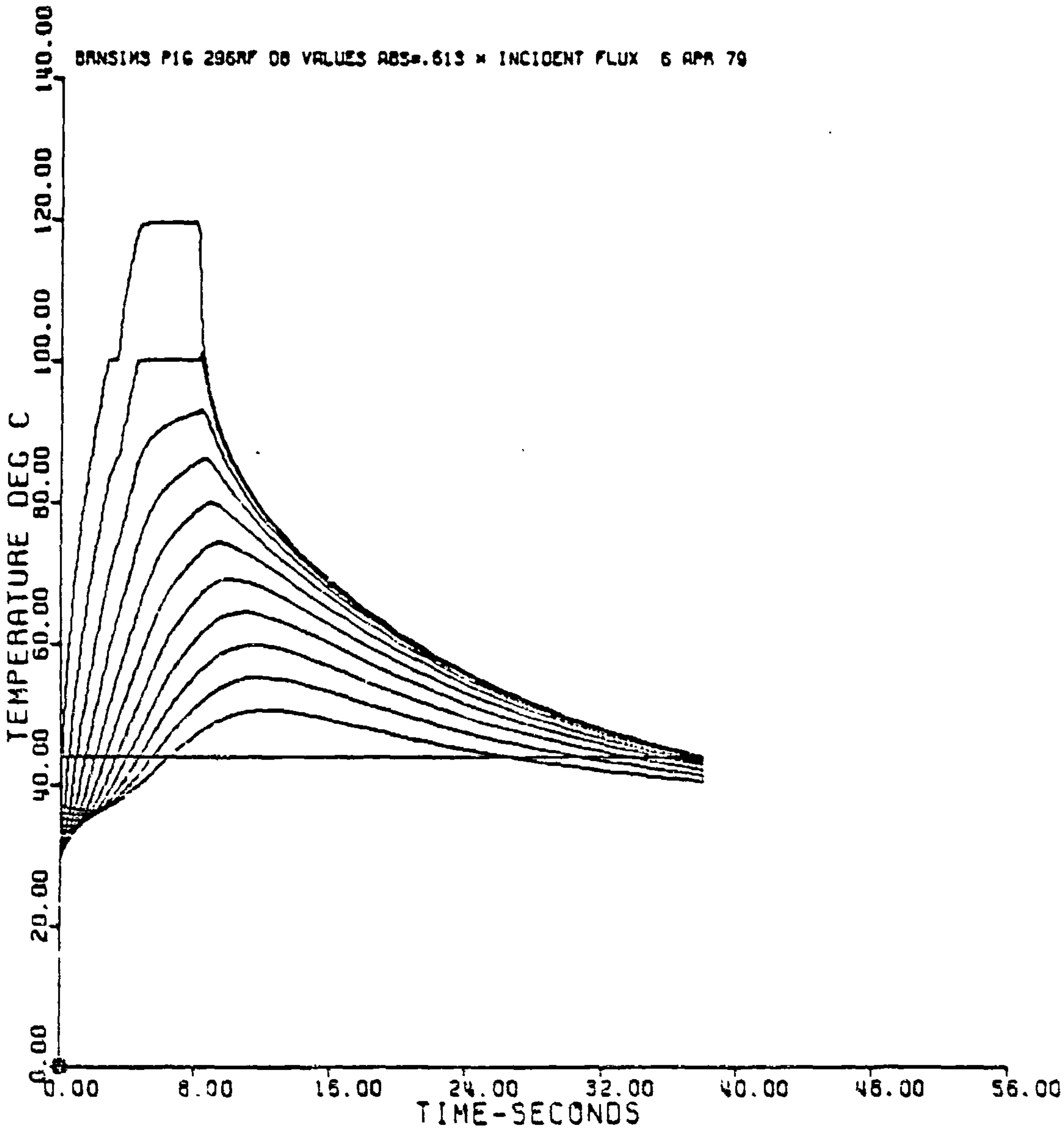

MODEL 3 FIG 29SRF DB VALUES ABS=.613 *INCIDENT FLUX 6 APR 79
TEMPERATURE DEG C
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
TIME-SECONDS
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00

Figure 28.

```
MODEL NAME OR DESCRIPTION: BENSIMB PIG 296BF DB VALUES ABS=.613 * INCIDENT FLUX  6 APR 79
                                                            SKIN DIFFUSION DATA
                                                           INPUT PARAMETER LIST

                                                           TEMP10=   27.0000
                                                           DENS=   1.00000
                                                           QI=   2.36000
                                                           BL=  0.220000
                                                           AK=  0.100000E-01
                                                           JINC=     12
                                                           TEMPB= 10.2000
                                                           ABSORB=  0.613000
                                                           BOIL=   100.150

                                                           PL2=       2.24
                                                           PLM2=    239.47
                                                           PL1=       1.46
                                                           PLM1=    147.37
                                                           DE2=  80000.00
                                                           DE1=  50000.00
                                                           ETIME=      9.20
                                                           ITIME=     80.00
                                                           NXTRA=   0
                                                           BLOOD=    0.0010
FLUX FILE I.D.:             0.00    2

FLUX(I)=
    1   2.360     2   2.360

W=          0.17115E+02
W=          0.66940E+00
W=          0.28305E-01

D=          0.73778E+01
D=          0.74955E+01
D=          0.76009E+01

W =           0.10649E+18     AT DEPTH (IN MICRONS)=        0.112535E-06
W =           0.31153E+13     AT DEPTH (IN MICRONS)=         200.000
W =           0.21686E+11     AT DEPTH (IN MICRONS)=         400.000
W =           0.31133E+09     AT DEPTH (IN MICRONS)=         600.000
W =           0.69079E+07     AT DEPTH (IN MICRONS)=         800.000
W =           0.22440E+06     AT DEPTH (IN MICRONS)=         1000.00
W =           0.90919E+04     AT DEPTH (IN MICRONS)=         1200.00
W =           0.40101E+03     AT DEPTH (IN MICRONS)=         1400.00
W =           0.17115E+02     AT DEPTH (IN MICRONS)=         1600.00
W =           0.66940E+00     AT DEPTH (IN MICRONS)=         1800.00
W =           0.28305E-01     AT DEPTH (IN MICRONS)=         2000.00
W =           0.13716E-02     AT DEPTH (IN MICRONS)=         2200.00

MAXIMUM TEMPERATURE =  119.515

THRESHOLD DEPTH =            1775.

FINAL TIME =   30.10
```

Figure 29.



BRNSIMS PIG 296RF 08 VALUES ABS=.613 × INCIDENT FLUX 6 APR 79
TEMPERATURE DEG C
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
TIME-SECONDS

Figure 30.

TABLE VIII

Test No.	T_o	Exposure Time(S)	Fabric	T_D+ Obs. (μm) Normalized	Corrected	Model II	T_D Calc. (μm) Model* III_A	Model** III_B
Sim 21208	31.8	2.97±.02	NWN	129	147	<222	99	252
Sim 21213	32.2	2.97±.02	AFN	237	296	222-444	0	87
Sim 31208	31.8	2.97±.02	PBI	152	201	565	54	143
Sim 31213	32.2	2.97±.02	HT4	62	59	563	49	141
212,36,11	29.8±1.2	4.97±.02	AFN	968±508	1200±529	973±541(3)	689±81	1031±92
28,33,39	31.3±0.8	4.97±.02	PBI	766±361	943±453	757±194(3)	761±190	1049±196
23,27,29,211,310	30.0±1.8	4.97±.02	HT4	847±633	945±650	626±144(5)	561±239	884±295
26,210,37,38,312	29.7±1.7	4.97±.02	NWN	866±500	1043±549	756±47(5)	799±41	1131±36

+ T_D = Threshold Depth - mean ± 1 S.D. (N)

* Heat Flux, Q, = Q absorbed by sensor with skin absorptivity = .60

** Heat Flux, Q, = Q incident to sensory with skin absorptivity = .64

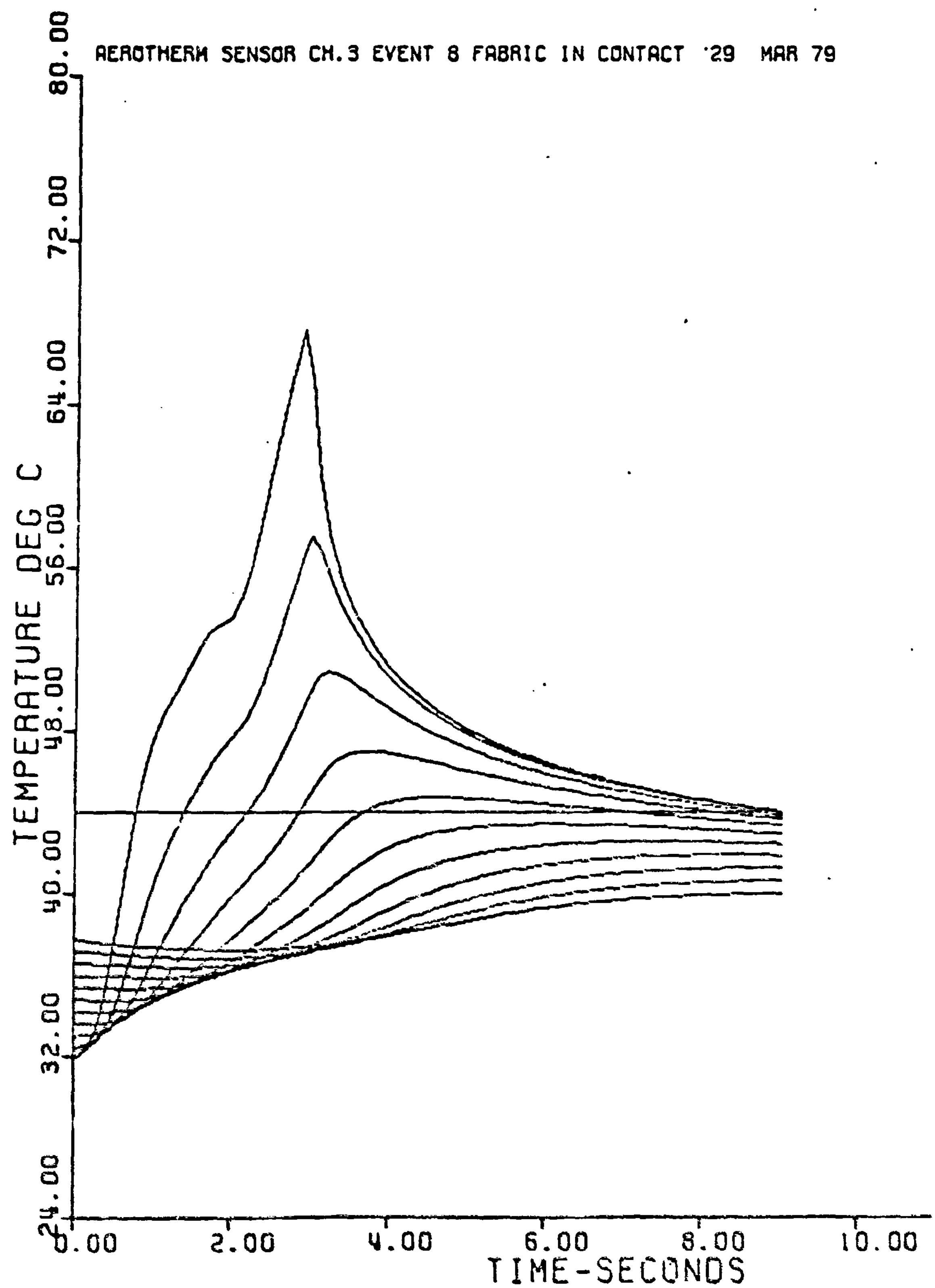

AEROTHERM SENSOR CH.3 EVENT 8 FABRIC IN CONTACT 29 MAR 79
TEMPERATURE DEG C
80.00
72.00
64.00
56.00
48.00
40.00
32.00
24.00
0.00
2.00
4.00
6.00
8.00
10.00
TIME-SECONDS

Figure 31.

different heat fluxes. The most nearly correct flux would be incident flux with an absorptivity of .613. Once again the RMS error generally favors normalized depths and would be even better with proper flux input (see Table IX).

Once again the error in shallow burn depths is pointed up. The depths for SIM31213 should be compared with the micro grades of 4 and 5 indicating from partial to complete epidermal-dermal separation. Using Table I, this would give a normalized burn depth of from 125 to 200μm, much more in line with a Model III_B prediction of 141μm.

10.0 COMPARISON WITH WEAVER AND STOLL (7)

The results of just two simulations are presented here in Figures 32 and 33. First, Model 3 (M12VB0120) was run for Stoll's human burn data (.4 cal cm^{-2} sec^{-1}, Absorptivity = 0.94, ETIME = 5.6 sec and initial skin temperature of 32.5°C) using a slightly lower than normal value for blood (.0007 vs. .001) and Stoll's integration constants (PL1, PLN1, etc.). The resulting calculations for Ω at 80μ are different by 9.4% and the total time by less than 0.4%. In Model 3 the blood cooling is turned on linearly from 0 to maximum during the first 20 seconds. There is some indication, see Figures 20, 21, and 22, that the cooling by blood does not visibly take effect until about 16 seconds after the beginning of exposure. An indication that a slightly different model, in which the blood is turned on from 37 to 45 seconds after the beginning of exposure, may be better, is shown in Figures 34 and 35. Here the predictions are different from Stoll's by 0.8% for total damage, Ω, at 80μm and by 0.35% for total time. This is very good agreement considering the differences between the models -- Stoll: measured human skin surface temperature, no blood cooling, thermal properties constant as a function of depth, changes in conductivity as a function of time and human skin thermal properties versus Model 3: calculated pig skin surface temperature, cooling by blood, pig skin thermal properties variable as a function of depth, and initial thermal gradient.

Substitution of Takata's (15) values for the activation energy (DE) and frequency factor (PL and PLN) in the first case above results in a predicted depth of 57.1μm compared with 105.2μm. This indicates that different values for DE, PL and PLN should be used for the epidermal and dermal nodes. This combination of factors has not been tried.

11.0 UNANALYZED SENSOR DATA

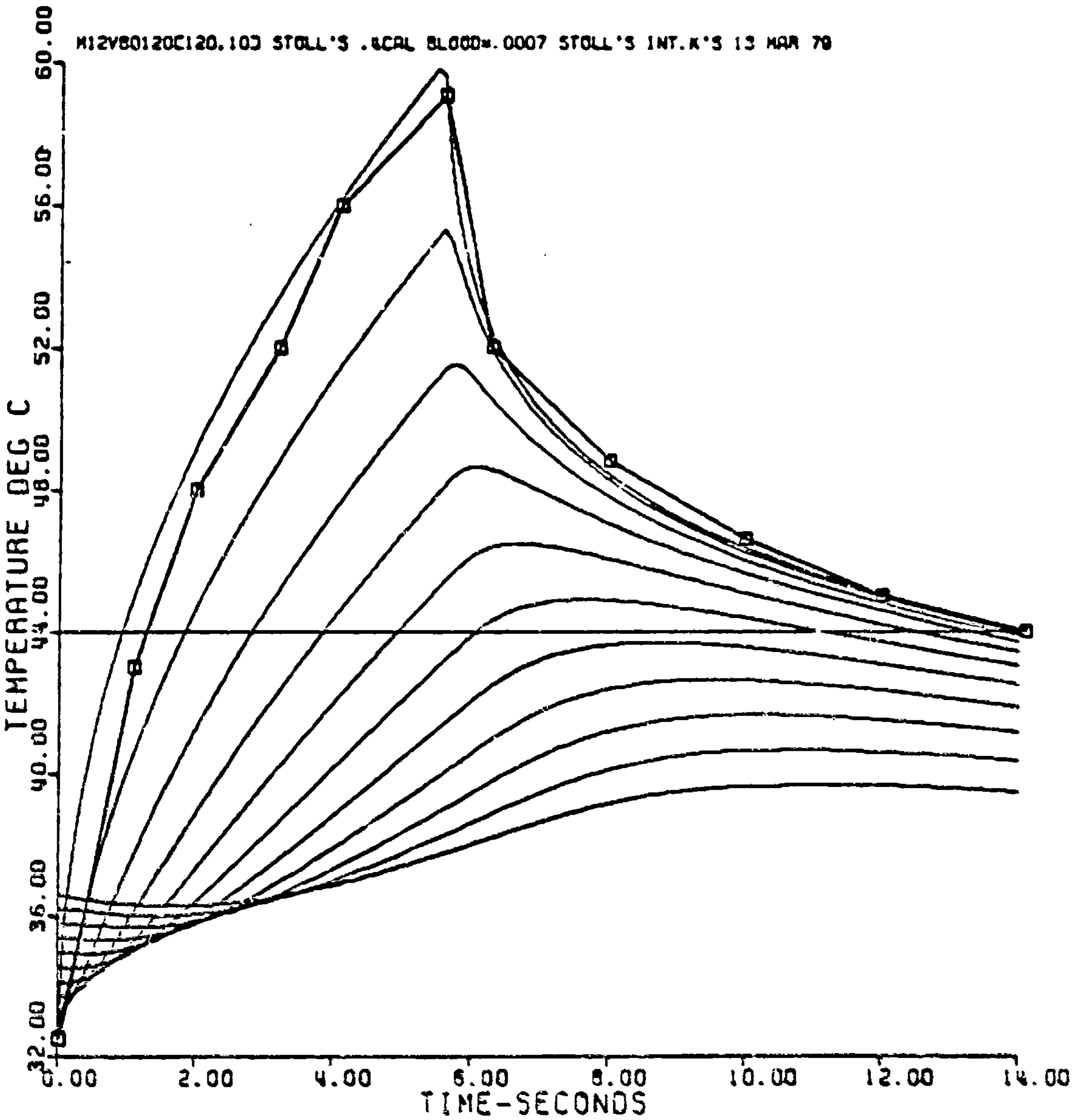
One set of experimental data collected during the 1972/73 period remains to be analyzed. Both Aerotherm Sensors and Fabric Research Labs skin simulants were subjected to the heat from a ½ inch thick steel plate mounted in the furnace. Unfortunately the only record of these experiments is in the form of strip chart recordings. The peak temperatures of the sensors were analyzed by IITRI (4)

TABLE IX

RMS ERROR		MODEL II	III_A	III_B
#212 thru 312	Normalized	123.5	204.5	197.3
	Corrected	259.9	357.6	113.2
Sim21208 thru Sim31213	Normalized	331.0	129.3	104.8
	Corrected	313.6	167.0	127.3

```
MODEL NAME OR DESCRIPTION: M12/081200(120.18) STOLL'S .4CAL BLOOD=.0007 STOLL'S INT.K'S 13 MAR 79

                                                      SKIN DIFFUSION DATA
                                                     INPUT PARAMETER LIST

                                                     TEMP10=   32.5000
                                                     DENS=   1.00000
                                                     Q1=  0.400000
                                                     BL=  0.220000
                                                     AK=  0.100000E-01
                                                     JINC=    12
                                                     TEMPB=  4.5000
                                                     ABSORB=  0.940000
                                                     BOIL=   100.150

                                                     PL2=      0.60
                                                     PLN2=    117.43
                                                     PL1=      0.70
                                                     PLN1=    285.52
                                                     DE2=  39109.30
                                                     DE1=  92534.90
                                                     ETIME=      5.60
                                                     ITIME=     80.00
                                                     NXTRA=   8
                                                     BLOOD=    0.0007

EXTRA NODES:   30.0  40.0  60.0  80.0 100.0 130.0 160.0 190.0

FLUX FILE I.D.:            0.01   2

FLUX(I)=
    1   0.400    2   0.400

W=          0.22340E+01
W=          0.52990E+00
W=          0.14571E+00

D=         -0.16000E+02
D=          0.52983E+01
D=          0.59915E+01

W=1 LIES ABOVE NODE 2.  INTERCOLLATING VALUES OF D AND W
COMPUTED FROM INTERPOLATED VALUES OF D AND TEMPERATURE

W=          0.10384E+01
W=          0.94170E+00
W=          0.68745E+00

D=          0.44052E+01
D=          0.48675E+01
D=          0.50752E+01

W =          0.22340E+01     AT DEPTH (IN MICRONS)=       0.112535E-06
W =          0.18999E+01     AT DEPTH (IN MICRONS)=        20.0000
W =          0.16230E+01     AT DEPTH (IN MICRONS)=        40.0000
W =          0.13926E+01     AT DEPTH (IN MICRONS)=        60.0000
W =          0.12001E+01     AT DEPTH (IN MICRONS)=        80.0000
W =          0.10334E+01     AT DEPTH (IN MICRONS)=        100.000
W =          0.84170E+00     AT DEPTH (IN MICRONS)=        130.000
W =          0.68745E+00     AT DEPTH (IN MICRONS)=        160.000
W =          0.56308E+00     AT DEPTH (IN MICRONS)=        190.000
W =          0.52994E+00     AT DEPTH (IN MICRONS)=        200.000
W =          0.14571E+00     AT DEPTH (IN MICRONS)=        400.000
W =          0.23935E-01     AT DEPTH (IN MICRONS)=        600.000

MAXIMUM TEMPERATURE =60.857

THRESHOLD DEPTH =            105.2

FINAL TIME =    14.05
```

Figure 32.

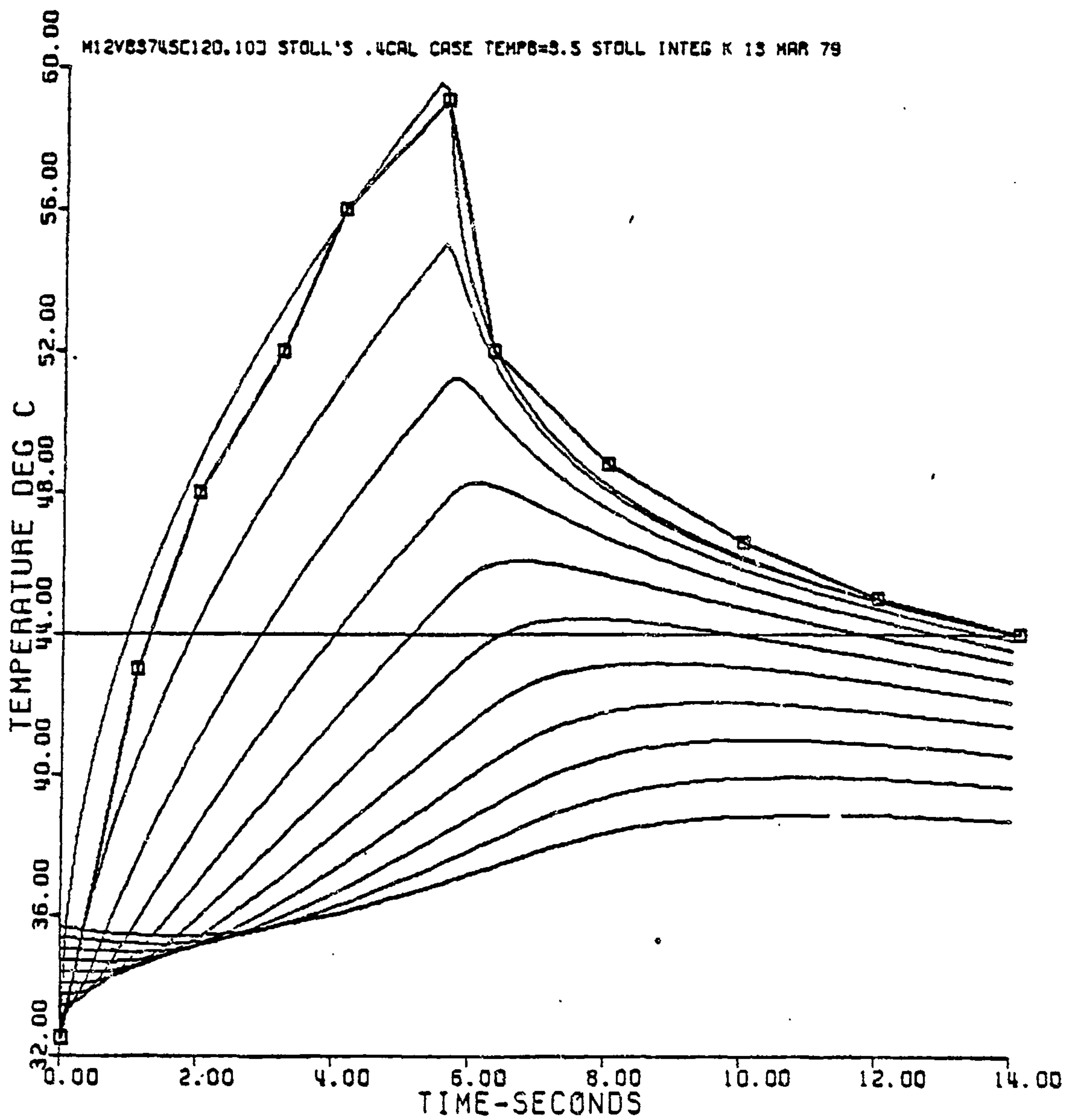


M12V80120C120.10J STOLL'S .&CAL BLOOD=.0007 STOLL'S INT.K'S 13 MAR 79
60.00
56.00
52.00
48.00
44.00
40.00
36.00
32.00
TEMPERATURE DEG C
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
TIME-SECONDS

Figure 33.

```
MODEL NAME OR DESCRIPTION: M12VE3745C120.10] STOLL'S .4CAL CASE TEMPB=3.5 STOLL INTEG K 13 MAR'79

                                                SKIN DIFFUSION DATA
                                                INPUT PARAMETER LIST

                                                TEMPID=   32.5000
                                                DENS=   1.00000
                                                OI=  0.400000
                                                BL=  0.220000
                                                AK=  0.100000E-01
                                                JINC=    12
                                                TEMPB=  3.5000
                                                ABSORB=  0.940000
                                                BOIL=   100.150

                                                PL2=      0.60
                                                PLN2=    117.43
                                                PL1=      0.78
                                                PLN1=    285.52
                                                DE2=  39189.80
                                                DE1=  93534.90
                                                ETIME=     5.60
                                                ITIME=    80.00
                                                NXTRA=   8
                                                BLOOD=    0.0010

EXTRA NODES:   20.0  40.0  60.0  80.0 100.0 130.0 160.0 190.0

FLUX FILE I.D.:            0.01   2

FLUX(I)=
    1   0.400    2   0.400

W=         0.20083E+01
W=         0.47228E+00
W=         0.12208E+00

D=        -0.16000E+02
D=         0.52983E+01
D=         0.59915E+01

W=1 LIES ABOVE NODE 2.  INTERCOLLATING VALUES OF D AND W
COMPUTED FROM INTERPOLATED VALUES OF D AND TEMPERATURE

W=         0.10750E+01
W=         0.93214E+00
W=         0.75456E+00

D=         0.43820E+01
D=         0.46052E+01
D=         0.48675E+01

W =        0.20083E+01     AT DEPTH (IN MICRONS)=        0.112535E-06
W =        0.17081E+01     AT DEPTH (IN MICRONS)=        20.0000
W =        0.14590E+01     AT DEPTH (IN MICRONS)=        40.0000
W =        0.12516E+01     AT DEPTH (IN MICRONS)=        60.0000
W =        0.10750E+01     AT DEPTH (IN MICRONS)=        80.0000
W =        0.93214E+00     AT DEPTH (IN MICRONS)=        100.000
W =        0.75456E+00     AT DEPTH (IN MICRONS)=        130.000
W =        0.61500E+00     AT DEPTH (IN MICRONS)=        160.000
W =        0.50430E+00     AT DEPTH (IN MICRONS)=        190.000
W =        0.47228E+00     AT DEPTH (IN MICRONS)=        200.000
W =        0.12208E+00     AT DEPTH (IN MICRONS)=        400.000
W =        0.17497E-01     AT DEPTH (IN MICRONS)=        600.000

MAXIMUM TEMPERATURE =   59.765

THRESHOLD DEPTH =          90.17

FINAL TIME =   14.09
```

Figure 34.



M12V8374SC120.103 STOLL'S .4CAL CASE TEMPB=3.5 STOLL INTEG K 13 MAR 79
TEMPERATURE DEG C
60.00
56.00
52.00
48.00
44.00
40.00
36.00
32.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
TIME-SECONDS

Figure 35.

to ascertain their accuracy and reproducibility. When these recordings are manually read and digitized then the voltage-time profiles can be converted to flux-time profiles and used to drive the model. It will be important to complete this analysis since some of the sensors were covered with fabric spaced ¼" away from the surface, and represent the only such data available.

12.0 DISCUSSION

The data base has been reviewed and corrected and is now ready for release to those who wish to pursue model development on their own. As can be seen in the graphic presentations of the data, there is still a great deal of scatter which, to some extent, is unavoidable in experiments of this type. There are statistical tricks for dealing with scatter but the emphasis throughout this project has been to attempt to understand the sources of the observed variability. Uncontrolled variables such as skin temperature, time between induction of anesthesia and exposure, disagreement among pathologists regarding gradings, and unrecorded variation in shutter performance all have had an effect which cannot be removed.

An empirical, multidiscriminant model was developed to predict clinical or micro grade; but further development of it or some more appropriate model was temporarily shelved in favor of analytical model development when it was realized that the immediate need was for a model compatible with both laboratory testing and fire pit testing of thermally protective fabrics. As we better understand the relationship among total flux, exposure time and burn depth, a simplified, empirically based model may become available. For example, if, as Stoll suggested (14), plots of log exposure time versus log flux parameterized by burn grade/depth results in a family of well behaved curves or straight lines, then such plots might prove useful in screening fabrics. The first try at this approach was not entirely satisfactory. The data base and plotting routines are now available to investigate this more fully.

An analytical model was developed which takes into account tissue water boiling, a temperature gradient, a thermal properties gradient, skin absorptivity, either constant or variable (tabulated) heat flux corrected for attenuation by hair and a 10% convective component. It has been shown to predict, with reasonable accuracy, burns in pigs when they are exposed bare or protected by experimental fabrics and when the heat flux is a constant or when it is variable and derived from output of an Aerotherm sensor.

13.0 CONCLUSIONS AND RECOMMENDATIONS

1. The USAARL Porcine Burn Data Base is ready for release.

2. Data handling and graphing programs are now available which facilitate the further use and study of these data.

3. A multi-discriminant model exists which predicts clinical and micro burn grades but requires further development and study to be useful.

4. An analytical model, BRNSIM, has been developed which predicts burn depths over a wide range with reasonable accuracy.

5. It is recommended that the recently detected flaw in BRNSIM be corrected and that BRNSIM be further tested, not only with data from the USAARL data base and the University of Rochester, but also with data from the instrumented manikins as used in the Natick Fire pit.

6. It is recommended that BRNSIM be tested against the Aerotherm manikin model in its ability to predict burns over a wide range of conditions.

7. It is recommended that skin cooling by blood and tissue water boiling be further studied to clarify the dynamics of these phenomena.

8. It is recommended that BRNSIM be further tested using Stoll's extensive human burn data base.

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APPENDIX A

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Knox, Francis S. III, Thomas L. Wachtel, G. R. McCahan, Jr., Calvin B. Lum, and Walter P. Trevethan. The effect of fiber and dye degradation products (FDP) on burn wound healing. USAARL-LR-73-4-1-1, Dec., 1972. Reviewed by Pruitt et al, U. S. Army Institute of Surgical Research. Ft. Sam Houston, Texas, 78234.

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Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Mathematical models of skin burns induced by simulated postcrash fires as aids in thermal protective clothing design and selection. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-15, June, 1978.

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Knox, F. S. III. Realistic evaluation of fabrics for thermal protective clothing. Presented to Survival and Flight Equipment Association 10th Annual Symposium, 2-5 October, 1972, Phoenix, Arizona.

Knox, Francis S. III, George R. McCahan, Jr. and Thomas L. Wachtel. The use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. Presented to Eighth Scientific Sessions of the Joint Committee on Aviation Pathology, 8-12 October, 1972. Colorado Springs, Colorado.

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Knox, Francis S. III, Stanley C. Knapp, Thomas L. Wachtel and George R. McCahan, Jr. Bioassay of thermal protection afforded by candidate flight suit fabrics. Tenth Scientific Session of the Joint Committee on Aviation Pathology, Halton, England, Sept. 6-12, 1976.

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Knox, F. S. III, T. L. Wachtel and S. C. Knapp. Mathematical models of skin burns induced by simulated postcrash fires as aids in thermal protective clothing design and selection. Army Scientific Conference, U. S. Military Academy, Westport, N.Y., 20-22 June, 1978.

APPENDIX B

BIBLIOGRAPHY - THERMAL ANALYSIS PROGRAM

Abstracts of Reports and Papers in Preparation:

Knox, F. S., Peter Saurmilch, S. C. Knapp, Thomas Wachtel, George McCahan and Lynn Alford. "A Fire Simulator/Shutter System for Testing Protective Fabrics and Calibrating Thermal Sensors" (USAARL Report 79-4) Ft. Rucker, Alabama: U. S. Army Aeromedical Research Laboratory, March, 1979.

The design, construction, calibration and use of a JP-4 fuel, shuttered furnace is described. Based on a NASA design this furnace simulates the radiative and convective thermal environment of a postcrash fire in rotary winged aircraft. Heat fluxes ranged from 0.5 to 3.6 ± 3% calories per square centimeter per second with steady-state furnace wall temperatures from 519°C (967°F) to 1353°C (2450°F) and a radiative/total flux ratio of approximately 0.9. A pneumatically propelled, water cooled shutter, mounted in a rolling animal carrier, controlled the exposure of pigs and thermal sensors to the fire. An electronic data acquisition and control system is also described. This system automatically controlled the opening and closing of the shutter and provided strip chart and FM magnetic tape records of exposure time, furnace wall temperature, heat flux, and sensor output. Sources of error including nonuniformity of flame front and shutter dynamics are discussed. Methods of animal handling, burn grading and photographic documentation are introduced along with a brief description of some nine experimental protocols carried out using this fire simulator shutter system.

Knox, F. S. III, Thomas L. Wachtel, S. C. Knapp. "Experimental porcine burn injury data base: listings and graphic representation."

Pigs, as human skin analogs, were exposed to simulated postcrash fires of various intensitites for various durations. Some pigs were exposed bare, others with blackened skin and still others protected by thermally protective fabrics. For each exposure the location of the burn, exposure time, heat flux, initial skin temperature, date, clinical and histopathological evaluations of burn injury, corrected and normalized burn depth and a quality control number are listed. The data base contains over 45,000 items and summarizes most of the porcine burn data collected using the USAARL fire simulation furnace/shutter system. The report also includes graphic representations of items within the data base such as log exposure time versus log flux parameterized by gross grade, gross grade versus normalized burn depth, new micro grade versus normalized burn depth, gross grade versus corrected burn depth, new micro grade versus corrected burn depth, gross grade versus new micro grade, new micro grade versus total flux, gross grade versus total flux, normalized burn depth versus total flux parameterized by exposure time. These plots will show not only the relationships among various variables but also indicate the variability seen in biological data of this kind. These data are presented for use by those who wish to continue development of mathematical models to predict burn injury.

Knox, F. S. III, Thomas L. Wachtel, George McCahan. "Thermal Properties Calculated from Measured Water Content as a Function of Depth in Porcine Skin".

In order to develop a realistic tissue water boiling routine for a mathematical model of burn development, it was necessary to know the water content of skin and the thermal properties as a function of depth. Split thickness skin samples were obtained from several pigs using an air powered dermatome. Alternate segments of these skin grafts were processed for skin water content determination and for histopathologic measurements of skin thickness. Tissue samples were weighed, dried and subsequently weighed again in a standardized protocol to determine tissue water content. In some instances the volume of tissue was also determined in order to allow the calculation of tissue density. Given a table of measured values of water content as a function of skin thickness, a least squares cubic polynomial was fit to the data and water content as a function of depth was computed from the following formula: $w(T-d) = T/d \times (W_T - W_{T-d}) + W_{T-d}$ where T is the total thickness of a slab, W_T is the fraction of water computed from the cubic equation, d is the thickness of the thin slab at a depth T-d, and W_{T-d} is the fraction of water above the thin slab. The thermal properties, as a function of depth, were then calculated using the formulations of Cooper and Trezek (Aerospace Med. 42(1):24-27, 1971.).

Knox, F. S. III, Nelson O'Young, Daniel D. Reneau, Chester Ellis, Thomas L. Wachtel. "BRNSIM - An Analytical Model for Predicting Thermal Cutaneous Injury". BRNSIM is a computer model written in FORTRAN IV run on a DEC PDP11/40 with 80K of core.

Since, for all practical purposes, skin is essentially opaque to thermal radiation within a postcrash fire, it can be considered to transfer energy internally by conduction only. This energy transfer in skin can be described by the heat conduction or Fourier equation. This equation was implemented in a 12 node model with appropriate boundary conditions which were initially: 1) no back radiation at the surface, 2) an adiabatic back wall, and 3) no cooling by blood. The equation set was solved by applying Crank-Nicholson method to the second order of partial derivatives and corresponding explicit methods to the first order of partials. The implicit differencing method is noted for characteristics of stability and convergence. Correct increment sizes yield reliable convergence. The model was implemented in FORTRAN using solution techniques of Thomas as described by Bruce. The initial model was subsequently revised to allow energy flux across the surface during heating, convective heat loss at the skin surface during cooling, heat transfer into deep tissues including conduction into fat and convective cooling by the blood, tissue water boiling, variable thermal properties for each node and an initial temperature profile from the surface to deep structures. The model is run interactively with most variables changeable for each run. This model calculates in depth tissue temperatures as a function of time for each node. These temperatures are converted to a damage rate assuming first order kinetics. The damage rate is then integrated to give an indication of total damage at each node and the interpolation routine finds the depth at which the total damage, Ω, equals one. The parameters of the entire model were adjusted so that the calculated temperatures agreed with recorded intraskin temperature profiles and so that the calculated damage (threshold depth) agreed with experimental data obtained by exposing pigs, as a human skin analog, to simulated postcrash fires of various intensities. It was found that the inclusion of tissue water boiling, proper thermal properties for the skin, an initial temperature profile and heat loss to deep structures by conduction and convection were necessary to obtain calculated temperature profiles which agree with the experimentally determined profiles. It was felt that until this agreement was obtained, further adjustments in the activation energy and frequency factors of the Arrhenious relationship was an exercise in futility. The model prints a one page summary of the calculations and, at the user's option, will produce a one page plot of the calculated temperature profiles on which any experimentally determined temperature points can be overlayed. The model is designed to take heat flux as a constant value or as a table of values simulating heat flux as a function of time; thus the model can be employed using output from heat flux sensors such as those in thermoman, the U. S. Air Force/Aerotherm instrumented manikin.

Knox, F. S. III, Thomas L. Wachtel, Chester Ellis. "A Comparison of BRNSIM, a Model for Predicting Thermal Cutaneous Injury with Four Earlier Models in Their Ability to Precit Experimantally Determined Burn Injury from Three Separate Studies".

BRNSIM, a computer model described earlier, was run using activation energies and frequency factors as proposed by Moritz and Henriques, Green and Stoll, Takata, and Mehta and Wong. Experimental burn data collected by the University of Rochester study (Report No. 394), Stoll and USAARL using pigs, humans and pigs respectively were used to test the various models' ability to make accurate predictions over the entire range of burns from minor epidermal injury to complete dermal necrosis. Suggestions are made regarding the use of such models and fabric testing.

Knox, Francis S. III, Chester Ellis, Ransom Nockton. "Thermal Analysis Program: Computer Programs for Data Base Manipulation".

Twelve programs written primarily in FORTRAN IV are presented completed with source listings, comments and a brief user's manual. All of these programs have been run on a Digital Equipment Corporation PDP11/40 with 80K words of core. Programs include the following:

Program Name	Description
TAPE	Reads digitized data from tape and constructs named files for each channel of data.
MERGE	Reads data files PIG.DAT and PI.DAT on disk which have been previously read from cards and merges the two files into the data base; computes shutter corrections, normalized burn depths, group numbers, and converts temperatures to Centigrade.
SCANSEQ	Scans the sequence channel for the tapes read by program TAPE and creates a file of "events" and "cycles" for each tape to be used in locating data for a given pig.
PIGBOOK	1) Creates the pig directory PIG.DIR which locates pig data by tape, cycle number, and burn site. 2) Looks up data in the pig directory. 3) Lists the pig directory (sorted or unsorted) on the terminal or printer. 4) Edits and/or lists the event tables created by SCANSEQ. 5) Edits and/or lists the flux directory FLUX.DIR created by program FLUX. 6) Edits the data base. 7) Appends the data to the data base.
PIGWRT	Separates the digitized data for a given channel and cycle (burn) into files containing the data for a single event to be used by the data processing programs.
FLUX	Computes the flux seen by the slug calorimeter, using the files created by PIGWRT for calibration and data reduction.
TEMPFILE	Computes a temperature profile from the copper-constantan thermocouples to be used by the model program.
FURNACE	Computes the mean furnace wall temperatures seen by the Chromel-Alumel thermocouples.
PREDISC	Builds a file of values of variables selected by input to be used by the plotting program PLOTS or as input to the discriminant program.

Program Name	Description
DISCRM	Performs a linear regression analysis on data from the data base selected by program PREDISC.
PLOTS	Plots any variables in the PREDISC file vs. any other on either linear or log scales with the capability to parameterize the plot by a third variable using an input table of values and symbols.
LSTMRGD	Builds a formated file with labels of the data base to be printed by PIP (the system utility Peripheral Interchange Program).

Knox, F. S. III, and Charles Yuile. "Pitfalls in the Use of the USAARL Histopathology Grading System".

One hundred biopsy specimens from the USAARL bioassay study (USAARL Report 78-11) were reread with a view toward determining those aspects of the grading process where error and/or disagreement among the pathologists might arise. 400 biopsy specimens from the University of Rochester's studies as reported in UR Report 338 and 553 were prepared and read to ascertain whether the shrinkage seen in more severe burns in the USAARL study was also seen in the Univerity of Rochester studies so that shrinkage correction factors could be used to make the data more consistently predictable by mathematical models such as USAARL's BRNSIM.

Takata, Arthur N., John Rouss, Thomas Stanley, F. S. Knox III, and S. C. Knapp. "Thermal Analysis Program: Thermal Studies and Mathematical Model Development in Support of USAARL Experimental Studies".

The objective of this program is to develop means for using skin simulants to assess the thermal protection afforded human beings in accidental aviation-fuel fires by various candidate fabrics. In order to achieve this objective, USAARL (U. S. Army Aeromedical Research Laboratory) has exposed pigs and skin simulants (with and without fabrics) to aviation-fuel fires burning within a specially constructed furnace. Results were then used by IITRI (IIT Research Institute) to formulate a criterion of burn depth and a code to translate simulant temperature data into burn predictions.

Other supporting endeavors of note include: a determination of the effect of pig hairs in shielding the skin from radiation; a determination of the character of the heating i.e., radiation versus convection; a determination of the water content of pig tissue with respect to depth; and analytical studies indicating the importance of thermal properties, flux and exposure time on burns. Also computer codes have been prepared to place all experimental data on disk files for ready computer assess.

Saurmilch, Peter, F. S. Knox III. "User's Manual for the Burn Prediction Computer Model Developed by IITRI."

The model described in the form of a computer program which takes the output of a physical heat flux sensor and converts that measurement of heat flux to a prediction of skin damage. Included with this report are: 1) a description of model components, (2) development of background mathematics, (3) discussion of the FORTRAN statements and (4) the User's Manual. The burn prediction model is the first in a series of models based on the data collected using the USAARL fire simulation system and the porcine bioassay technique. It incorporates tissue water boiling but does not incorporate varying thermal parameters, cooling of the skin by blood and corrrection for thermal shrinkage observed in the experimental data.

Wachtel, Thomas L., Edward E. Wachtel, Francis S. Knox III, and Jerry M. Shuck. "The Prevention of Thermal Cutaneous Injury by Hair".

The protective or detrimental effects of scalp and facial hair (beards and mustaches) during thermal injuries has not been determined. We have used three separate approaches to study this problem.

In a rat model, half their flank hair was alternately clipped or not clipped. Three groups of four animals were exposed to a flame heat source for one, three or ten seconds. The burns were graded clinically and histologically. Exposure versus grade curves were plotted. Hair population and density calculations were made. The protective and detrimental effects of hair were determined in a retrospective review of 407 burn victims with 154 head and facial burns. A prospective study of twenty-five human burns was undertaken to determine more accurately the protective or detrimental effects of hair on the burned skin by observation, photographic record, hair style and hair population and density determinations. The thermal input necessary for decomposition and ignition of hair samples was determined. The thermal energy deposited into the hair is represented by the formula $I = I_0 \exp(-\alpha x)$ and the formula $2 \cdot \int_0^{\pi/2} \exp-(N \cdot \xi_1) \cdot \cos\theta \cdot \sin\theta \, d\theta$ describes the fraction of the incident radiation that will escape interception by the hairs. From the data and these formulae the protective effect of hair was determined mathematically.

Hair cover showed significant protection to the underlying skin in the rat model in both the gross clinical grading and the histological sections throughout the entire 10 second exposure curve. In the retrospective studies the scalp was protective in all cases except in the most severe incincerations. The scalp hair and facial hair were especially protective in flash exposures. The prospective study showed beards, mustaches, sideburns and scalp hair cover to be protective of the underlying skin in contrast to adjacent nude areas in all cases. Hair populations and density determinations varied widely, but theoretically and clinically hair protects the individual from burns.

APPENDIX C

BRNSIM 3 - LISTING OF THE INTERACTIVE ANALYTICAL MODEL BRNSIM

INPUTS:

TEMPIØ	=	Initial Surface Temp. °C
Density	=	Density of skin = 1.0
Q_I	=	Incident Heat Flux either constant or as a File of Fluxes
BL	=	Internode depth = 220μ
AK	=	Calculation interval nominally .01 sec.
JINC	=	Nodes nominally 12
TEMPB	=	Differences between TEMPIØ and backwall (fat/core) Temp. °C
Absorb	=	Absorptivity usually .613
Boil	=	Temperature when boiling occurs = 100.15 temperature °C
ETIME	=	Exposure Time in seconds
ITIME	=	Maximum calculation time usually 80-100 sec.
Nxtra	=	Number of extra nodes between the surface and node 1 at 220μm
Blood	=	Factor to adjust amount of cooling by blood usually set at .ØØ1
DE_1 & DE_2	=	$\Delta E/R$ from the Arrehemius relationship for tissue temperatures from 44 to 50°C or over 50°C respectively

PL_1, PLN, or PL_2 and PLN_2 = log P = logN + ylog10
= PL + PLN
again for temperatures from 44°C-50°C or over 50°C

Cp(J)	=	Heat capacity as a function of depth

OUTPUTS:

IPUTS

TITLE

Flux File I.D., if used

Flux (I) - tabulated Heat flux as a function of time

DAMAGE, W, at each Depth (Node)

Maximum Temperature

Threshold Depth in μm

Final Time - total calculation time

File of calculated temperatures for later plotting by TCPLOT

File summarizing simulation

File of temperature as printed each second on the terminal

```
      C
      C
      C     ******************** 12-POINT BURN PREDICTION MODEL ****************
      C
      C     PROGRAM PIGBRN            ! BURN PREDICTION MODEL WITH WATER BOILING
      C                               ! AND USE OF EITHER CONSTANT OR TABULATED FLUX
      C                               ! AND VARIABLE COOLING BY BLOOD FROM NODES 2 AND
      C                               ! 3 BEGINING AT .01 SEC AND LINEARLY INCREASING
      C                               ! TO 20 SEC AND THEN REMAINGING CONSTANT
      C......
      C
      C     THIS MODEL WAS DEVELOPED UNDER CONTRACT FOR THE U.S.ARMY
      C     MEDICAL RESEARCH AND DEVELOPMENT COMMAND, AND THE U.S.ARMY
      C     AEROMEDICAL RESEARCH LABORATORY, FORT RUCKER AL. 36362,
      C     STANLEY C. KNAPP, COL, MC, COMMANDING, BY FRANCIS S. KNOX,III,PH.D.
      C     WITH THE ASSISTANCE OF DANIEL D. RENEAU, PH.D., NELSON O'YOUNG,
      C     AND CHET ELLIS,M.S.
      C
      C
      C
      C     QUESTIONS AND COMMENTS SHOULD BE ADDRESSED TO:
      C
      C         FRANCIS S. KNOX,III, PH.D.
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      C         SHREVEPORT, LA. 71130
      C         (318)226-3134
      C
      C.....
0001        REAL*4 NOFIL,ITIME
0002        INTEGER BB
0003        LOGICAL*1 RESP,YES
      C.....
0004        DIMENSION T(12),F(12),G(12),H(12),Z(12),U(12),W(12)
0005        DIMENSION SV(12),CP(12,2),BK(12,2),D(12),DSCRPT(20)
0006        DIMENSION ID(4),FILNAM(5),FLUX(150),SUM(12),DW(12)
0007        DIMENSION IFLAG(12),Q(12),XTIME(12),ZTIME(12),JFLAG(12)
0008        DIMENSION WATER(12,2),DP(12,12),THCON(2),ROCON(2),CPCON(2)
0009        DIMENSION XW(8),XTRA(8),XTRALG(8),XTMP(8),XDW(8)
      C.....
0010        EQUIVALENCE (NOFIL,IBLNK)
      C
0011        DATA YES/'Y'/,NOFIL/'    '/
0012        DATA MAXDIM/12/,D2/200./
0013        DATA THCON/1.084316E-3,4.1568401E-4/
0014        DATA ROCON/6.1827743E-2,.93817226/
0015        DATA CPCON/.595,.405/
      C.....
      C     LOGICAL UNIT 1  INPUT : 'RENEAU12.DAT': TABLES
      C     LOGICAL UNIT 1 SCRATCH: 'XKRCH.TMP'; VALUES OF XDW (IF COMPUTED)
      C     LOGICAL UNIT 2 SCRATCH: 'SCRCH.TMP'; VALUES OF DW (COMPUTED)
      C     LOGICAL UNIT 3 OUTPUT : 'PIGBOIL.DAT': TEMPERATURE PROFILES
      C     LOGICAL UNIT 4  INPUT : FILNAM: NAME OF FLUX FILE
      C     LOGICAL UNIT 4 OUTPUT : 'PIGBOIL.PLT': DATA FOR PLOTTING TEMPERATURE
      C                   PROFILES
      C     LOGICAL UNIT 7 OUTPUT : DEFAULT 'FOR007.DAT': SUMMARY PRINTOUT
      C.....
```

```
C     ARITHMETIC FUNCTIONS FOR THERMAL CONDUCTIVITY (THKON) AND
C     DENSITY*HEAT CAPACITY
C
      THKON(Z) = (THCON(1)*Z+THCON(2))/(ROCON(1)*Z+ROCON(2))
      ROCP(Z) = (CPCON(1)*Z+CPCON(2))/(ROCON(1)*Z+ROCON(2))
C
      CALL ASSIGN(1,'RENEAU12.DAT')
      CALL ASSIGN(2,'SCRCH.TMP')
      CALL ASSIGN(3,'PIGBOIL.DAT')
C      SET UP PARAMETERS FOR THIS RUN
C.....
      READ(1,901)TEMPI0,DENS,Q0,BL,AK,BOIL,ABSORB
901     FORMAT(7F10.5)
      READ(1,902)JINC,TEMPB,ITIME,ETIME,PCWATR,BLOOD
902     FORMAT(1I10,7F10.5)
      READ(1,901)(CP(J,2),J=1,JINC)
      READ(1,901)(BK(J,2),J=1,JINC)
      READ(1,901)PL2,PLN2,PL1,PLN1,DE2,DE1
      READ(1,901)(WATER(I,2),I=1,JINC)
      CALL CLOSE(1)
      CALL ASSIGN(1,'XKRCH.TMP')
        FLUX(1) = Q0
      FLUX(2) = Q0
      NFLX = 2
      FILNAM(1) = NOFIL
      PPL1 = PL1
      PPLN1 = PLN1
      DDE1 = DE1
      NXTRA = 0
      NXTRA0 = 0
700   TYPE 910
      TYPE 911,TEMPI0,DENS,FLUX(1),BL,AK,JINC,TEMPB,ABSORB,BOIL
      TYPE 104,PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
      IF (NXTRA) TYPE 7003,(XTRA(I),I=1,NXTRA)
7003  FORMAT('0EXTRA NODES: ',8F6.1)
4       TYPE 906
906     FORMAT(1X,'CONTINUE ? Y/N',T15,$)
        ACCEPT 220,RESP
        IF(RESP.NE.YES) GO TO 290
5     CONTINUE
      TYPE 699
699   FORMAT('1FUNCTION #''S'/'01 - REENTER INITIAL VALUES'/
     1,' 2 - CHANGE SELECTED INITIAL VALUES'/' 3 - NO CHANGES'/
     2,' 4 - EXIT'//'$ENTER FUNCTION NO.:')
      ACCEPT 801,ANSR
      IANSR=ANSR
      TYPE 710 ,ANSR
710   FORMAT('0ANSR=',F10.0)
      BB = 0
      IF(IANSR.EQ.2)BB=1
      GO TO (20,80,230,1111)IANSR
20    TYPE 800,TEMPI0
800   FORMAT(//' PLEASE PROVIDE THE REQUESTED VALUES:'//
     1T5,'TEMPI0',G16.8,T15,$)
      ACCEPT 801,TEMPI0
801   FORMAT(F10.0)
      GO TO (200)BB
21    TYPE 802,DENS
```

```
802   FORMAT(/T5,'DENS',G16.8,T15,$)
      ACCEPT 801,DENS
      GO TO (200)BB
22    TYPE 1
1     FORMAT(/'$FLUX FILE NAME (BLANK IF CONSTANT FLUX): ')
      ACCEPT 2,FILNAM
2     FORMAT(5A4)
      IF (FILNAM(1).EQ.NOFIL) GO TO 799
      CALL ASSIGN(4,FILNAM)
      READ(4)ID,TDELT,NFLX
      TYPE 3,ID,TDELT,NFLX
      READ(4)(FLUX(I),I=1,NFLX)
      CALL CLOSE (4)
      GO TO (200)BB
      GO TO 23
799   TYPE 788,FLUX(1)
788   FORMAT(/'$CONSTANT Q-VALUE = ',G16.8,'NOW, IT SHOULD BE Q = ')
      ACCEPT 801,FLUX(1)
      FLUX(2)=FLUX(1)
      NFLX = 2
      DO 777 I=1,4
777   ID(I) = IBLNK
      GO TO (200)BB
23    TYPE 804,BL
804   FORMAT(/T5,'BL',G16.8,T15,$)
      ACCEPT 801,BL
      GO TO (200)BB
24    TYPE 805,AK
805   FORMAT(/T5,'AK',G16.8,T15,$)
      ACCEPT 801,AK
      GO TO (200)BB
25    TYPE 806,JINC
806   FORMAT(/T5,'JINC',I10,T15,$)
      ACCEPT 820,JINC
      IF (JINC.GT.MAXDIM) JINC=MAXDIM
      GO TO (200)BB
820   FORMAT(I10)
26    TYPE 807,TEMPB
807   FORMAT (/T5,'TEMPB',F10.0,T15,$)
      ACCEPT 801,TEMPB
      GO TO (200)BB
27    TYPE 808,ETIME
808   FORMAT(/T5,'ETIME',G16.8,T15,$)
      ACCEPT 801,ETIME
      GO TO (200)BB
28    TYPE 809,PL1
809   FORMAT(/T5,'PL1',G16.8,T15,$)
      ACCEPT 801,PL1
      PPL1=PL1
      GO TO (200)BB
29    TYPE810,PLN1
810   FORMAT(/T5,'PLN1',G16.8,T15,$)
      ACCEPT 801,PLN1
      PPLN1=PLN1
      GO TO (200)BB
30    TYPE 811,PL2
811   FORMAT(/T5,'PL2',G16.8,T15,$)
      ACCEPT  801,PL2
```

```
      GO TO (200)BB
31    TYPE 812,PLN2
812   FORMAT(/T5,'PLN2',G16.8,T15,$)
      ACCEPT 801,PLN2
      GO TO (200)BB
32    TYPE 813,DE1
813   FORMAT(/T5,'DE1',G16.8,T15,$)
      ACCEPT 801,DE1
      DDE1=DE1
      GO TO (200)BB
33    TYPE 814,DE2
814   FORMAT(/T5,'DE2',G16.8,T15,$)
      ACCEPT 801,DE2
      GO TO (200)BB
34    TYPE 815,ITIME
815     FORMAT(/T5,'ITIME',G16.8,T15,$)
      ACCEPT 801,ITIME
      GO TO (200)BB
35    TYPE 816,ABSORB
816   FORMAT(/T5,'ABSORB',G16.8,T15,$)
      ACCEPT 801,ABSORB
      GO TO (200)BB
36    TYPE 817,BOIL
817   FORMAT(/T5,'BOIL',G16.8,T15,$)
      ACCEPT 801,BOIL
      GO TO (200) BB
7100  TYPE 7005,NXTRA
      NXTRA0 = NXTRA
7005  FORMAT(/T5,'NO. OF EXTRA NODES ',I4,2X,$)
      ACCEPT 7007,NXTRA
7007  FORMAT(I4)
      IF (NXTRA.EQ.0) GO TO 7230
      IF (NXTRA.GT.8) NXTRA=8
      IF (NXTRA0) TYPE 7009,(XTRA(I),I=1,NXTRA0)
7009  FORMAT('0CURRENT: ',8F6.1)
      TYPE 7011
7011  FORMAT('0ENTER NEW VALUES SEPARATED BY COMMAS, OR <CR> IF PROGRAM'
     1/' IS TO CALCULATE VALUES:')
      ACCEPT 7013,XTRA
7013  FORMAT(8F8.1)
      IF (XTRA(1)) GO TO 7210
C
C NUMERATOR IN NEXT STATEMENT IS SPECIFIC FOR N-POINT MODEL
C
      DXTRA = D2/(NXTRA+1)
      DO 7200 I=1,NXTRA
7200  XTRA(I)  = DXTRA*I
7210  DO 7220 I=1,NXTRA
7220  XTRALG(I) = ALOG(XTRA(I))
7230  CONTINUE
      NXTRA0 = NXTRA
      GO TO (200)BB
37    TYPE 818,BLOOD
818   FORMAT(/'$ BLOOD = ',F10.4,3X)
      ACCEPT 801,BLOOD
      GO TO 200
80    TYPE 600
600   FORMAT(/T5,'PICK A NUMBER',//T10,'1=TEMP10',T30,'8=ETIME',//
```

```
         1T10,'2=DENS',T30,'9=PL1',/T10,'3=Q1',T30,'10=PLN1',//
         1T10,'4=BL',T30,'11=PL2',/T10,'5=AK',T30,'12=PLN2',//
         1T10,'6=JINC',T30,'13=DE1',/T10,'7=TEMPB',T30,'14=DE2',//
         1T10,'15=ITIME',T30,'16=ABSORBTIVITY'/
         1T10,'17=BOIL',T30,'18=EXTRA NODES'/T10,'19=BLOOD',T30//)
          BB=1
          ACCEPT 601,INUM
    601   FORMAT(I2)
          GO TO (20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36
         1,7100,37)INUM
    C
    C     ANOTHER VALUE?
    C
    200   TYPE 210
    210   FORMAT(/'$ANOTHER CHANGE ? TYPE Y/N')
          ACCEPT 220,RESP
    220   FORMAT(A1)
          IF(RESP.EQ.YES)GO TO 80
          GO TO 700
    230      REWIND 1
          TYPE 907
    907   FORMAT('0ENTER MODEL NAME OR DESCRIPTION (80 CHARACTERS)')
          ACCEPT 908,DSCRPT
    908   FORMAT(20A4)
          WRITE(3,909)DSCRPT
          WRITE(7, 909)DSCRPT
    909   FORMAT(' MODEL NAME OR DESCRIPTION: ',20A4)
    C
    C ASSIGN LOGICAL UNIT 4 FOR PLOT OUTPUT
    C
          CALL ASSIGN(4,'PIGBOIL.PLT')
          WRITE(4)DSCRPT
          AJ=JINC
          Q1 = FLUX(1)
          H1=BL/(AJ-1.0)
    C
    C     INITIALIZE DEPTH NODES D(J)
    C
          D(1) = -16.
           DO 106 I=2,JINC
          D(I) = H1*(I-1)*1.E4
    106      D(I) = ALOG(D(I))
          DTJ = TEMPB/(JINC-1)
          DO6J=1,JINC
          WATER(J,1) = WATER(J,2)
          CP(J,1) = CP(J,2)
          BK(J,1) = BK(J,2)
          XTIME(J) =0.
          ZTIME(J) =0.
          IFLAG(J) =0.
          JFLAG(J) =0.
    6     T(J) = DTJ*(J-1)+TEMPI0
          WRITE(4)0.,(T(J),J=1,JINC)
          WRITE(3,910)
          WRITE(7, 910)
      910 FORMAT(1H0,55X,'SKIN DIFFUSION DATA'/,55X,'INPUT PARAMETER LIST'/)
          WRITE(3,911)TEMPI0,DENS,Q1,BL,AK,JINC,TEMPB,ABSORB,BOIL
          WRITE(7, 911)TEMPI0,DENS,Q1,BL,AK,JINC,TEMPB,ABSORB,BOIL
```

```
      911 FORMAT(1X,52X,8H TEMP10=,G14.6/54X,5HDENS=,G14.6/54X,3HQ1=,G14.6/
         154X,3HBL=,G14.6/54X,3HAK=,G14.6/54X,5HJINC=,I6/54X,6HTEMPB=,F8.4/
         154X,'ABSORB=',G14.6/54X,'BOIL=',G14.6/)
          WRITE(3,104)PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
          IF (NXTRA) WRITE(3,7003)(XTRA(I),I=1,NXTRA)
          WRITE(7, 104)PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
          IF (NXTRA) WRITE(7,7003)(XTRA(I),I=1,NXTRA)
      104 FORMAT(1X,53X,'PL2=',F10.2/54X,'PLN2=',F10.2/54X,'PL1=',F10.2/
         154X,'PLN1=',F10.2/54X,'DE2=',F10.2/54X,'DE1=',F10.2/
         154X,'ETIME=',F10.2/54X,'ITIME=',F10.2/54X,'NXTRA=',I4/54X
         1,'BLOOD=',F10.4)
          WRITE(3,3)ID,TDELT,NFLX,(I,FLUX(I),I=1,NFLX)
          WRITE(7, 3)ID,TDELT,NFLX,(I,FLUX(I),I=1,NFLX)
    3     FORMAT('0FLUX FILE I.D.: ',4A2,F7.2,I4://' FLUX(I)='
         1/(' ',10(I5,F8.3)))
          JJJJ=0
          F(1)=-BK(2,1)/(2.0*H1*H1)-BK(1,1)/(2.0*H1*H1)
          G(1) = (BK(1,1)+BK(2,1))/(2.0*H1*H1)+DENS*CP(1,1)/AK
          H(1)=0.0
          ITTR = 0
          IFLX = 1
          EITIM1 = ITIME+1.
          IF (FILNAM(1).EQ.NOFIL) TDELT=AK
          FFDG = TDELT/AK
          KFDG = FFDG+.0001
          TMPMAX = 0.
          QCONST = ABSORB*60.892
          BLUD = 0.
          M = -1
          TIME = 0.
          ITFLG = 0
          GO TO 12
C
C STATEMENT 11 AUTOMATICALLY CHOOSES PROPER INTERVAL IN FLUX TABLE
C FOR COMPUTATION OF QT AND Q1 FOR EITHER CONSTANT OR VARIABLE
C FLUX.
C
C KFDG (=FFDG) = 1 FOR CONSTANT FLUX
C              = [RATIO] OF TABULAR TIME STEP TO MODEL TIME STEP FOR
C           TABULATED FLUX
C           [...] MEANS INTEGER VALUE OF....
C
   11     IF (MOD(ITTR,KFDG).EQ.0.AND.IFLX.LT.NFLX) IFLX=IFLX+1
          ITTR = ITTR+1
          P = (ITTR-KFDG*(IFLX-2))/FFDG
          QT = (1.-P)*FLUX(IFLX-1)+P*FLUX(IFLX)
          Q1 = QT*QCONST
          JJJJ = JJJJ+1
          TIME=JJJJ*AK
          IF (TIME.GE..01.AND.TIME.LE.20.) BLUD=(TIME-.01)/19.99*BLOOD
C
C VALUE 23.9 IS QUESTIONABLE  SHOULD BE STUDIED (RESOLVED)
C
          IF(TIME.GE.ETIME) Q1=-5.E-4*(T(1)-23.9)
          Z(1)=-F(1)*T(2)-((BK(1,1)+BK(2,1))/(2.0*H1*H1)-(DENS*CP(1,1))/AK)
         1*T(1)+Q1
          N=JINC-1
          DO10J=2,N
```

```
        F(J)=-BK(J+1,1)/(2.0*H1*H1)
        G(J)=(BK(J,1)+BK(J+1,1))/(2.0*H1*H1)+DENS*CP(J,1)/AK
        H(J)=-BK(J,1)/(2.0*H1*H1)
        Z(J)=-F(J)*T(J+1)-((BK(J,1)+BK(J+1,1))/(2.*H1*H1)-DENS*CP(J,1)
       1/AK)*T(J)-H(J)*T(J-1)
        IF (J.GT.3) GO TO 10
        Z(J) = Z(J)-1.675*H1/BK(J,1)*BLUD*(T(J)-TEMP10+TEMPB)
10      CONTINUE
        F(JINC)=0.0
        G(JINC)=(BK(JINC,1)+BK(JINC-1,1))/(2.0*H1*H1)+DENS*CP(JINC,1)/AK
        H(JINC)=-(BK(JINC,1)+BK(JINC-1,1))/(2.0*H1*H1)
        DT=T(JINC-1)-(TEMP10+TEMPB)
        Z(JINC)=(H(JINC)+(DENS*CP(JINC,1)/AK))*T(JINC)
       1-H(JINC)*T(JINC-1)-BK(JINC,1)*DT/H1**2
        W(1)=G(1)
        U(1)=Z(1)/W(1)
        DO40J=2,JINC
        JM1=J-1
        SV(JM1)=F(JM1)/W(JM1)
        W(J)=G(J)-H(J)*SV(JM1)
     40 U(J)=(Z(J)-H(J)*U(JM1))/W(J)
        T(JINC)=U(JINC)
        KK=JINC-1
        DO50J=1,KK
        KMJ=JINC-J
        IF (IFLAG(KMJ).EQ.1) GO TO 203
        T(KMJ)=U(KMJ)-SV(KMJ)*T(KMJ+1)
        IF (JFLAG(KMJ).EQ.1) GO TO 50
        IF (T(KMJ).LT.BOIL) GO TO 50
        T(KMJ) = BOIL
        IF (KMJ.EQ.1) GO TO 109
        Q(KMJ) = BK(KMJ,1)*(T(KMJ)-T(KMJ+1))/H1
        GO TO 205
109     Q(KMJ) = QT
205     XTIME(KMJ) = 539.*H1/Q(KMJ)*WATER(KMJ,1)
        ZTIME(KMJ) = XTIME(KMJ)+TIME
        IFLAG(KMJ) = 1
        GO TO 50
203     IF (TIME.LT.ZTIME(KMJ)) GO TO 50
        WATER(KMJ,1) = PCWATR
        CP(KMJ,1) = ROCP(WATER(KMJ,1))
        BK(KMJ,1) = THKON(WATER(KMJ,1))
        IFLAG(KMJ) = 0
        XTIME(KMJ) = 0.
        JFLAG(KMJ) = 1
50      CONTINUE
C
C INTERPOLATE EXTRA TEMPERATURES BETWEEN SURFACE AND 2ND NODE IF CALLED FOR
C
        IF (NXTRA.EQ.0) GO TO 7360
        IF (T(2).NE.T(1)) GO TO 7320
C
C CONSTANT TEMPERATURE
C
        DO 7310 I=1,NXTRA
7310    XTMP(I) = T(2)
        GO TO 7360
7320    IF (T(2).NE.T(3))GO TO 7340
```

```
C
C LINEAR INTERPOLATION
C
            DO 7330 I=1,NXTRA
            P = XTRA(I)/D2                    !D(1) = 0.
      7330  XTMP(I) = (1.-P)*T(1)+P*T(2)
            GO TO 7360
C
C 3-POINT LAGRANGE INTERPOLATION FOR EQUALLY SPACED ABSCISSAE
C
      7340  DO 7350 I=1,NXTRA
            P = (XTRA(I)-D2)/D2               !D(1) = 0. (SURFACE)
      7350  XTMP(I) = .5*P*(P-1.)*T(1)+(1.-P**2)*T(2)+.5*P*(P+1.)*T(3)
      7360  CONTINUE
            IF (ABS(ETIME-TIME).GT..5*AK) GO TO 48
            DO 44 I=1,JINC
            IF (IFLAG(I).EQ.0) GO TO 44
            WATER(I,1) = (ZTIME(I)-TIME)/XTIME(I)*(WATER(I,1)-PCWATR)+PCWATR
            CP(I,1) = ROCP(WATER(I,1))
            BK(I,1) = THKON(WATER(I,1))
      44    CONTINUE
            DO 45 I=1,JINC
            XTIME(I) = 0.
            IFLAG(I) = 0
      45    JFLAG(I) =1
      48    CONTINUE
            IF (T(1).GT.TMPMAX) TMPMAX=T(1)
            ITFLG = -1  !ITFLG SET TO 0 IF ANY TEMPERATURE .GE. 44 DEGREES
            DO 13 J=1,JINC
            IF (T(J).GE.44.) GO TO 14
            DW(J) = 0.
            GO TO 13
      14    CONTINUE
            ITFLG = 0
            IF(T(J).GE.50.) GO TO 51
            PL1 = PPL1
            PLN1 = PPLN1
            DE1 = DDE1
            GO TO 15
      51      PL1=PL2
            PLN1=PLN2
            DE1=DE2
      15    DWLN=PL1+PLN1-DE1/(T(J)+273.)
            DW(J) = EXP(DWLN)
      13    CONTINUE
            WRITE(2)DW
            IF (NXTRA.EQ.0) GO TO 7400
            DO 7395 J=1,NXTRA
            IF (XTMP(J).GE.44.) GO TO 7370
            XDW(J) = 0.
            GO TO 7395
      7370  IF (XTMP(J).GE.50.) GO TO 7380
            PL1 = PPL1
            PLN1 = PPLN1
            DE1 = DDE1
            GO TO 7390
      7380  PL1 = PL2
            PLN1 = PLN2
```

```
            DE1 = DE2
      7390  DWLN = PL1+PLN1-DE1/(XTMP(J)+273.)
            XDW(J) = EXP(DWLN)
      7395  CONTINUE
            WRITE(1)XDW
      7400  CONTINUE
            EMTIME = AINT(1000.*(TIME+.00001))/100.
            IF (TIME.LT.10..AND.AMOD(EMTIME,1.).EQ.0..OR.TIME.GE.10..AND.
           1 AMOD(EMTIME,10.).EQ.0.) WRITE(4)TIME,T
            IF (ITFLG.AND.TIME.GE.ETIME) GO TO 12
            IF(JJJJ.EQ.M*100.OR.JJJJ.EQ.1) GO TO 12
            GO TO 11
         12 WRITE(3,840)TIME
            TYPE 840,TIME,(T(I),XTIME(I),I=1,JINC)
        840 FORMAT('0',45X,5HTIME=,F10.6:,T4,'T= ',6X,'XTIME='/(' ',2G12.4))
            WRITE(3,842)(XTIME(I),I=1,JINC)
      842   FORMAT(2X,'XTIME=',F10.5)
            WRITE(3,914)T(1),CP(1,1),BK(1,1)
            IF (NXTRA.EQ.0) GO TO 7420
            DO 7410 J=1,NXTRA
      7410  WRITE(3,914)XTMP(J)
      7420  WRITE(3,914)(T(J),CP(J,1),BK(J,1),J=2,JINC)
        914 FORMAT(2X,'T=',G16.5:,2X,'CP=',G16.5,2X,'BK=',G16.5)
            M=M+1
            EM = M
            IF(TIME.GE.ITIME.OR.ITFLG.AND.TIME.GE.ETIME) GO TO 100
            GO TO 11
      100   CONTINUE
            REWIND 2
            READ(2)DW
            DO 17 I=1,JINC
      17    SUM(I) = .5*DW(I)
            DO 16 J=2,JJJJ-1
            READ(2)DW
            DO 16 I=1,JINC
      16    SUM(I)=SUM(I)+DW(I)
            READ(2)DW
            DO 88 I=1,JINC
      88    W(I) = (SUM(I)+.5*DW(I))*AK
            REWIND 2
            IF (NXTRA.EQ.0) GO.TO 7460
            REWIND 1
            READ(1)XDW
            DO 7430 J=1,NXTRA
      7430  SUM(J) = .5*DW(J)
            DO 7440 I=2,JJJJ-1
            READ(1)XDW
            DO 7440 J=1,NXTRA
      7440  SUM(J) = SUM(J)+XDW(J)
            READ(1)XDW
            DO 7450 J=1,NXTRA
      7450  XW(J) = (SUM(J)+.5*XDW(J))*AK
            REWIND 1
      7460  CONTINUE
      C
      C       SELECT W(J) AND D(J) NEAR W(J) =1
              NN = 3
              DO 110 J=1,JINC
```

```
            JLT1 = J
            IF(W(J).GT.1.)GO TO 110
            IF(W(J).EQ.1.)GO TO 111
            IF (J.EQ.1) JLT1=2
            IF (J.EQ.JINC) JLT1=JINC-1
            GO TO 112
      110     CONTINUE
            JLT1 = JINC              ! EXTRAPOLATE
            NN = 2
      112   WRITE(3,120)(W(K),K=JLT1-1,JLT1+1)
           WRITE(7, 120)(W(K),K=JLT1-1,JLT1+1)
      120   FORMAT(/(1X,'W=',E20.5))
            WRITE(3,121)(D(K),K=JLT1-1,JLT1+1)
           WRITE(7, 121)(D(K),K=JLT1-1,JLT1+1)
      121   FORMAT(/(1X,'D=',E20.5))
           IF (NXTRA0.EQ.0.OR.JLT1.GT.2) GO TO 1005
           TYPE 7015
     7015  FORMAT('0W=1 LIES ABOVE NODE 2.  INTERCOLLATING VALUES OF D AND W'/
          1.' COMPUTED FROM INTERPOLATED VALUES OF D AND TEMPERATURE'/)
           WRITE(3,7015)
           WRITE(7,7015)
           WRITE(1)D(1)
           WRITE(2)W(1)
           DO 7470 J=1,NXTRA
           WRITE(1)XTRALG(J)
     7470  WRITE(2)XW(J)
           DO 7480 J=2,JINC
           WRITE(1)D(J)
     7480  WRITE(2)W(J)
           REWIND 1
           REWIND 2
           DO 7490 J=1,JINC
           READ(1)D(J)
     7490  READ(2)W(J)
           REWIND 1
           REWIND 2
           NXTRA0 = 0
           GO TO 7460
     1005  CONTINUE
           NXTRA0 = NXTRA
           IF (W(JLT1+1).EQ.0..AND.NN.EQ.3) NN=2
           CALL DEPTH(D(JLT1-1),W(JLT1-1),NN,TD,IERR)
           IF (IERR.EQ.0) GO TO 102
           TYPE 1002
           WRITE(3,1002)
           WRITE(7,1002)
     1002  FORMAT('0ERROR IN SUBROUTINE "DEPTH". EXITING.'/)
           GO TO 290
      102  CONTINUE
            IF (NN.EQ.2.AND.JLT1.EQ.JINC) GO TO 1000
            GO TO 1020
      111   TD=EXP(D(J))
      999   FORMAT(/,1X,'THRESHOLD DEPTH = ',G20.4)
            GO TO 1020
     1000   WRITE(3,1001)MAXDIM
           WRITE(7, 1001)MAXDIM
     1001  FORMAT(/1X,'THE MODEL BLEW UP: DAMAGE > 1 AT NODE ',I2/)
     1020   WRITE(3,101)(W(I),I=1,JINC)
```

```
0519          WRITE(7,2010)(W(I),EXP(D(I)),I=1,JINC)
0520     101   FORMAT(/(1X,'W=',E20.5))
0521    2010    FORMAT(/(1X,'W =',E20.5,5X,'AT DEPTH (IN MICRONS)=',G20.6))
0522           WRITE(3,103)TMPMAX
0523          WRITE(7, 103)TMPMAX
0524          WRITE(3,999)TD
0525          WRITE(7,999)TD
0526          WRITE(3,1021)TIME
0527          WRITE(7,1021)TIME
0528    1021  FORMAT(/,1X,'FINAL TIME = ',F7.2)
0529    103    FORMAT('0MAXIMUM TEMPERATURE = ',F8.3)
0530           TYPE 999,TD
0531           TYPE 103,TMPMAX
0532          TYPE 1021,TIME
        C
0533          CALL CLOSE (4)
        C
0534    290    TYPE300
0535    300    FORMAT(/'$DO YOU WANT ANOTHER RUN ? TYPE Y/N')
0536          WRITE(3,98)
0537          WRITE(7, 98)
0538    98    FORMAT('1')
0539           ACCEPT 220,RESP
0540           IF (RESP.EQ.YES) GO TO 700
0542    1111  CONTINUE
0543          IOER = 0
0544          CALL DELEET(1,IOER)
0545          CALL DELEET(2,IOER)
0546          IF (IOER) TYPE 1112
0548    1112  FORMAT('0ERROR IN DELETING FILE(S) ''SCRCH.TMP'' OR'
             1,' '')XKRCH.TMP''')
0549           TYPE 99
0550    99     FORMAT('1',T20,'PRINTED OUTPUT IN FILE ''PIGBOIL.DAT'''/T29,
             1'USE  "PIP" TO PRINT')
0551           WRITE(5,1050)
0552    1050   FORMAT('0',T20,'TEMPERATURES FOR PLOT IN ''PIGBOIL.PLT'''/T29,
             1'USE TCPLOT AND THEN [7,11]BASM TO PLOT')
0553          TYPE 1051
0554    1051  FORMAT('0',T20,'SUMMARY PRINTOUT IN FILE FOR007.DAT'/
             1' ',T27,'USE PIP TO PRINT'/)
0555           CALL EXIT
0556           END
```

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES	
T	000006	REAL*4	ARRAY (12)
F	000066	REAL*4	ARRAY (12)
G	000146	REAL*4	ARRAY (12)
H	000226	REAL*4	ARRAY (12)
Z	000306	REAL*4	ARRAY (12)
U	000366	REAL*4	ARRAY (12)
W	000446	REAL*4	ARRAY (12)
SV	000526	REAL*4	ARRAY (12)
CP	000606	REAL*4	ARRAY (12,2) VECTORED
BK	000746	REAL*4	ARRAY (12,2) VECTORED
D	001106	REAL*4	ARRAY (12)
DSCRPT	001166	REAL*4	ARRAY (20)
ID	001306	INTEGER*2	ARRAY (4)
FILNAM	001316	REAL*4	ARRAY (5)
FLUX	001342	REAL*4	ARRAY (150)
SUM	002472	REAL*4	ARRAY (12)
DW	002552	REAL*4	ARRAY (12)
IFLAG	002632	INTEGER*2	ARRAY (12)
Q	002662	REAL*4	ARRAY (12)
XTIME	002742	REAL*4	ARRAY (12)
ZTIME	003022	REAL*4	ARRAY (12)
JFLAG	003102	INTEGER*2	ARRAY (12)
WATER	003132	REAL*4	ARRAY (12,2) VECTORED
DP	003272	REAL*4	ARRAY (12,12) VECTORED
THCON	004372	REAL*4	ARRAY (2)
ROCON	004402	REAL*4	ARRAY (2)
CPCON	004412	REAL*4	ARRAY (2)
XW	004422	REAL*4	ARRAY (8)
XTRA	004462	REAL*4	ARRAY (8)
XTRALG	004522	REAL*4	ARRAY (8)
XTMP	004562	REAL*4	ARRAY (8)
XDW	004622	REAL*4	ARRAY (8)
NOFIL	004662	REAL*4	VARIABLE
ITIME	011534	REAL*4	VARIABLE
BB	011540	INTEGER*2	VARIABLE
RESP	011542	LOGICAL*1	VARIABLE
YES	004666	LOGICAL*1	VARIABLE
IBLNK	004662	INTEGER*2	VARIABLE
MAXDIM	004670	INTEGER*2	VARIABLE
D2	004672	REAL*4	VARIABLE
THKON	011400	REAL*4	PROCEDURE
ROCP	011362	REAL*4	PROCEDURE
ASSIGN	000000	REAL*4	PROCEDURE
TEMP10	011544	REAL*4	VARIABLE
DENS	011550	REAL*4	VARIABLE
Q0	011554	REAL*4	VARIABLE
BL	011560	REAL*4	VARIABLE
AK	011564	REAL*4	VARIABLE
BOIL	011570	REAL*4	VARIABLE
ABSORB	011574	REAL*4	VARIABLE
JINC	011600	INTEGER*2	VARIABLE
TEMPB	011602	REAL*4	VARIABLE
ETIME	011606	REAL*4	VARIABLE
PCWATR	011612	REAL*4	VARIABLE
BLOOD	011616	REAL*4	VARIABLE
J	011622	INTEGER*2	VARIABLE

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES	
PL2	011624	REAL*4	VARIABLE
PLN2	011630	REAL*4	VARIABLE
PL1	011634	REAL*4	VARIABLE
PLN1	011640	REAL*4	VARIABLE
DE2	011644	REAL*4	VARIABLE
DE1	011650	REAL*4	VARIABLE
I	011654	INTEGER*2	VARIABLE
CLOSE	000000	REAL*4	PROCEDURE
NFLX	011656	INTEGER*2	VARIABLE
PPL1	011660	REAL*4	VARIABLE
PPLN1	011664	REAL*4	VARIABLE
DDE1	011670	REAL*4	VARIABLE
NXTRA	011674	INTEGER*2	VARIABLE
NXTRA0	011676	INTEGER*2	VARIABLE
ANSR	011700	REAL*4	VARIABLE
IANSR	011704	INTEGER*2	VARIABLE
TDELT	011706	REAL*4	VARIABLE
DXTRA	011712	REAL*4	VARIABLE
ALOG	000000	REAL*4	PROCEDURE
INUM	011716	INTEGER*2	VARIABLE
AJ	011720	REAL*4	VARIABLE
Q1	011724	REAL*4	VARIABLE
H1	011730	REAL*4	VARIABLE
DTJ	011734	REAL*4	VARIABLE
JJJJ	011740	INTEGER*2	VARIABLE
ITTR	011742	INTEGER*2	VARIABLE
IFLX	011744	INTEGER*2	VARIABLE
EITIM1	011746	REAL*4	VARIABLE
FFDG	011752	REAL*4	VARIABLE
KFDG	011756	INTEGER*2	VARIABLE
TMPMAX	011760	REAL*4	VARIABLE
QCONST	011764	REAL*4	VARIABLE
BLUD	011770	REAL*4	VARIABLE
M	011774	INTEGER*2	VARIABLE
TIME	011776	REAL*4	VARIABLE
ITFLG	012002	INTEGER*2	VARIABLE
MOD	000000	INTEGER*2	PROCEDURE
P	012004	REAL*4	VARIABLE
QT	012010	REAL*4	VARIABLE
N	012014	INTEGER*2	VARIABLE
DT	012016	REAL*4	VARIABLE
JM1	012022	INTEGER*2	VARIABLE
KK	012024	INTEGER*2	VARIABLE
KMJ	012026	INTEGER*2	VARIABLE
ABS	000000	REAL*4	PROCEDURE
DWLN	012030	REAL*4	VARIABLE
EXP	000000	REAL*4	PROCEDURE
EMTIME	012034	REAL*4	VARIABLE
AINT	000000	REAL*4	PROCEDURE
AMOD	000000	REAL*4	PROCEDURE
EM	012040	REAL*4	VARIABLE
NN	012044	INTEGER*2	VARIABLE
JLT1	012046	INTEGER*2	VARIABLE
K	012050	INTEGER*2	VARIABLE
DEPTH	000000	REAL*4	PROCEDURE
TD	012052	REAL*4	VARIABLE

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES	
IERR	012056	INTEGER*2	VARIABLE
IOER	012060	INTEGER*2	VARIABLE
DELEET	000000	REAL*4	PROCEDURE
EXIT	000000	REAL*4	PROCEDURE

```
FORTRAN IV      V01C-03D        FRI 20-APR-79 10:21:01          PAGE 001
CORE=13K, UIC=[120,7]                        MODEL3,MODEL3=MODEL3.FTN;3

0001            SUBROUTINE DEPTH(X,Y,N,TD,IERR)
          C
          C     INVERSE INTERPOLATION ON TWO OR THREE POINTS TO DETERMINE
          C     THRESHOLD DEPTH (PREDICTED BURN DEPTH) USING EITHER
          C     Y OR LOG(Y)
          C
0002            DIMENSION X(1),Y(1),Z(3)
          C
0003            IERR = 0
0004            IF (N.LT.2) GO TO 999
0006            DO 100 I=1,N
0007      100   Z(I) = Y(I)
0008            Z0 = 1.
0009            IF (Z(1).EQ.0..OR.Z(2).EQ.0.) GO TO 140      !USE LOGARITHMS?
0011            IF (N.EQ.3.AND.Z(3).EQ.0.) GO TO 140
0013            IF (N.EQ.2) GO TO 140
0015            Z0 = 0.               !USE LOGARITHMS
0016            DO 120 I=1,N
0017      120   Z(I) = ALOG(Z(I))
0018      140   H0 = Z(2)-Z(1)
0019            IF (H0.EQ.0.) GO TO 999
0021            IF (N.EQ.2) GO TO 160
0023            H1 = Z(3)-Z(2)
0024            IF (H1.EQ.0.) GO TO 999
0026            H2 = Z(3)-Z(1)
0027            IF (H2.EQ.0.) GO TO 999
0029            DZ3 = Z0-Z(3)
0030      160   DZ2 = Z0-Z(2)
0031            DZ1 = Z0-Z(1)
0032            IF (N.EQ.2) GO TO 180
0034            TD = DZ1*DZ2*X(3)/(H1*H2)-DZ1*X(2)*DZ3/(H0*H1)+X(1)*DZ2*DZ3/
               1(H0*H2)
0035            GO TO 200
0036      180   TD = (DZ1*X(2)-X(1)*DZ2)/H0
0037      200   TD = EXP(TD)
0038            RETURN
0039      999   IERR = -1
0040            RETURN
0041            END
```

FORTRAN IV STORAGE MAP

NAME	OFFSET	ATTRIBUTES	
X	000014	REAL*4	PARAMETER ARRAY (1)
Y	000016	REAL*4	PARAMETER ARRAY (1)
Z	000026	REAL*4	ARRAY (3)
N	000020	INTEGER*2	PARAMETER VARIABLE
TD	000022	REAL*4	PARAMETER VARIABLE
IERR	000024	INTEGER*2	PARAMETER VARIABLE
I	000042	INTEGER*2	VARIABLE
Z0	000044	REAL*4	VARIABLE
ALOG	000000	REAL*4	PROCEDURE
H0	000050	REAL*4	VARIABLE
H1	000054	REAL*4	VARIABLE
H2	000060	REAL*4	VARIABLE
DZ3	000064	REAL*4	VARIABLE
DZ2	000070	REAL*4	VARIABLE
DZ1	000074	REAL*4	VARIABLE
EXP	000000	REAL*4	PROCEDURE

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