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

FINAL REPORT

BY

Francis S. Knox III, Ph.D.

June 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) 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			

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 procured, maintained and used in accordance with the Animal Welfare Act of 1970 and AR 70-18. The investigators adhered 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.

The author publicly extends his thanks to his colleagues Thomas L. Wachtel, M.D., George McCahan, D.V.M., and Stanley C. Knapp, M.D., to his consultants Charles Yuile, M.D., Daniel D. Reneau, Ph.D., George McCormick, M.D. and Pat Duffy, M.D., and his assistants Peter Sauermilch, B.S., Ransom Nockton, M.S. and Chester Ellis, M.S., and the staff of USAARL for their many and varied contributions.

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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, 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 ITRI (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 200 μ m, 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 base¹. 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

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

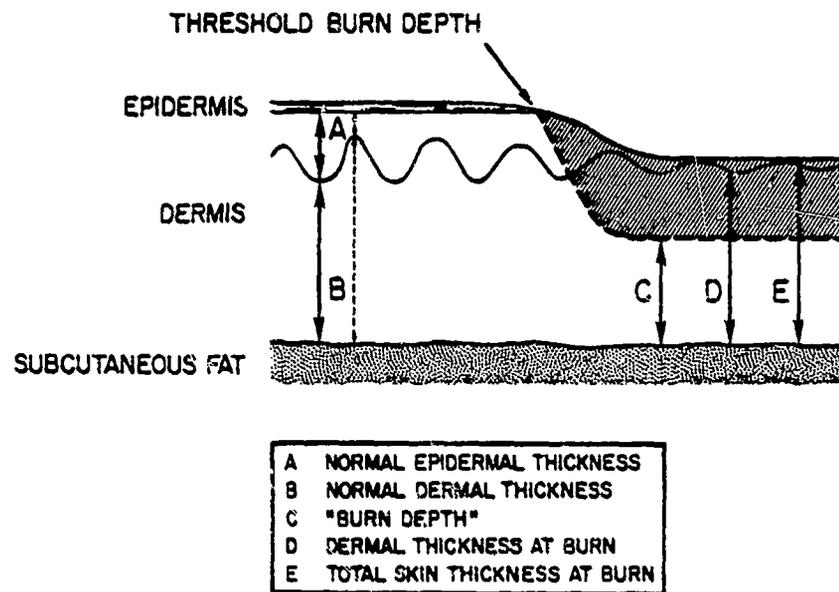


Figure 1. Schematic Diagram of Porcine Skin Showing Location of Measurements A through E recorded for each biopsy specimen.

TABLE 1
HISTOPATHOLOGICAL AND BURN DEPTH GRADING DEFINITIONS

Grade	Description	Approximate Depth (μm)		
		Nominal Range	Mid-Range	Mean Normalized 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: SKTSMRY.DAT ALL PIGS FOR SEPTEMBER AND OCTOBER 1972

MEANS	Order	Time	Temp. Cairns	% Hum.	Wind Vel.	% Cloud	Obs. Skin Temp.
	2.50	1163.34	79.34	53.44	4.54	35.57	90.44
STD. DEVIATIONS							
	1.12	159.43	18.21	8.33	2.94	30.72	4.82

CORRELATION MATRIX

	1	2	3	4	5	6	
1	1.000	0.033	0.041	-0.111	-0.037	-0.004	0.123
2	0.033	1.000	0.291	-0.348	0.102	0.113	0.471
3	0.041	0.291	1.000	-0.384	-0.236	-0.319	0.813
4	-0.111	-0.348	-0.384	1.000	0.436	-0.009	-0.310
5	-0.037	0.102	-0.236	0.436	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	1.326
3	0.442	0.025	17.387
4	-0.066	0.033	-1.991
5	0.400	0.036	4.662
6	0.038	0.008	4.733

INTERCEPT 91.088

OBSERVED PREDICTED RESIDUAL

OBSERVED	PREDICTED	RESIDUAL
90.50	94.62	-1.68
92.50	92.38	1.30
94.60	91.43	3.17
96.80	96.11	0.69
99.60	93.39	6.21
97.30	94.36	2.94
98.80	96.11	2.69
99.80	99.53	0.27
98.00	93.73	4.27
98.00	92.52	5.48
98.00	93.12	4.88
98.00	91.62	6.38
92.00	94.99	-2.99
92.00	94.79	-2.79
93.00	95.33	-2.33
93.00	93.23	0.10
96.00	88.53	7.47
99.00	99.32	0.18
94.00	91.86	2.14
94.00	91.80	2.20
93.00	92.61	0.39
94.75	94.21	0.54

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. Vertical 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 $8 \text{ cal/cm}^2 \cdot \text{sec}^{-1}$ versus 8 seconds at $1 \text{ cal/cm}^2/\text{sec}$. 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

GROSS GRADE VS. NORMALIZED BURN DEPTH

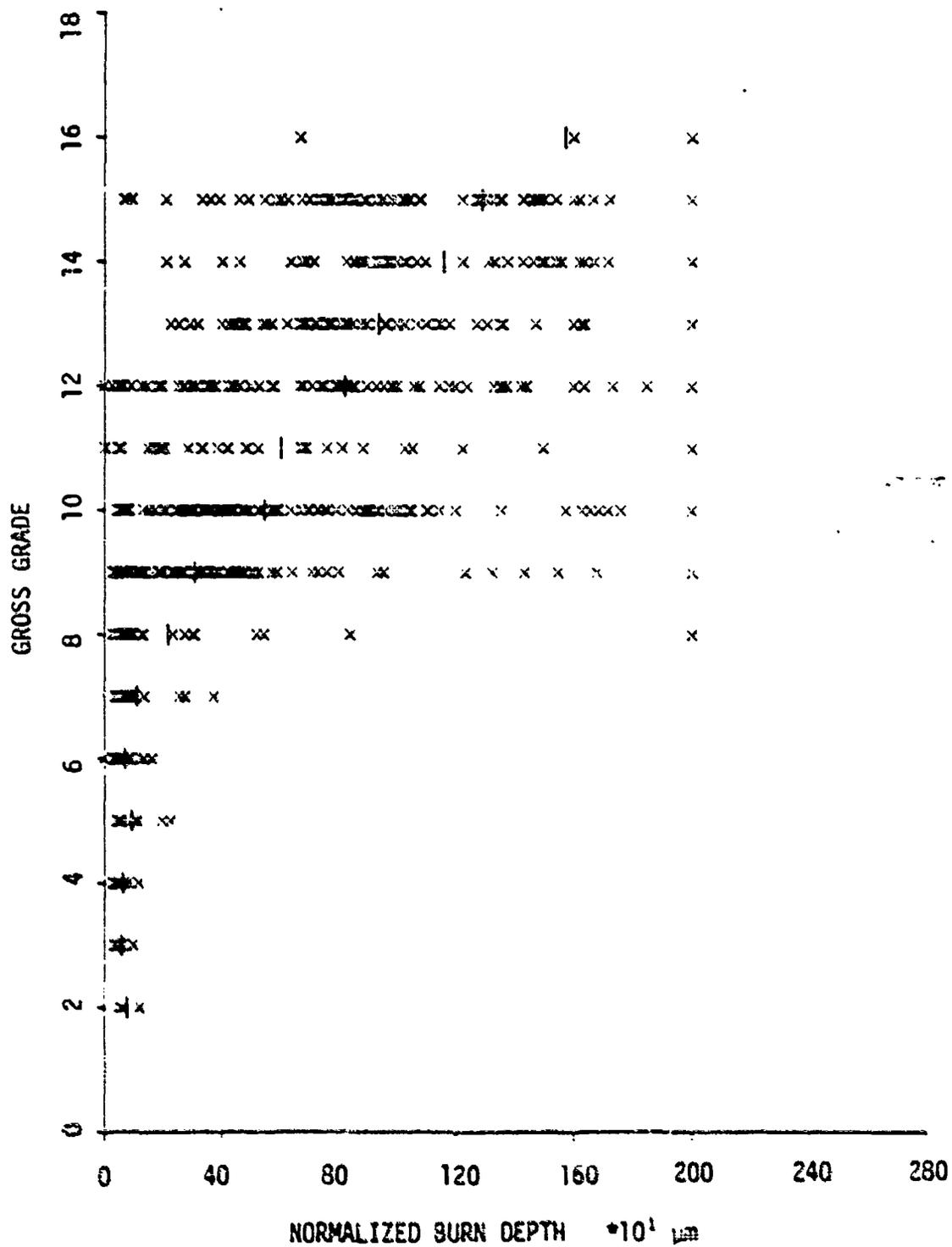


Figure 2.

GROSS GRADE VS. CORRECTED BURN DEPTH

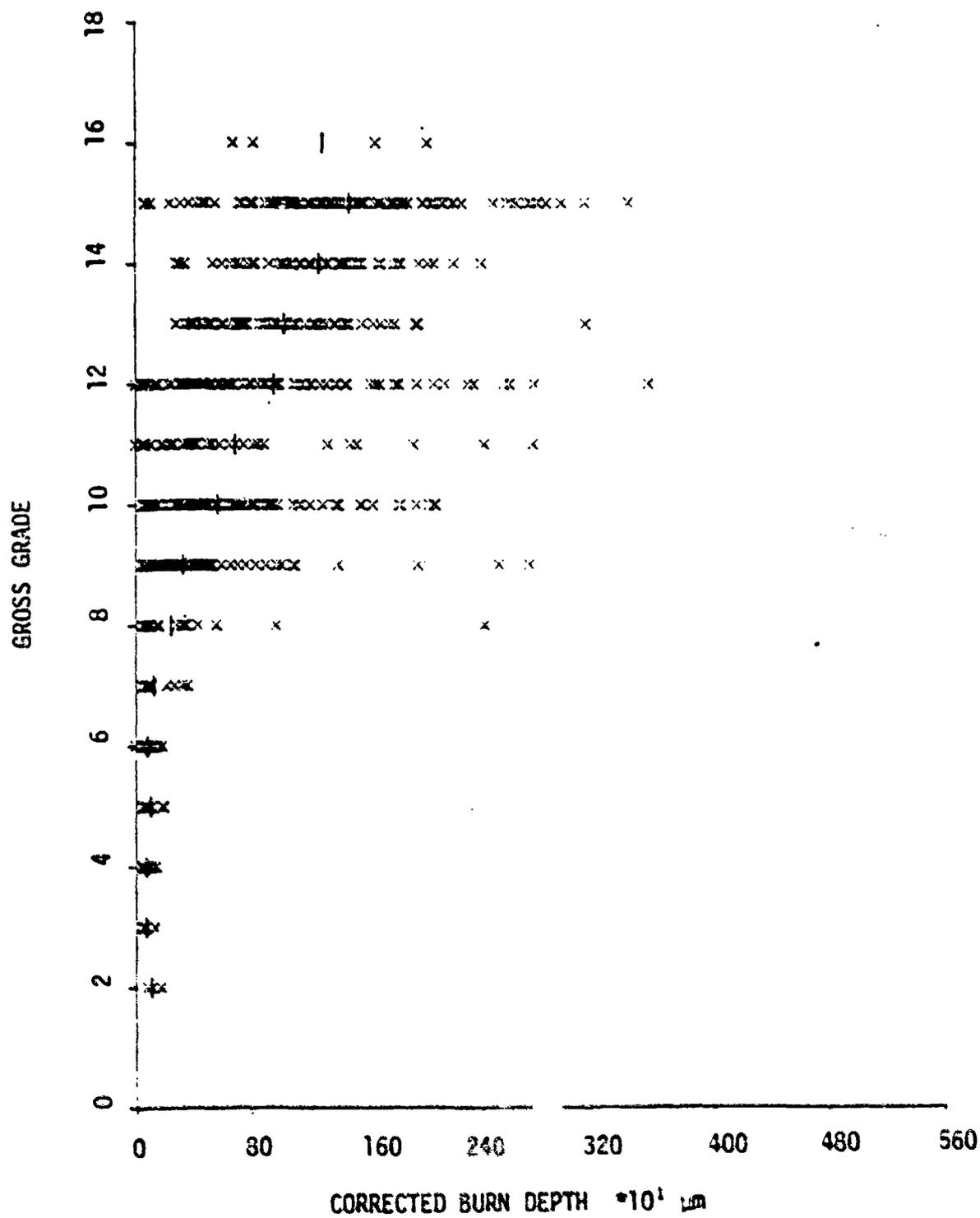


Figure 3.

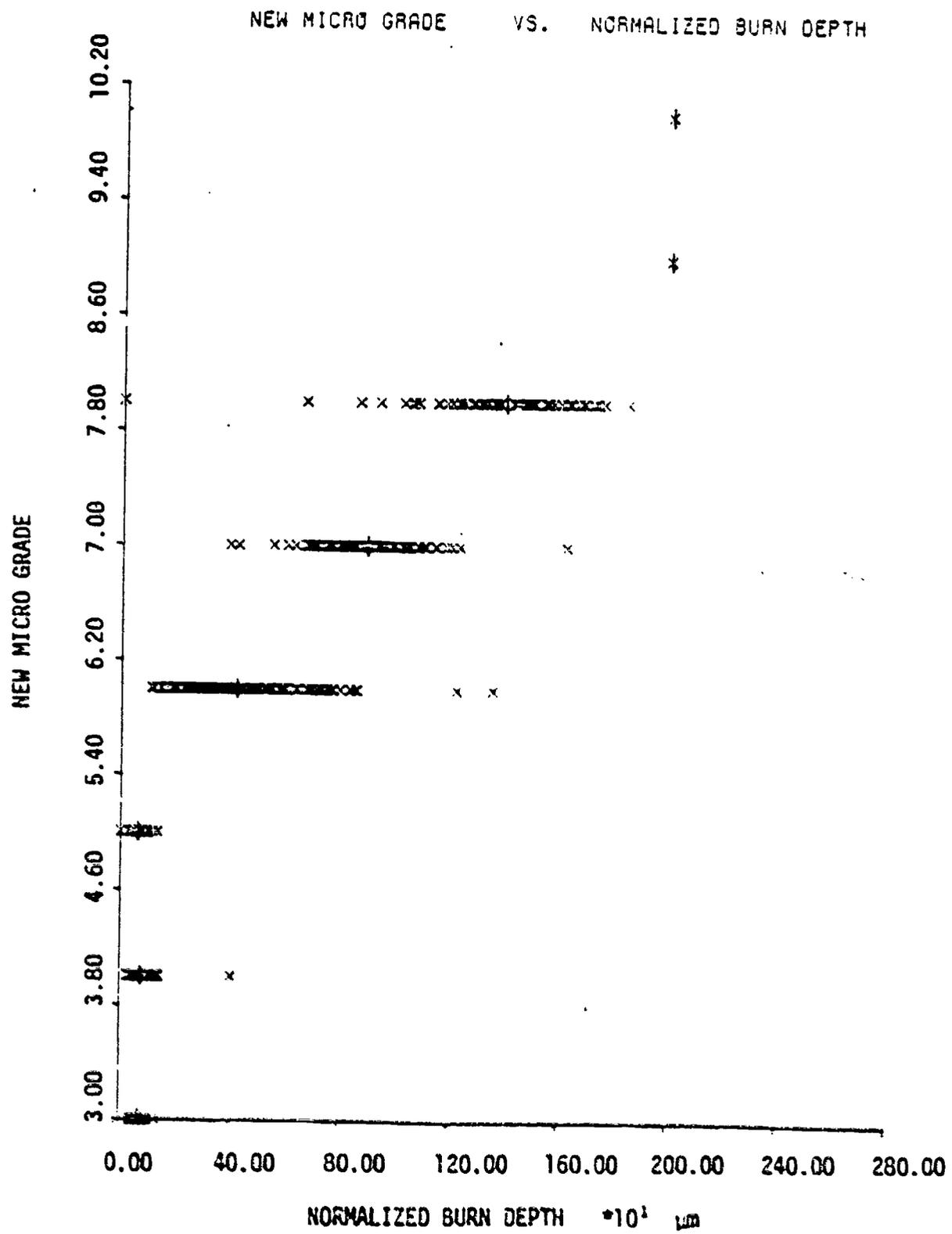


Figure 4.

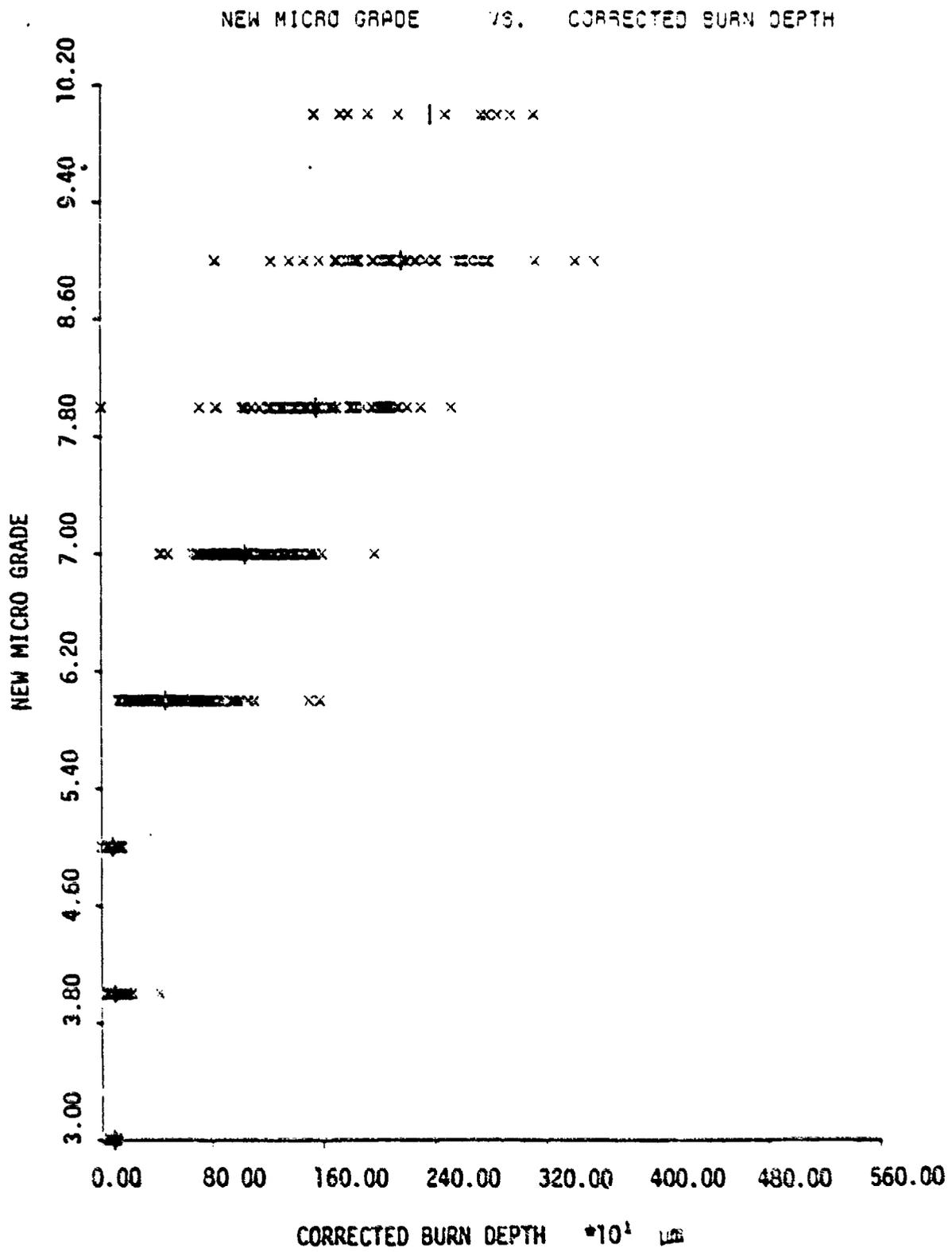


Figure 5.

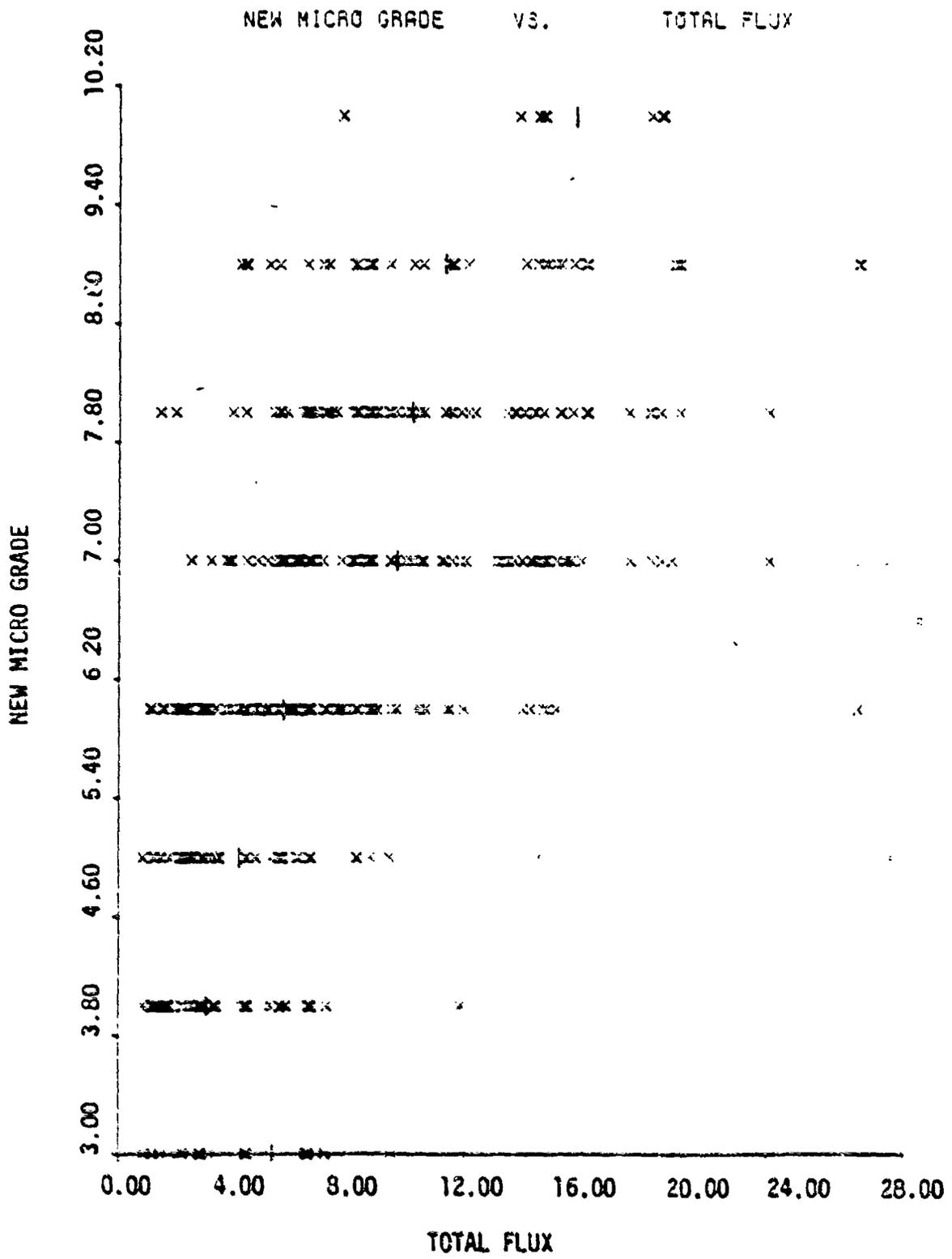


Figure 6.

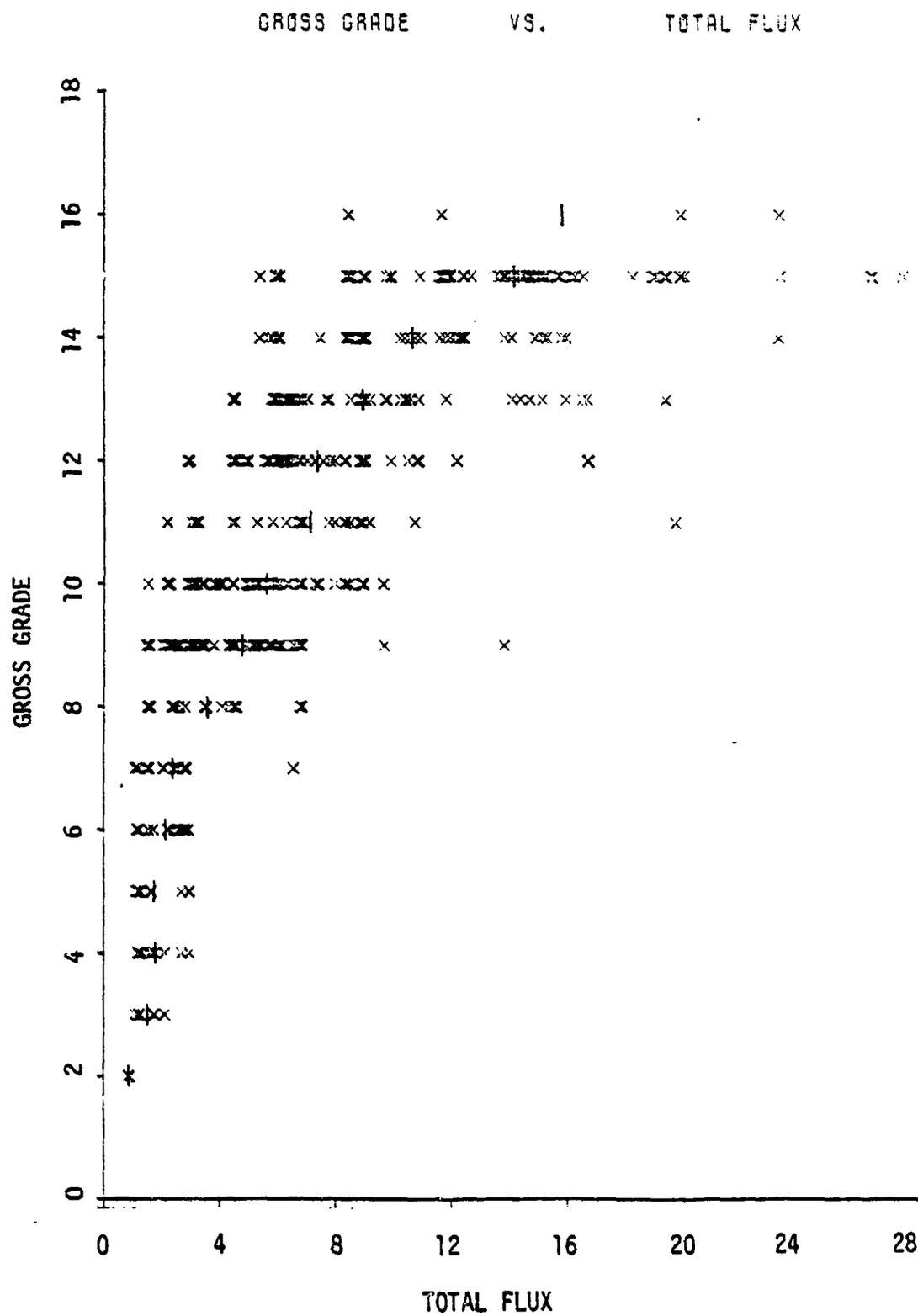


Figure 7.

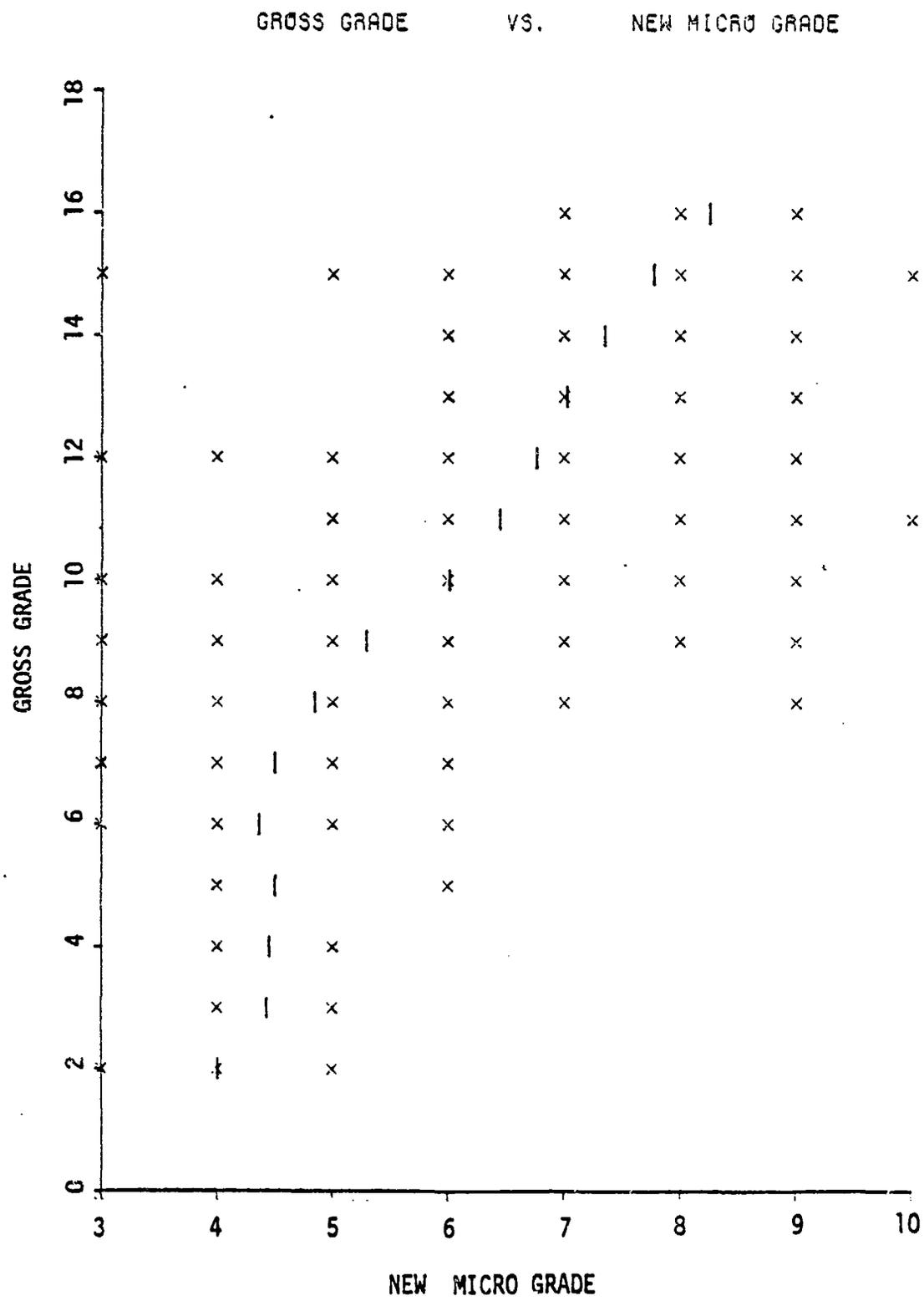


Figure 8.

LOG EXP. TIME VS. LOG FLUX
 PARAMETERIZED BY NEW MICRO GRADE 4

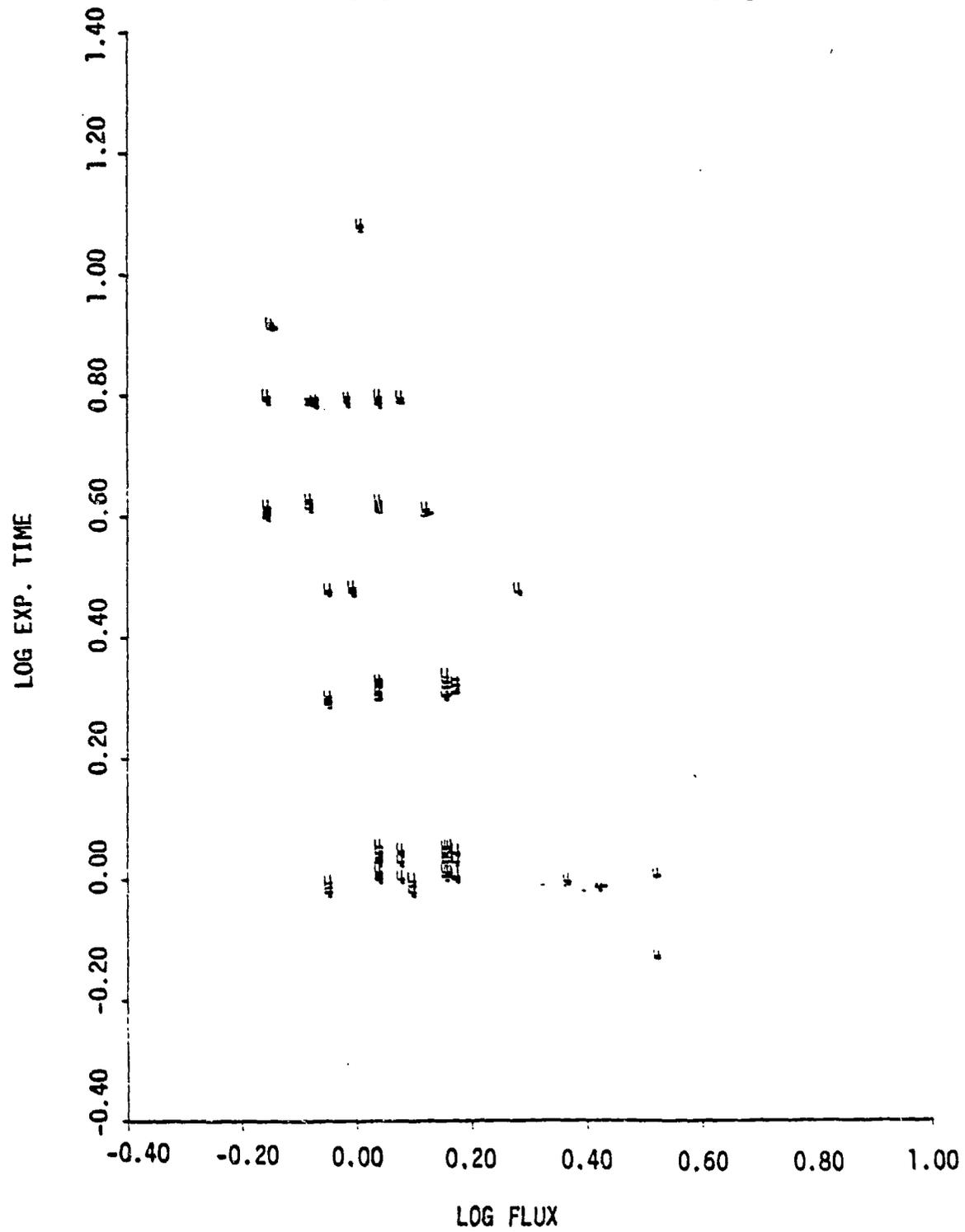


Figure 9.

LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 6

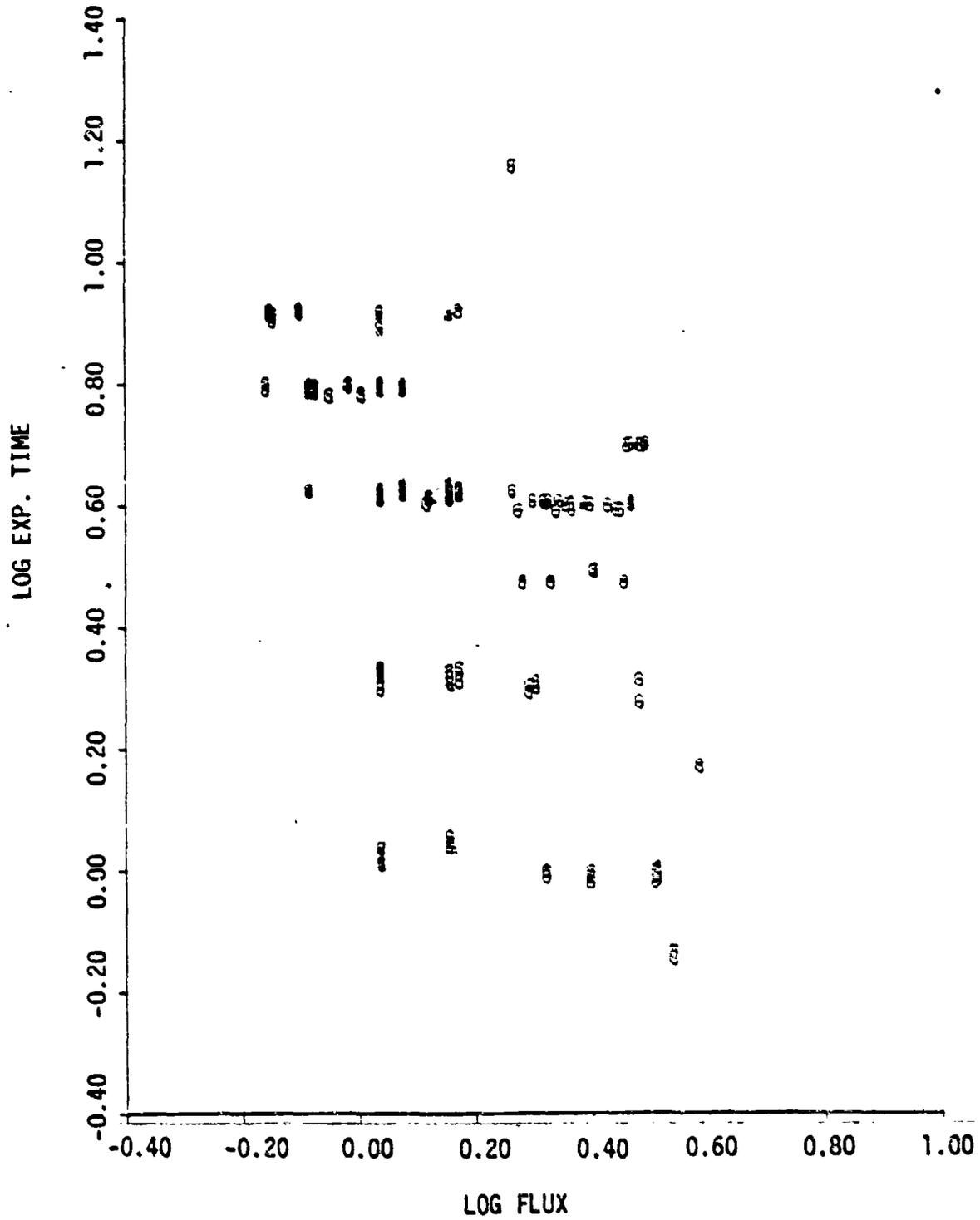


Figure 10.

LOG EXP. TIME VS. LOG FLUX
PARAMETERIZED BY NEW MICRO GRADE 9

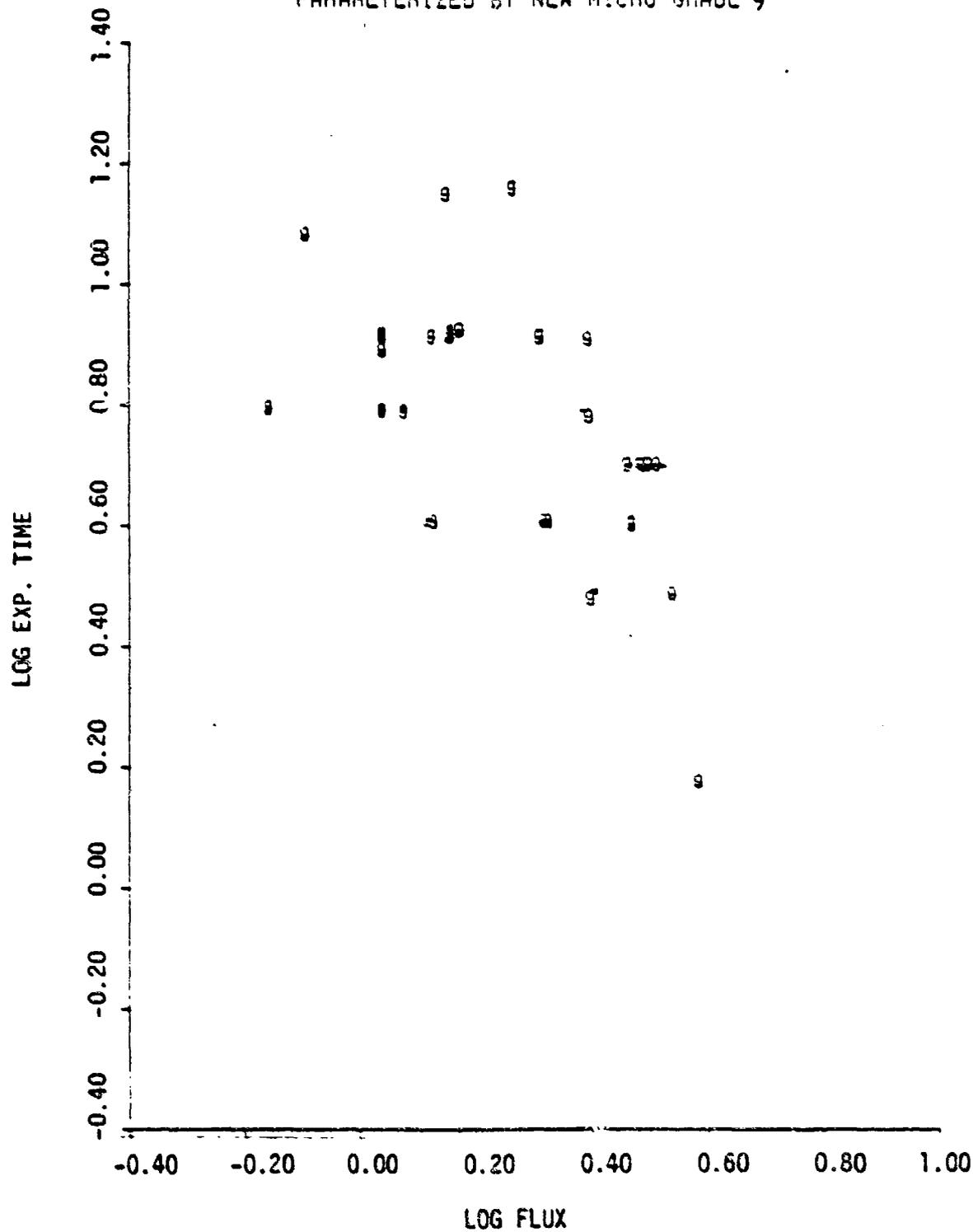


Figure 11.

NORMALIZED BURN DEPTH VS. TOTAL FLUX
PARAMETERIZED BY EXPOSURE TIME

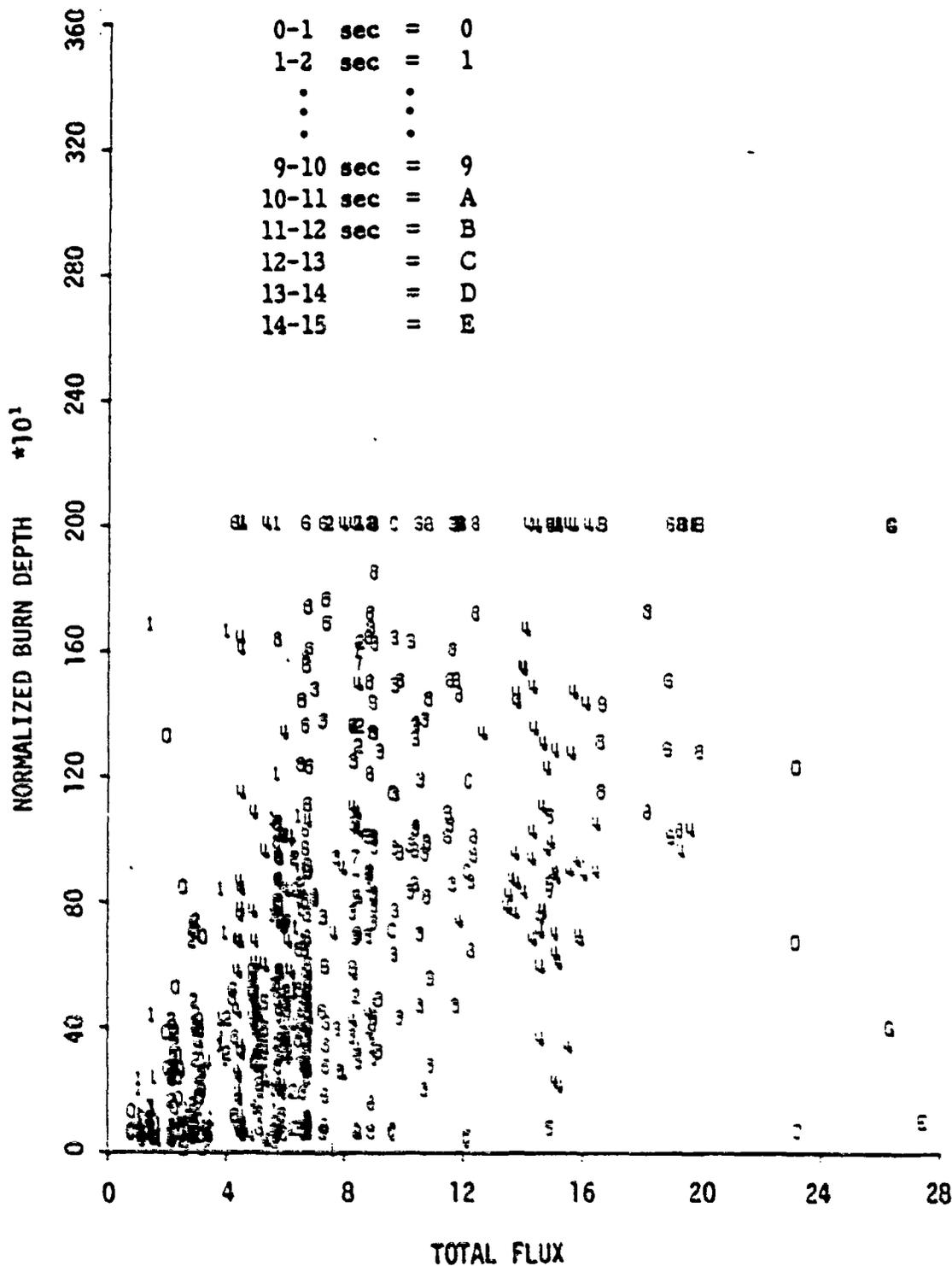


Figure 12.

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:

$$p \quad C_p \quad \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) + q \quad (1)$$

where,

p = density, gm/cm³

C_p = heat capacity, cal/gm/°C

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

TABLE IV

DISCRIMINANT ANALYSIS... CROSS BURN GRADE		EVALUATION OF CLASSIFICATION FUNCTIONS FOR EACH OBSERVATION								
GROUP	MEANS	TYPE	FLUX	MALL T.	T. T.	SKIN T.	SKIN COLOR	OBSERVATION	PROBABILITY ASSOCIATED WITH LARGEST DISCRIMINANT FUNCTION	DISCRIMINANT FUNCTION NO.
1	0.857	1.013	1138.868	0.000	0.000	99.160	0.648	23	0.464	2
2	1.099	1.016	1076.777	2.000	89.623	0.613	0.104	24	0.843	1
3	2.000	2.000	1039.260	0.571	85.319	0.104	0.104	25	0.945	1
4	0.875	2.070	1224.777	0.681	91.850	0.100	0.100	26	0.232	1
5	0.000	2.100	1022.101	15.363	89.725	0.133	0.133	27	0.810	1
GENERALIZED NAVALABOR D-CO-2E		1881.51845						28	0.461	2
DISCRIMINANT FUNCTION 1								29	0.877	1
CONSTANT * COEFFICIENTS								30	0.440	2
-347.601		0.002		-81.853		0.120		31	0.487	2
DISCRIMINANT FUNCTION 2								32	0.600	2
CONSTANT * COEFFICIENTS								33	0.110	3
-334.120		0.120		-83.633		0.100		34	0.105	4
DISCRIMINANT FUNCTION 3								35	0.245	4
CONSTANT * COEFFICIENTS								36	0.223	2
-341.655		0.040		-55.333		0.100		37	0.206	2
DISCRIMINANT FUNCTION 4								38	0.335	4
CONSTANT * COEFFICIENTS								39	0.525	4
-400.807		0.741		-84.001		0.187		40	0.021	2
DISCRIMINANT FUNCTION 5								41	0.081	2
CONSTANT * COEFFICIENTS								42	0.081	2
-400.813		0.237		-55.633		0.103		43		

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 energy¹, equation (1) applies only to the surface of the skin. For all conditions in which $x > 0$, equation (1) reduces to the following:

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

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 $0 < X < L$. 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, $0 < X < L$, is distributed within the system and cannot escape.

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

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

$$p C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) + q \quad @ x = 0 \quad (3)$$

$$p C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) \quad @ 0 < X < L$$

$$T = T_0, \quad 0 < X < L, \quad t = 0 \quad \text{Initial conditions}$$

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

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

¹A 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

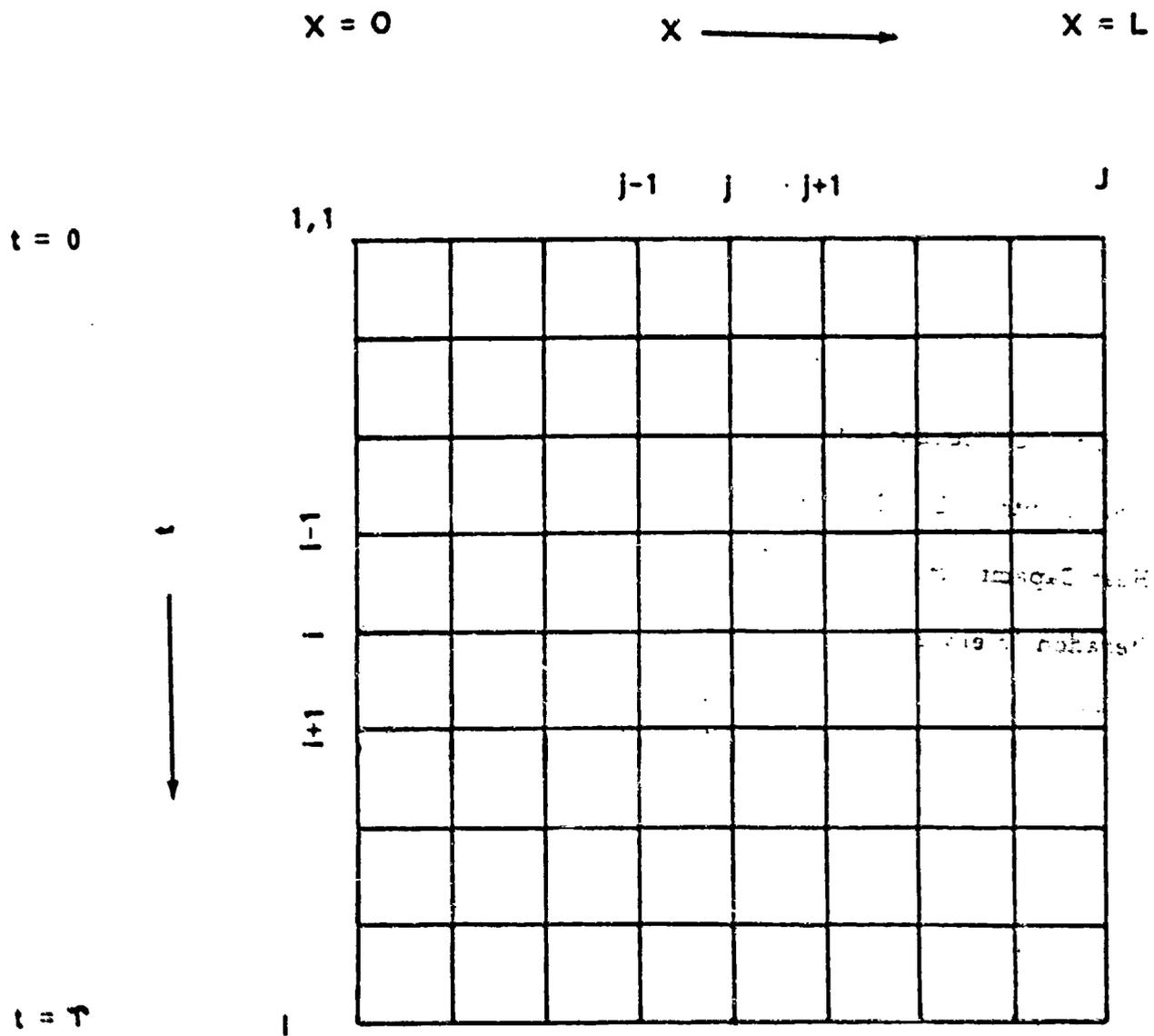
An analytical solution to equation set (3) was not considered feasible due to the variable nature of q , C_p and K ; so explicit differencing methods of numerical analysis were employed to solve the equations. Several investigators working with linear systems have found that the Crank-Nicholson six point 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 (TEMPIO)

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 ($^{\circ}\text{C}$)

Blood - Control Factor for Convective Tissue Cooling by Blood

TEMP B - Difference Between Backwall Tissue Temperature and TEMPIO

Absorptivity of Surface

Incident Flux, Q, ($\text{cal}/\text{cm}^2/\text{sec}$)

Nextra 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)

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

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

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

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: $\gamma = \frac{W_w}{\gamma_w} + \frac{W_f}{\gamma_f} + \frac{W_p}{\gamma_p}^{-1}$
- 2) heat capacity: $C_p = W_w C_{p_w} + W_f C_{p_f} + W_p C_{p_p}$
- 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, γ_n the density, C_{p_n} the heat capacity, and k_n the thermal conductivity of the respective components. Values of the various terms used were:

$\gamma_w = 1 \text{ gm/cc}$	$C_{p_w} = 1 \text{ cal/gm-}^\circ\text{C}$	$k_w = 1.5 \times 10^{-3} \text{ cal/cm-sec-}^\circ\text{C}$
$\gamma_f = 0.815 \text{ gm/cc}$	$C_{p_f} = 0.55 \text{ cal/gm-}^\circ\text{C}$	$k_f = 4.5 \times 10^{-4} \text{ cal/cm-sec-}^\circ\text{C}$
$\gamma_p = 1.54 \text{ gm/cc}$	$C_{p_p} = 0.26 \text{ cal/gm-}^\circ\text{C}$	$k_p = 4.3 \times 10^{-4} \text{ cal/cm-sec-}^\circ\text{C}$

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

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

and the resultant equations were:

$$\gamma = (6.18277 \times 10^{-2} W_w + .938172)^{-1}$$

$$K = \gamma (1.08432 \times 10^{-3} W_w + 4.15684 \times 10^{-4})$$

$$C_p = .595 W_w + .405$$

Using the equations above, the profile of thermal properties was calculated for skin depths of from 81 to 2290 μm . A linear extrapolation of tissue water content from a depth of 81 μm 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 81 μm 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 result 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 $3.47 \text{ cal cm}^{-2} \text{ sec}^{-1}$ 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 $1520\mu\text{m}$. Three observed temperature profiles are overlaid on the calculated temperature profiles (for nodal depths of 0, 220, 440...2200 μm) in Figures 16, 17 and 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 perceptibly 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= 239.47
PL1= 1.46
PLN1= 147.37
DE2= 80000.00
DE1= 50000.00
ETIME= 100.00
ITIME= 100.00
NXTRA= 8
BLOOD= 0.00000

EXTRA NODES: 22.2 44.4 66.7 88.9 111.1 133.3 155.6 177.8

FLUX FILE: 0.00000

FLUX FILE: 0.00000

W= 0.39972E+01
W= 0.48734E+00
W= 0.45386E-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+06	AT DEPTH (IN MICRONS) =	600.000
W =	0.84809E+04	AT DEPTH (IN MICRONS) =	800.000
W =	0.44495E+03	AT DEPTH (IN MICRONS) =	1000.000
W =	0.39339E+02	AT DEPTH (IN MICRONS) =	1200.000
W =	0.39372E+01	AT DEPTH (IN MICRONS) =	1400.000
W =	0.40754E+00	AT DEPTH (IN MICRONS) =	1600.000
W =	0.45306E-01	AT DEPTH (IN MICRONS) =	1800.000
W =	0.89937E-02	AT DEPTH (IN MICRONS) =	2000.000
W =	0.00000E+00	AT DEPTH (IN MICRONS) =	2200.000

MAXIMUM TEMPERATURE = 128.724

THRESHOLD DEPTH = 1520.

FINAL TIME = 100.00

Figure 14.

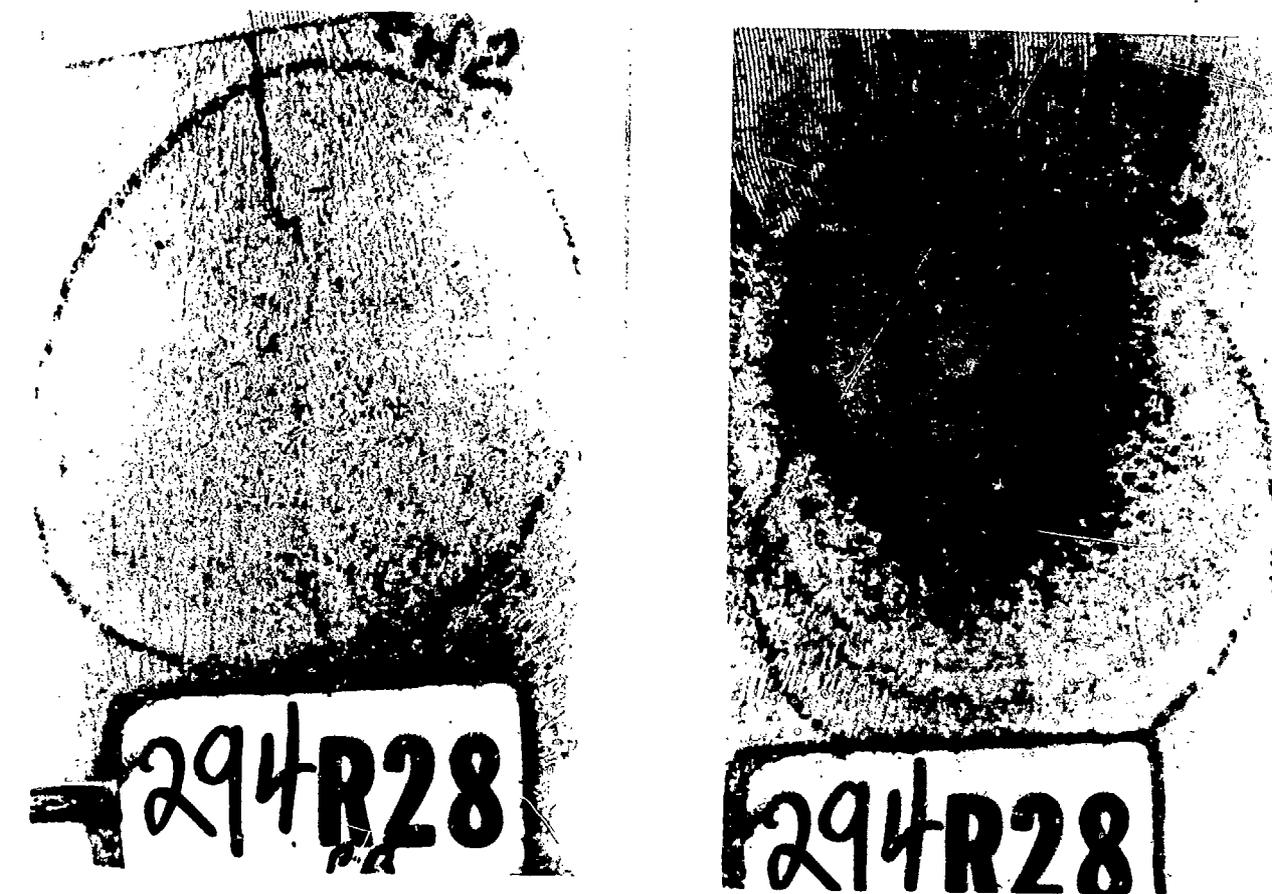


Figure 15. Intraskin thermocouple (0.003", "located superficially") shown prior to burn (left) and subsequent to exposure to $3.47 \text{ cal}\cdot\text{cm}^{-1}\cdot\text{sec}^{-1}$ for 3.02 seconds (right).

Gross grade = 13

New Micro grade = 8

Threshold depth = $1465\mu\text{m}$

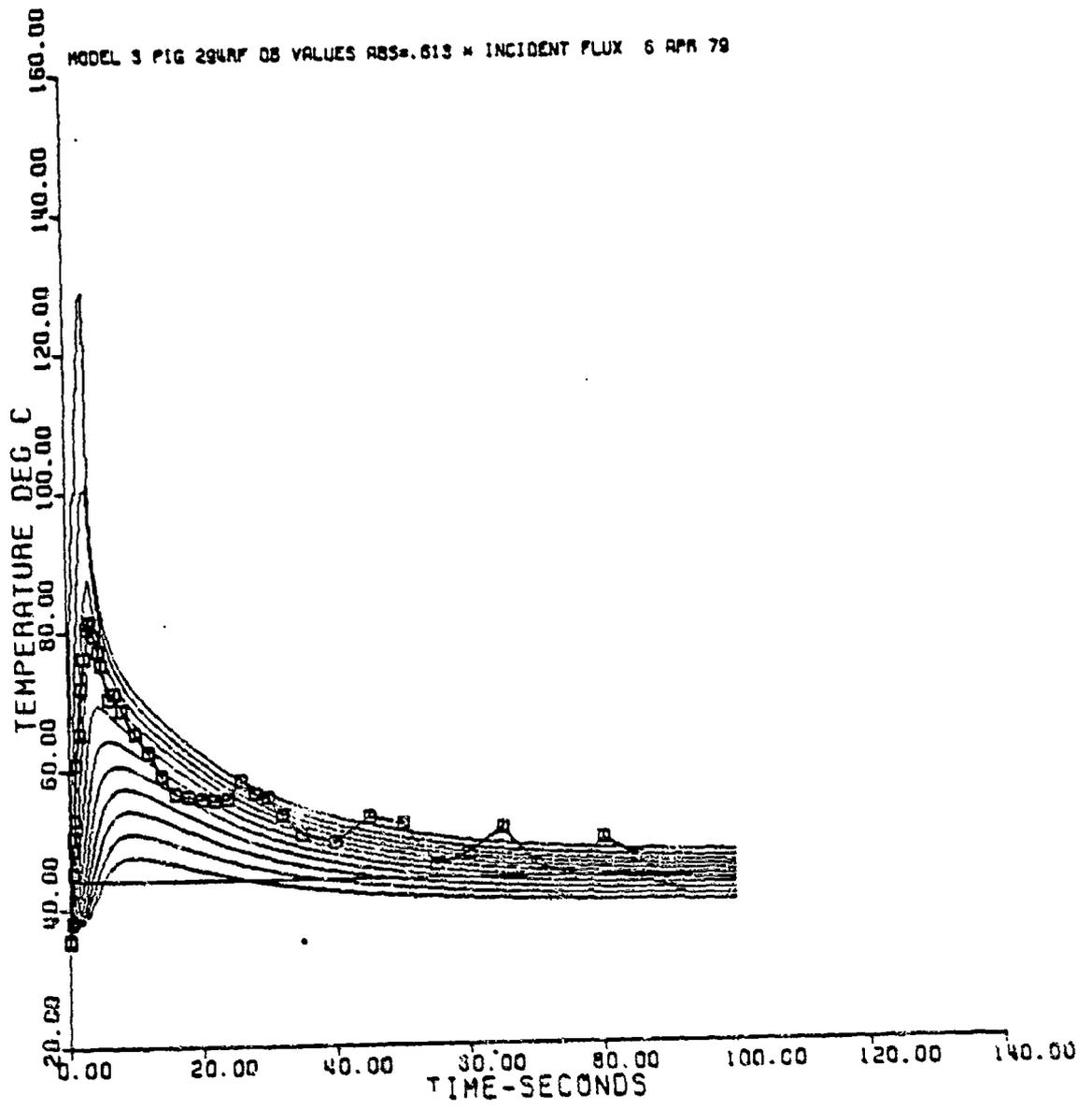


Figure 16.

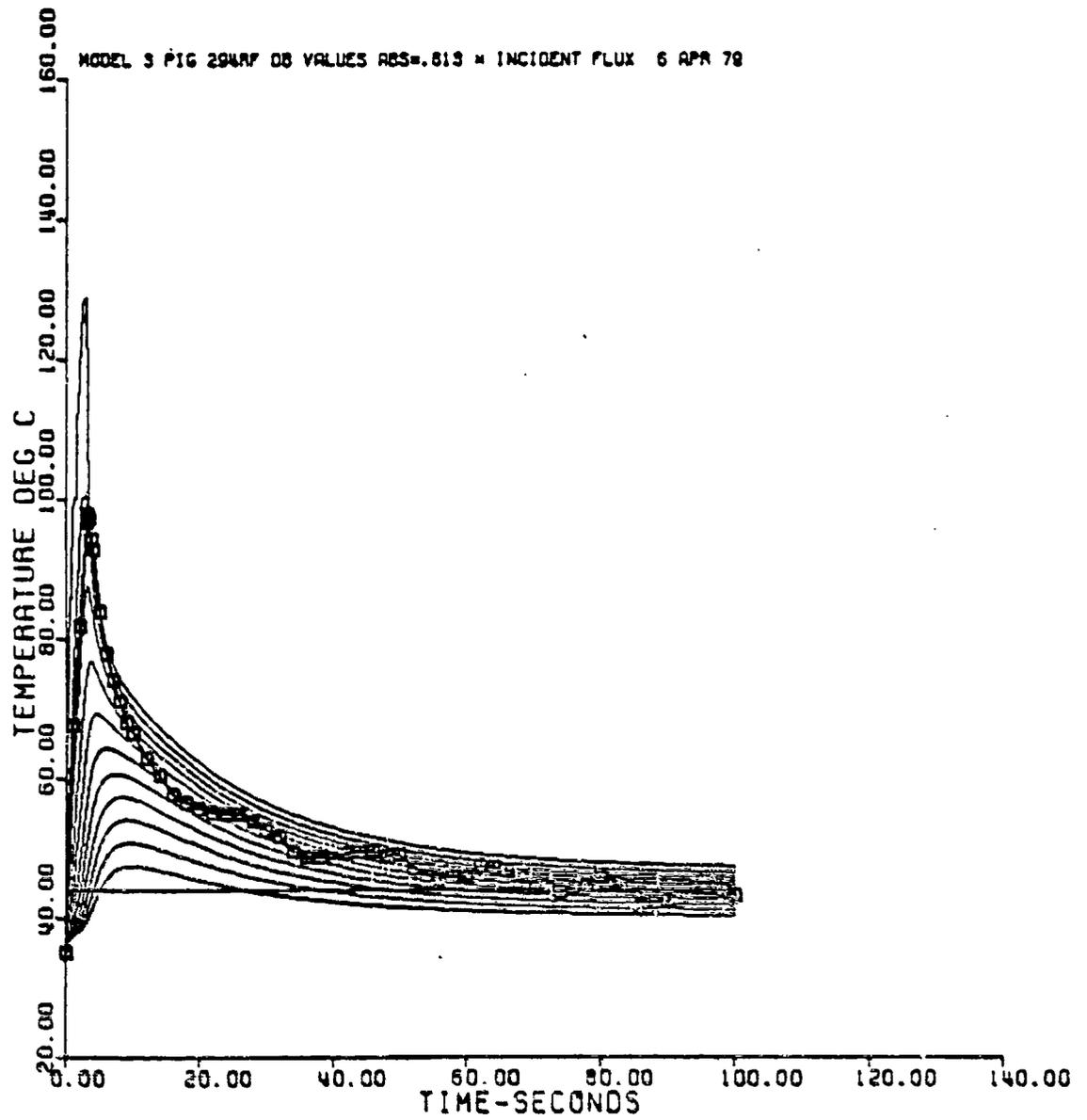


Figure 17.

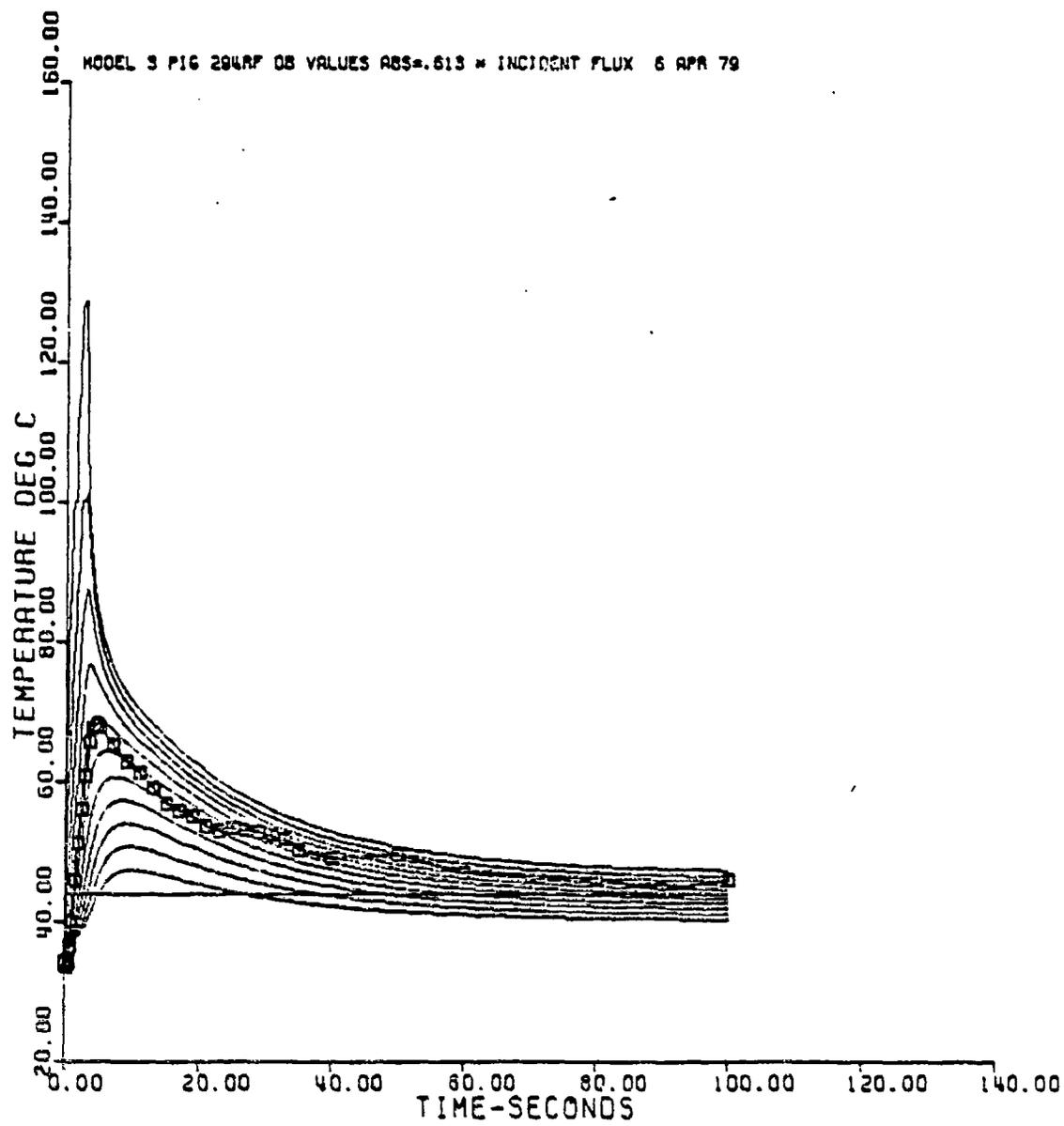


Figure 18.

MODEL NAME OR DESCRIPTION: M12/B0120 FIG 294 *27.28,29 WITH TEMPR,BLOOD=0 AND BOIL=250 4 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 34.9700
DENS= 1.00000
Q1= 3.74000
BL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMPB= 0.0000
ABSORB= 0.613000
BOIL= 250.000

PL2= 2.24
PLN2= 233.47
PL1= 1.46
PLN1= 147.37
DE2= 00000.00
DE1= 50000.00
ETIME= 3.02
ITIME= 100.00
MXTA= 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 *	0.96073E+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 *	0.32922E+06	AT DEPTH (IN MICRONS)=	800.000
W *	0.50035E+04	AT DEPTH (IN MICRONS)=	1000.00
W *	0.18037E+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 *	0.80000E+00	AT DEPTH (IN MICRONS)=	2200.00

MAXIMUM TEMPERATURE = 150.245

THRESHOLD DEPTH = 1547.

FINAL TIME = 30.12

Figure 19.

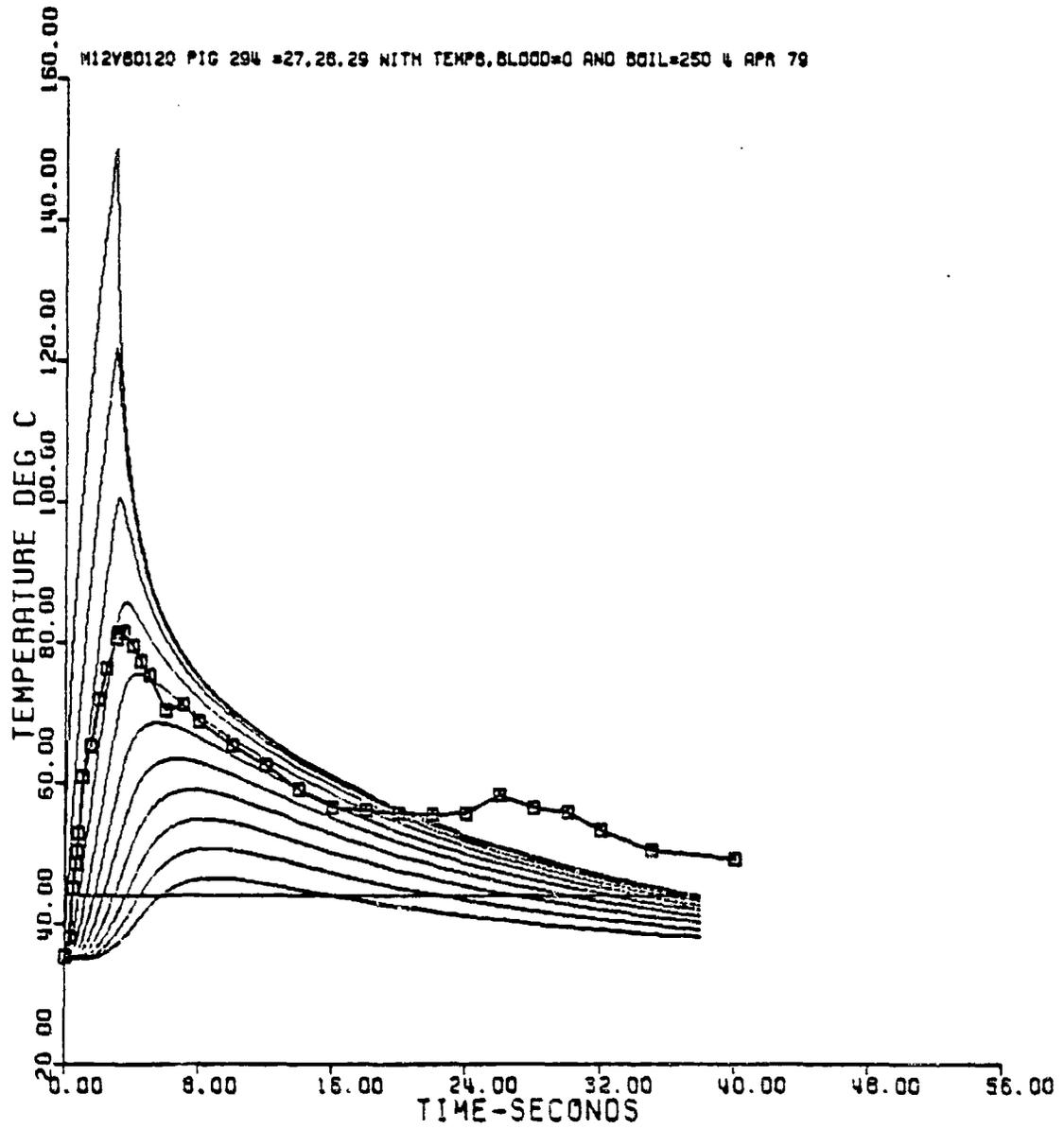


Figure 20.

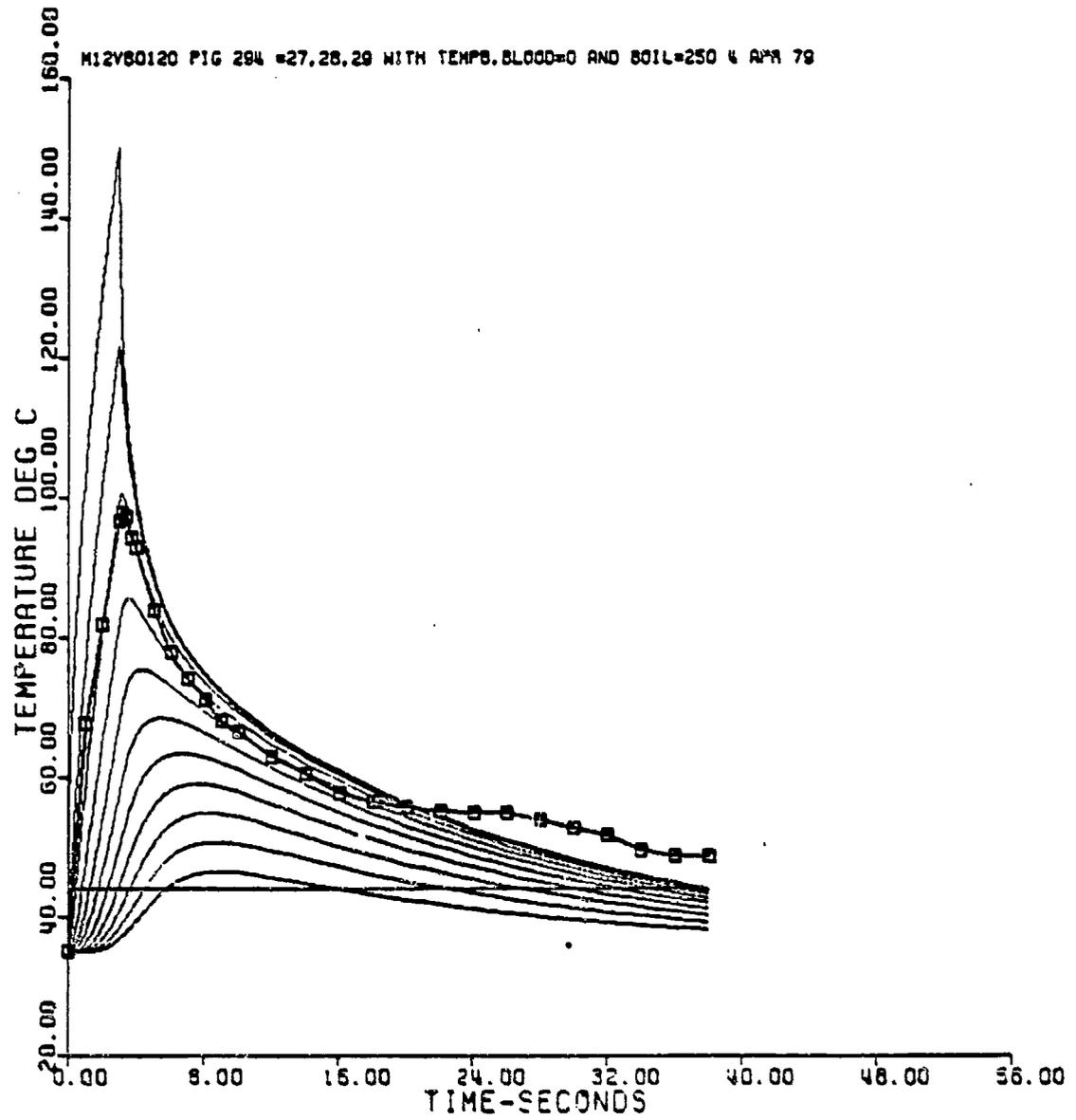


Figure 21.

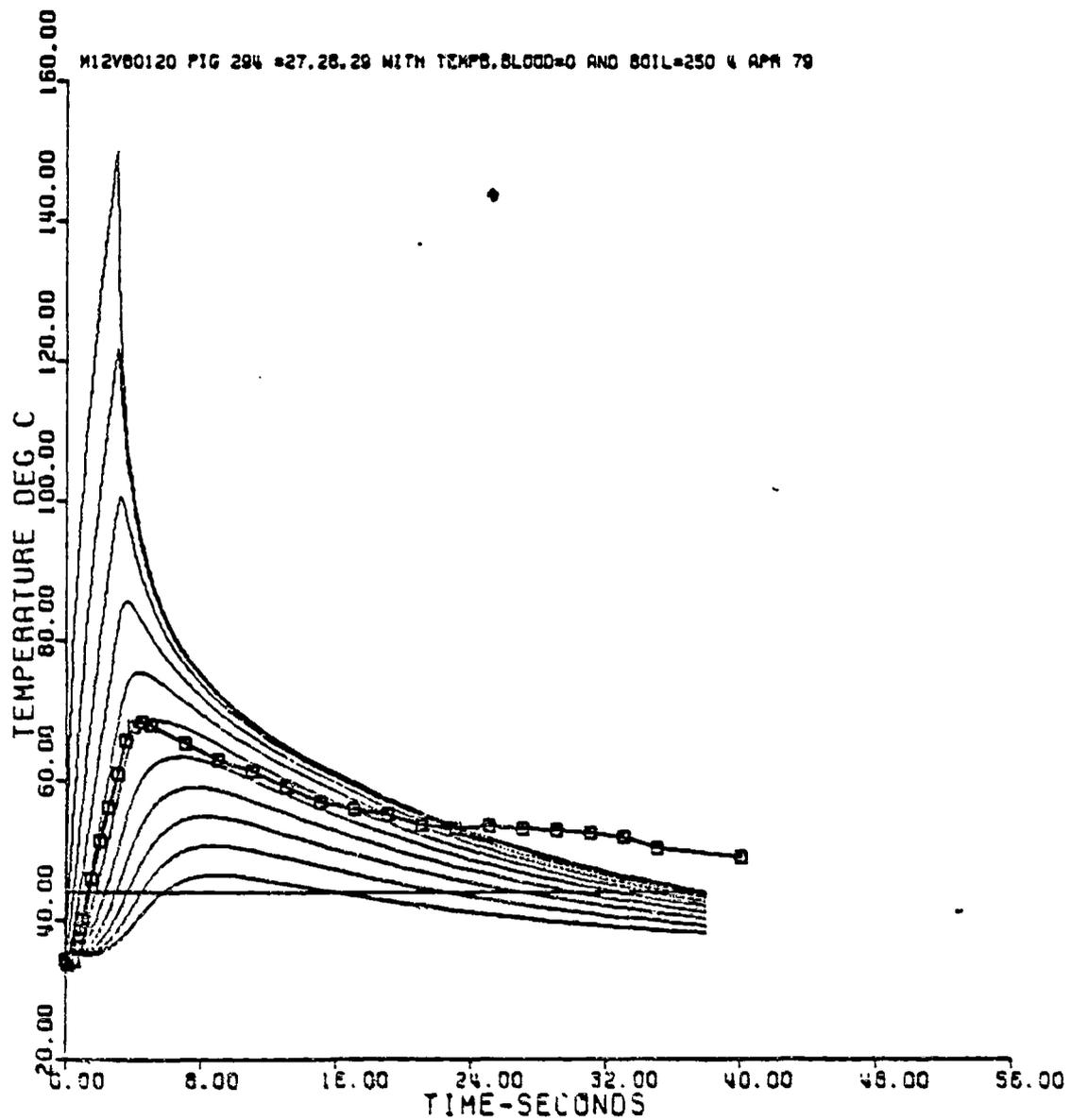


Figure 22.

MODEL NAME OR DESCRIPTION: SINSIMS FIG 294 *27.20.29 DB CORRECTED VALUES ABS=.613 VS M12/80120 5 APR

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 34.9700
DENS= 1.00000
Q1= 3.74000
SL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMP8= 3.3600
ABSORB= 0.613000
BOIL= 100.150

PL2= 2.24
PLN2= 239.47
PL1= 1.46
PLN1= 147.37
DEZ= 80000.00
DEL= 50000.00
ETIME= 3.02
ITIME= 100.00
NXTRA= 0
BLOOD= 0.0010

FLUX FILE I.D.: 0.00 2

FLUX(1)=
1 3.740 2 3.740

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

D= 0.72442E+01
D= 0.73779E+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	0.36773E+03	AT DEPTH (IN MICRONS)=	400.000
W	0.69683E+06	AT DEPTH (IN MICRONS)=	600.000
W	0.70237E+04	AT DEPTH (IN MICRONS)=	800.000
W	0.25842E+03	AT DEPTH (IN MICRONS)=	1000.00
W	0.15083E+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	0.32324E-02	AT DEPTH (IN MICRONS)=	2000.00
W	0.80000E+00	AT DEPTH (IN MICRONS)=	2200.00

MAXIMUM TEMPERATURE = 130.837

THRESHOLD DEPTH = 1433.

FINAL TIME = 33.93

Figure 23.

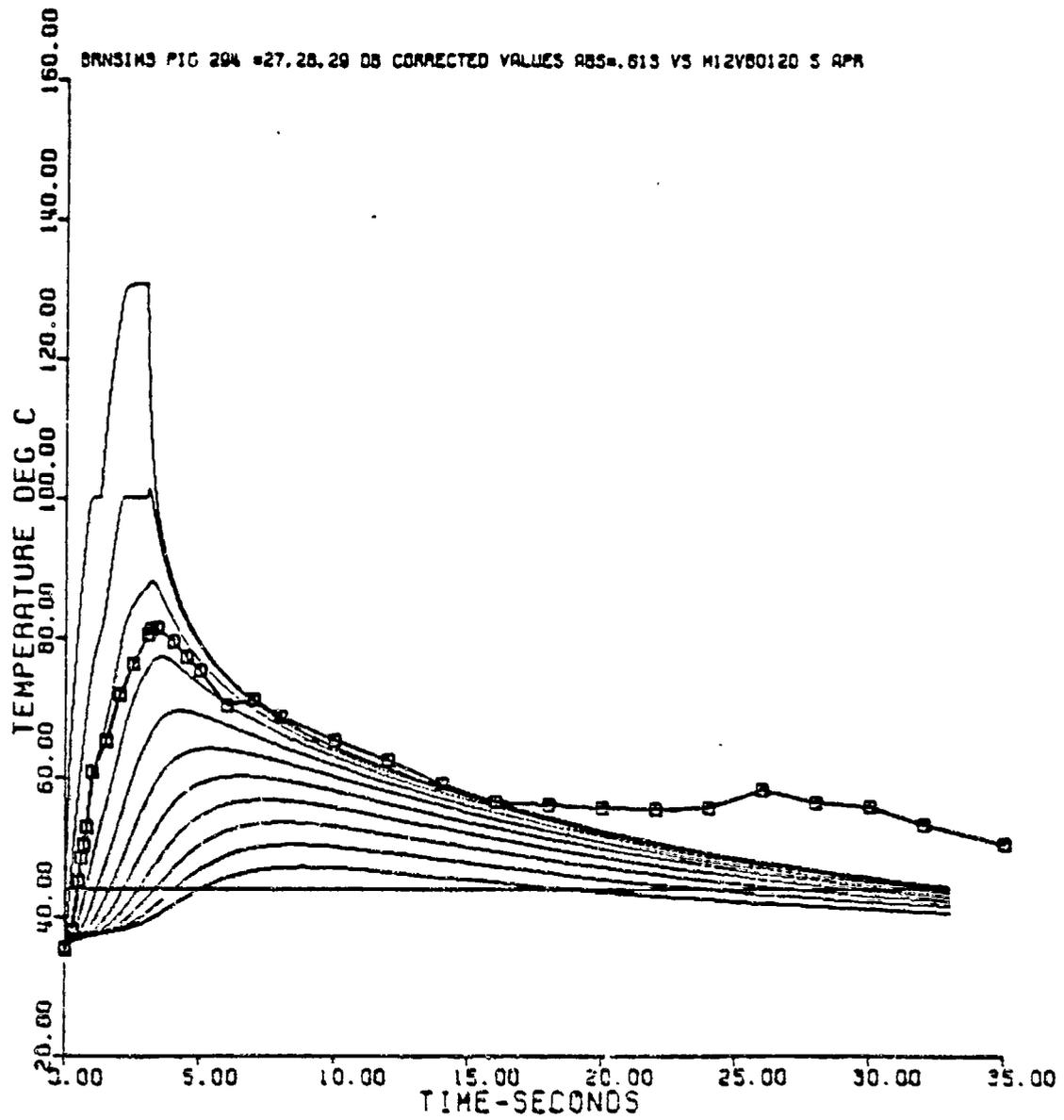


Figure 24.

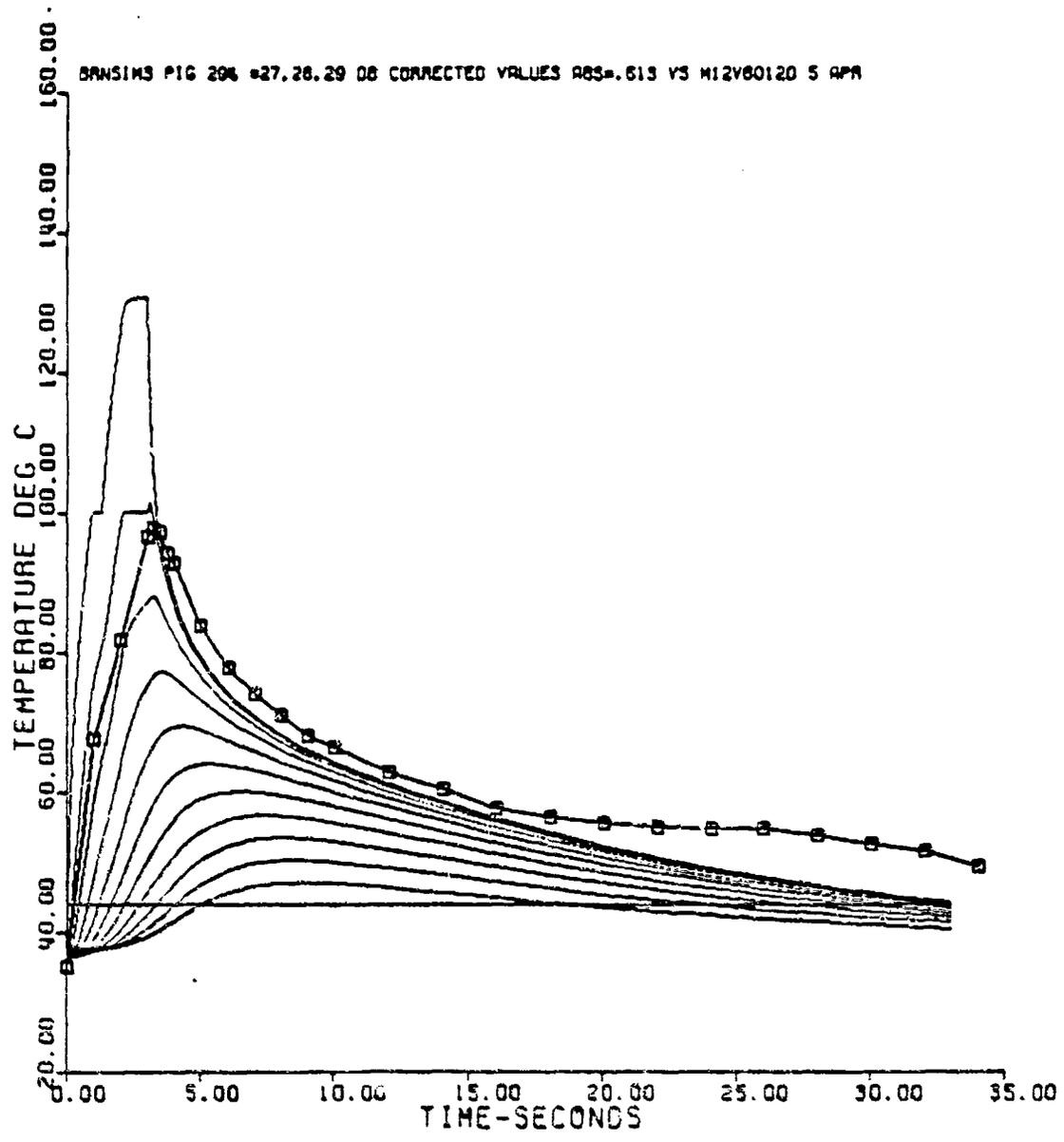


Figure 25.

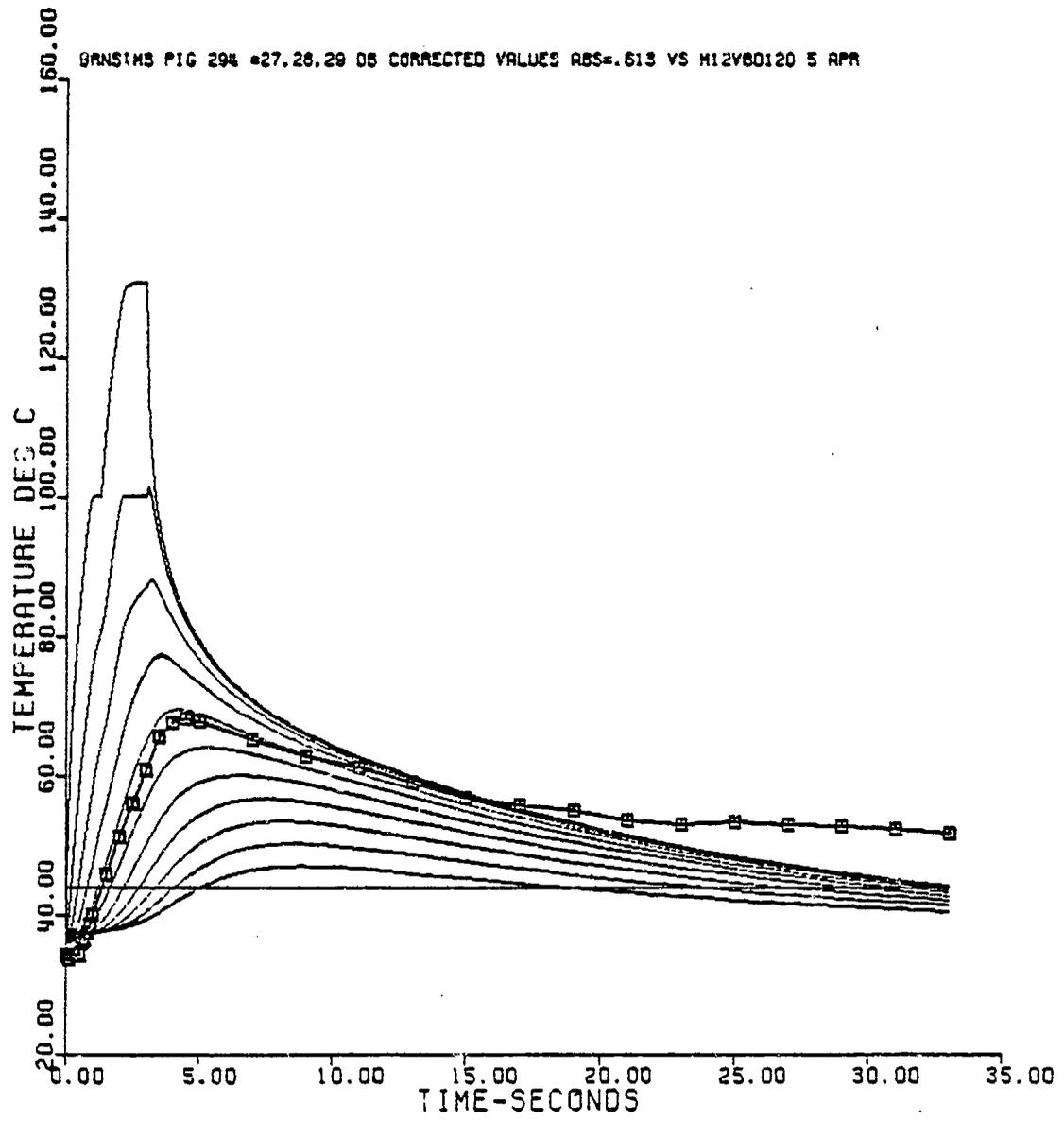


Figure 26.

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

Fig	Exposure Time (s) [†]	Incident Flux (cal cm ⁻² s ⁻¹)	Observed Burn		Skin Surface Temp. (°C)	Core Temp. (°C)	Surface Absorp-tivity	Predicted Depth (10 ⁻⁴ cm)	Calculated		Recorded Total Temp. (°C) Max.
			Normalized (10 ⁻⁴ cm) [†]	Depth (10 ⁻⁴ cm) [†]					Surface Temp. (°C)	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 200 μ m instead of 71 μ m for 296 LR and 300 μ m instead of 72 μ m for 296 RR.

MODEL NAME OR DESCRIPTION: MODEL 3 FIG 296RF DB VALUES ABS=.613 *INCIDENT FLUX 6 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 27.8000
DENS= 1.00000
Q1= 2.36000
SL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMP= 10.2000
ABSORB= 0.613000
BOIL= 100.150

PL2= 2.24
PLI2= 239.47
PL1= 1.46
PLI1= 147.37
DE2= 8000.00
DE1= 5000.00
ETIME= 8.20
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

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

D= 0.74955E+01
D= 0.76809E+01
D= 0.76962E+01

W =	0.11325E+10	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 =	0.18991E+10	AT DEPTH (IN MICRONS)=	800.000
W =	0.10182E+09	AT DEPTH (IN MICRONS)=	1000.00
W =	0.49823E+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.

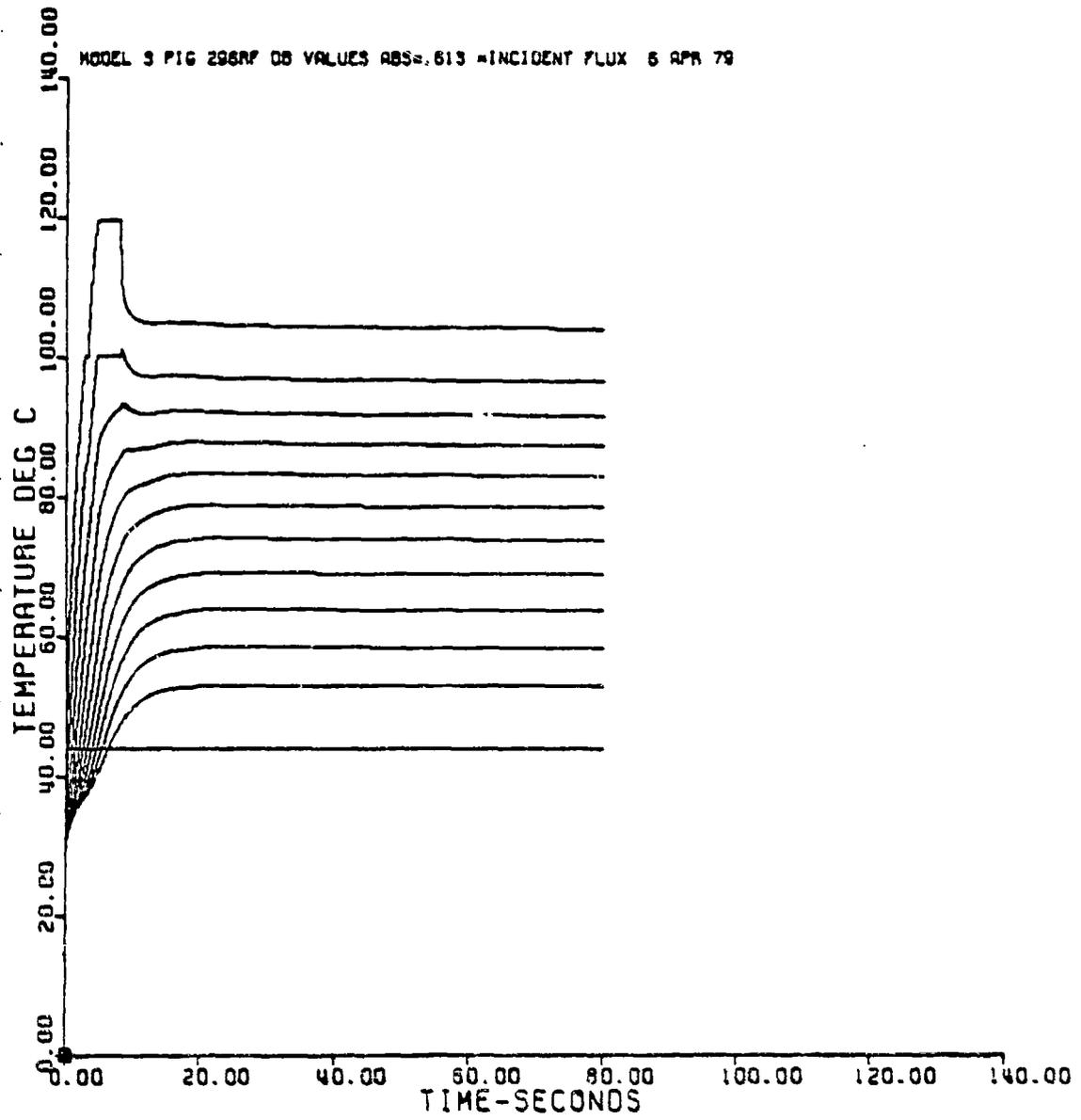


Figure 28.

MODEL NAME OR DESCRIPTION: BENSIMS PIG 2968F DB VALUES ABS=.613 * INCIDENT FLUX 6 APR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 27.8000
DENS= 1.00000
Q1= 2.36000
AL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMP8= 10.2900
ABSORB= 0.513000
BOIL= 100.150

PL2= 2.24
PLN2= 239.47
PL1= 1.46
PLN1= 147.37
DE2= 80000.00
DE1= 50000.00
ETIME= 8.20
ITIME= 80.00
MXTA= 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+10	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	0.69799E+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 = 119.315

THRESHOLD DEPTH = 1775.

FINAL TIME = 30.10

Figure 29.

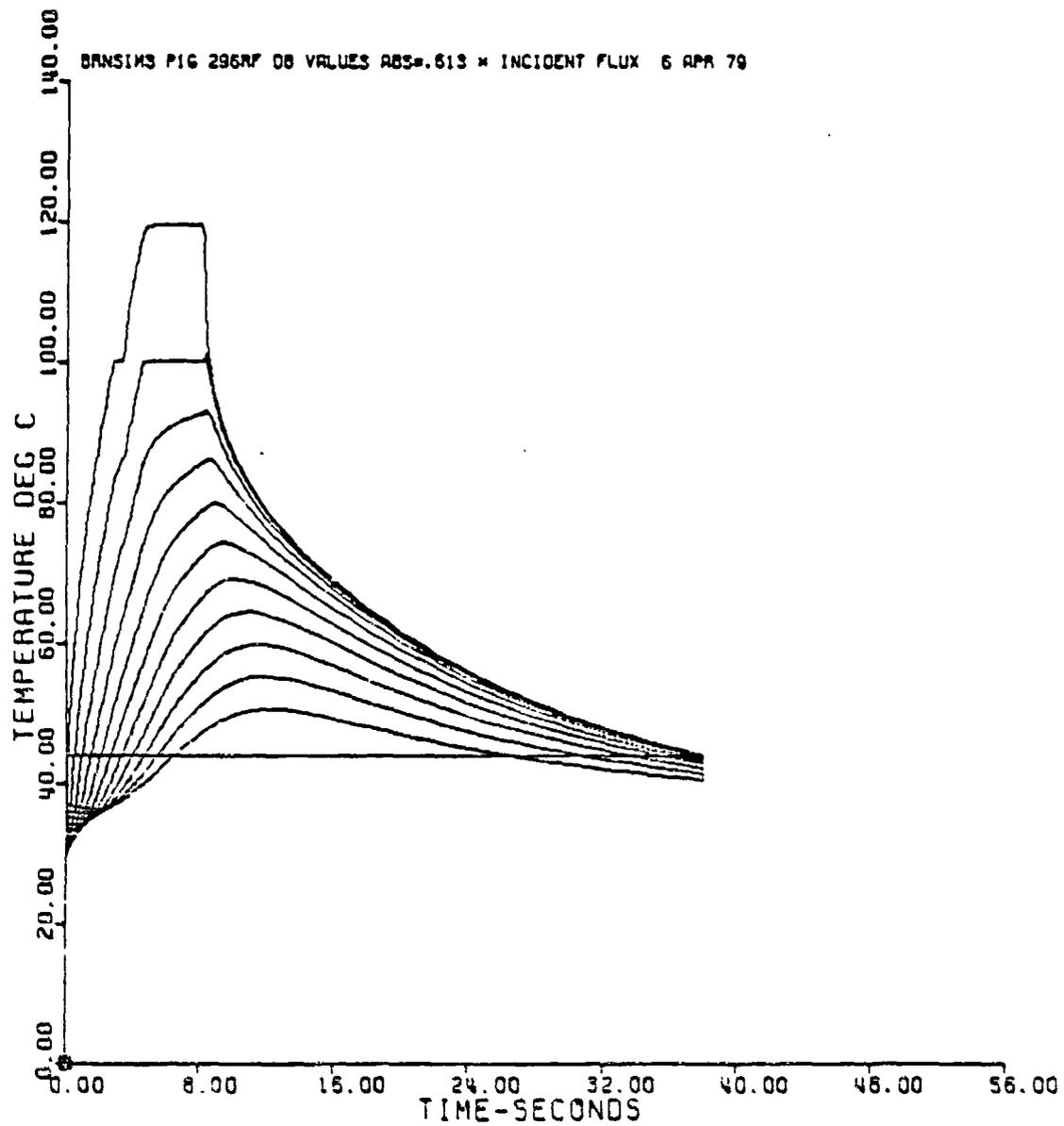


Figure 30.

TABLE VIII

Test No.	T _o	Exposure Time(S)	Fabric	T _D + Obs. (μm)		Model II	T _D Calc. (μm)	
				Normalized	Corrected		Model* IIIA	Model** IIIB
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

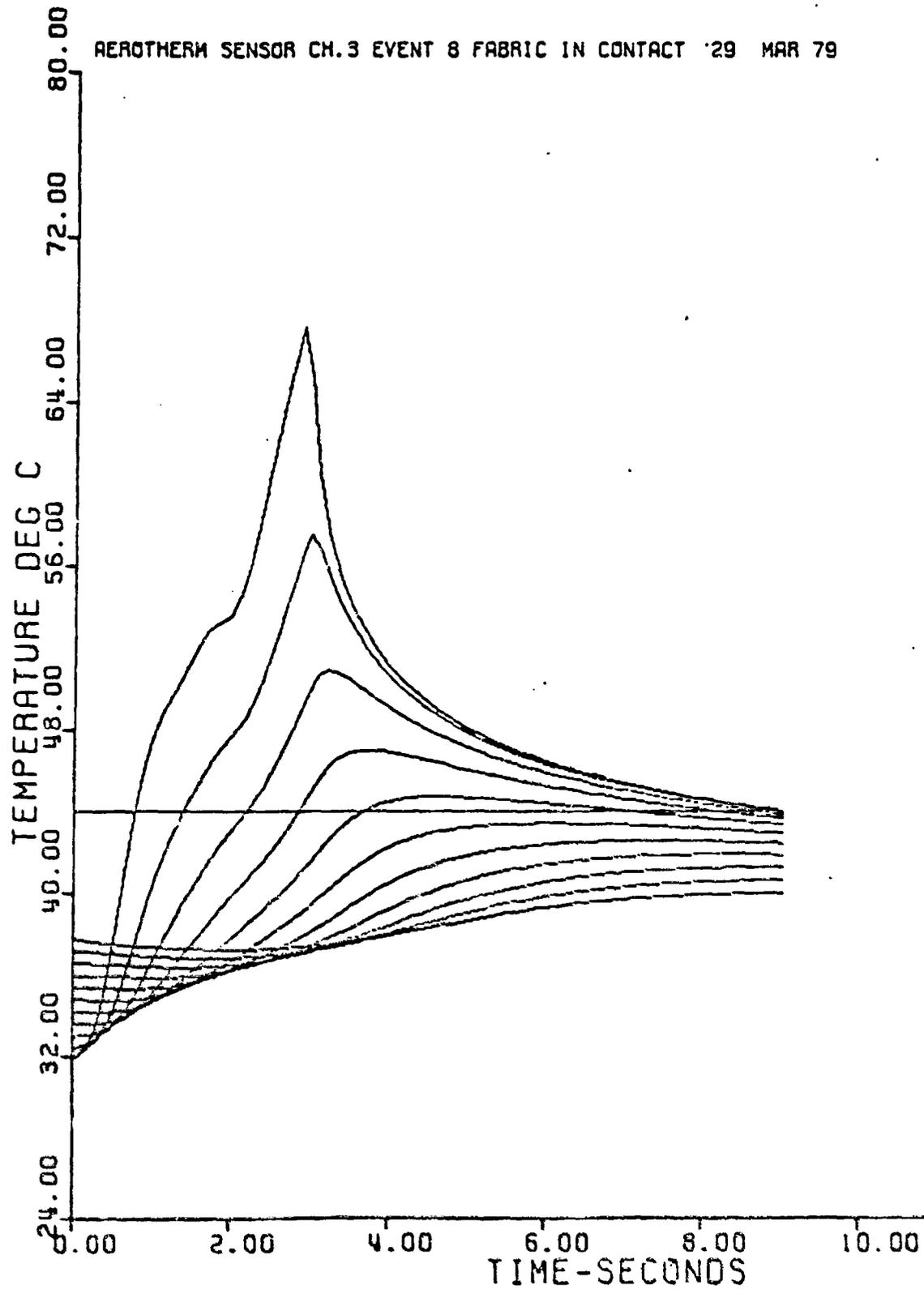


Figure 31.

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 200 μm , much more in line with a Model III_B prediction of 141 μm .

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 $\text{cm}^{-2} \text{sec}^{-1}$, 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 80 μ 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 80 μm 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 57.1 μm compared with 105.2 μm . 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 $\frac{1}{4}$ 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 ITRI (4)

TABLE IX

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

MODEL NAME OR DESCRIPTION: M12/88120(120.18) STOLL'S .4CAL BLOOD=.0007 STOLL'S INT.N'S 13 MAR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP1= 32.5000
DENS= 1.00000
Q1= 0.400000
SL= 0.220000
AK= 0.100000E-01
JINC= 12
TEMP2= 4.5000
ABSORB= 0.940000
BOIL= 100.150

PL2= 0.60
PLN2= 117.43
PL1= 0.78
PLN1= 285.52
DE2= 39189.98
DE1= 92534.98
ETIME= 3.60
ITIME= 88.00
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= 0.52994E+00
W= 0.14571E+00

D= -0.16000E+02
D= 0.52994E+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= 0.84170E+00
W= 0.68745E+00

D= 0.40532E+01
D= 0.48675E+01
D= 0.58732E+01

W	0.22340E+01	AT DEPTH (IN MICRONS)=	0.112935E-06
W	0.18999E+01	AT DEPTH (IN MICRONS)=	20.0000
W	0.16238E+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	0.10384E+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	0.56500E+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	0.23959E-01	AT DEPTH (IN MICRONS)=	600.000

MAXIMUM TEMPERATURE = 60.857

THRESHOLD DEPTH = 109.3

FINAL TIME = 14.03

Figure 32.

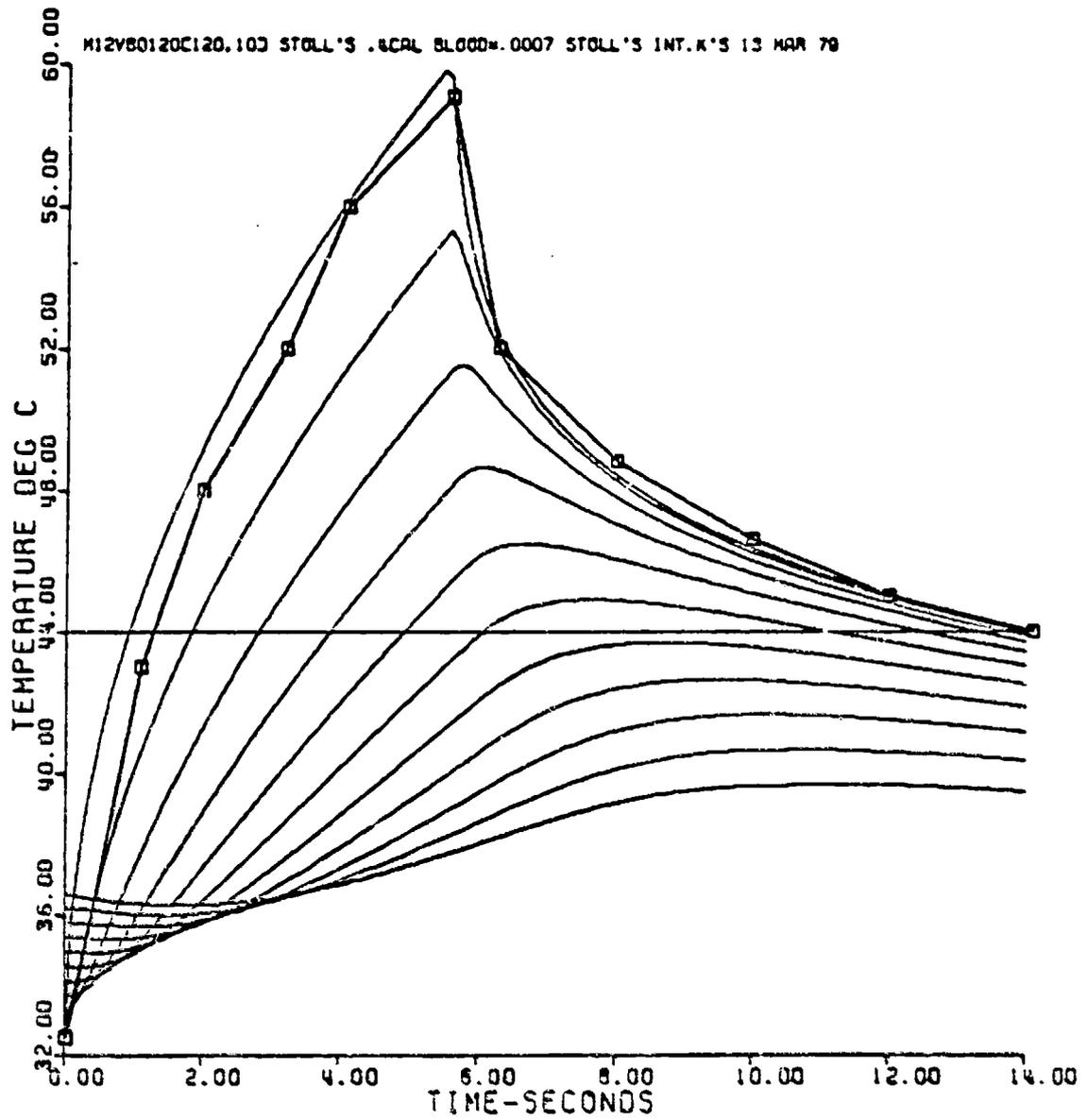


Figure 33.

MODEL NAME OR DESCRIPTION: M12V3745C(20.10) STOLL'S LOCAL CASE TEMPE=3.5 STOLL INTEG R 13 MAR 79

SKIN DIFFUSION DATA
INPUT PARAMETER LIST

TEMP10= 32.5000
DENS= 1.00000
Q1= 0.400000
BL= 0.220000
AN= 0.100000E-01
JINC= 12
TEMPE= 3.5000
ABSORB= 0.940000
BOIL= 100.150

PL2= 0.60
PLN2= 117.43
PL1= 0.78
PLN1= 205.52
DE2= 39105.00
DE1= 93534.90
ETIME= 5.00
ITIME= 80.00
NNTA= 8
BLOOD= 0.0010

ENTER 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(1)=
1 0.400 2 0.400

M= 0.20083E+01
M= 0.47328E+00
M= 0.12206E+00

D= -0.16000E+02
D= 0.52963E+01
D= 0.39915E+01

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

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

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

M	0.20083E+01	AT DEPTH (IN MICRONS)=	0.11253E-06
M	0.17081E+01	AT DEPTH (IN MICRONS)=	20.0000
M	0.14590E+01	AT DEPTH (IN MICRONS)=	40.0000
M	0.12516E+01	AT DEPTH (IN MICRONS)=	60.0000
M	0.10750E+01	AT DEPTH (IN MICRONS)=	80.0000
M	0.93214E+00	AT DEPTH (IN MICRONS)=	100.000
M	0.75456E+00	AT DEPTH (IN MICRONS)=	130.000
M	0.61500E+00	AT DEPTH (IN MICRONS)=	160.000
M	0.50430E+00	AT DEPTH (IN MICRONS)=	190.000
M	0.47328E+00	AT DEPTH (IN MICRONS)=	200.000
M	0.13206E+00	AT DEPTH (IN MICRONS)=	400.000
M	0.17497E-01	AT DEPTH (IN MICRONS)=	600.000

MAXIMUM TEMPERATURE = 59.765

THRESHOLD DEPTH = 90.17

FINAL TIME = 14.00

Figure 34.

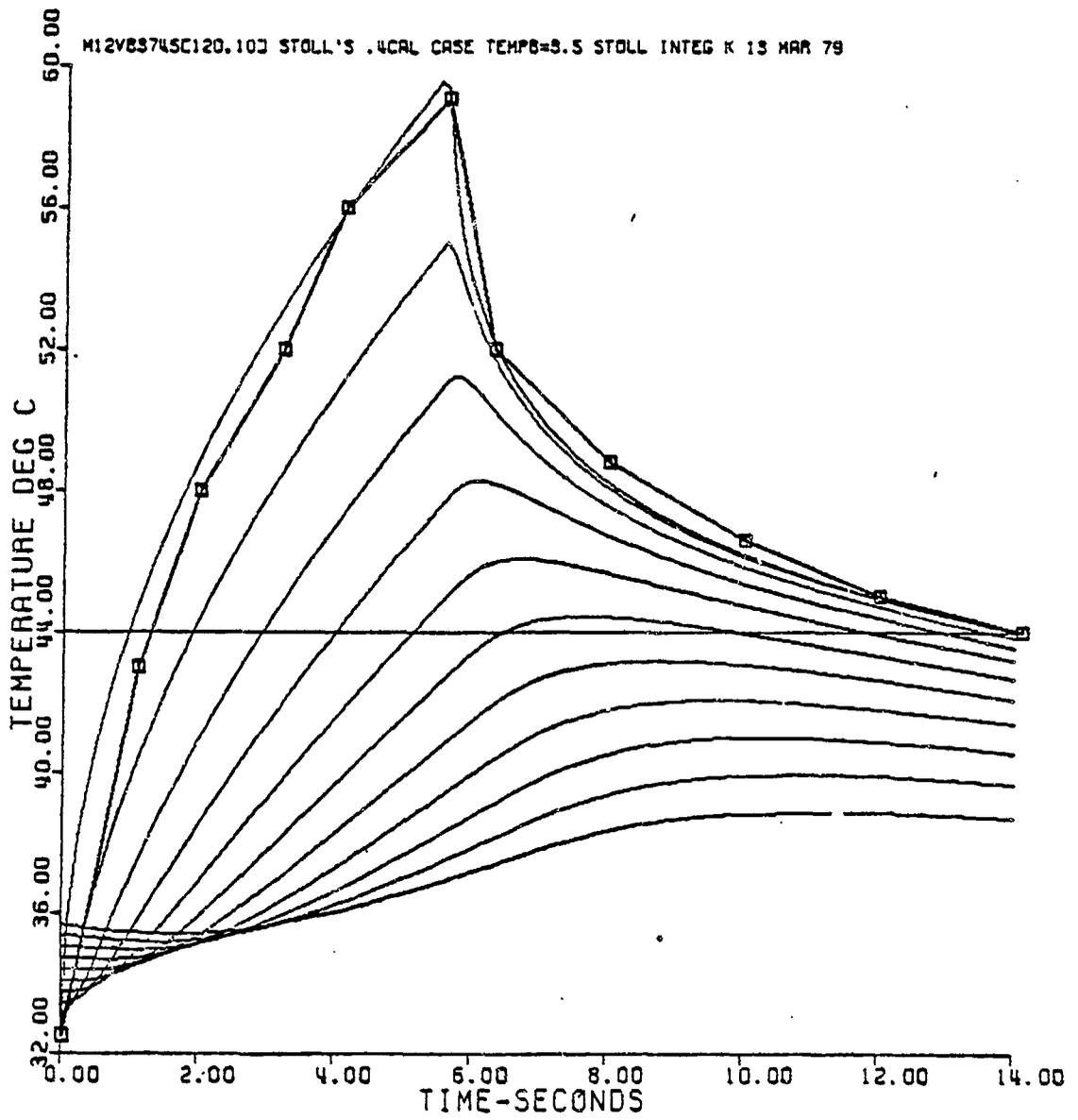


Figure 35.

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 $\frac{1}{4}$ " 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.

REFERENCES

1. Knox, F. S. III et al. Thermal Analysis Program, Final Report, Vol. 1 USAARL, Ft. Rucker, Alabama, Feb. 1974. Unpublished.
2. Knox, F. S. III, G. F. McCahan, Jr. and T. L. Wachtel. Use of the Pig as a Bioassay Substrate for Evaluation of Thermal Protective Clothing and Physical Sensor Calibration. Aerospace Med. 45(8):933-938, 1974.
3. Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Biomedical Constraints on Thermal Protective Flight Clothing Design: A Bioengineering Analysis. AGARD Conference Proceedings 255(63):1-11, Dec, 1978.
4. Takata, A. N., J. Rouse and T. Stanley. Thermal Analysis Program. Report No. ITRI-J6286, U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama, 36362, Contract No. DA13C01-G-0309, Feb., 1973.
5. Henriques, F. C. Studies of Thermal Injury. V. The Predictability and the Significance of Thermally Induced Rate Processes Leading to Irreversible Epidermal Injury. Archives of Path. 43:489-502, 1947.
6. Stoll, A. and L. C. Greene. Relationship between Pain and Tissue Damage Due to Thermal Radiation. J. Appl. Physiol. 14:373-382, 1959.
7. Weaver, J. A. and Stoll, A. M. Mathematical Model of Skin Exposed to Thermal Radiation. Aerospace Med. 40:24-30, 1969.
8. Mehta, A. and Wong, F. Measurement of Flammability and Burn Potential of Fabrics. Summary Report Dec. 1971-Jan. 1973. Project DSR 73884, Fuels Research Laboratory, M.I.T. Cambridge, Mass., Feb. 15, 1973.
9. Morse, H. L. et al. Analysis of the Thermal Response of Protective Fabrics. Technical Report AFML-TR-73-17, Jan. 1973. Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, 45433.
10. Calvin Lum, M.D., Trip Report: Microscopic Burn Damage Data - Consultation with Dr. Walter Trevethan, NAMI, Pensacola, Nov. 27-28, 1972.
11. Hinshaw, J. R. Progressive Changes in the Depth of Burns. Arch. Surg. 87:993-997, 1963.
12. Berkley, K. M., H. E. Pearse and T. P. Davis. Studies of Flash Burns: The Influence of Skin Temperature in the Production of Cutaneous Burns in Swine. University of Rochester Atomic Energy Project UR-338, August, 1954.

13. Perkins, J. B., H. E. Pearse and H. D. Kingsley. Studies on Flash Burns: The Relation of the Time and Intensity of Applied Thermal Energy to the Severity of Burns. University of Rochester, Atomic Energy Project, UR-217, December, 1952.
14. Stoll, Alice. Comments made during Thermal Protective Clothing Ad Hoc Working Conference (Tri-Service) - U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama, 3-4 April 1978.
15. Takata, A. N. Development of Criterion for Skin Burns. Aerospace Med. 45(6):634-637, 1974.
16. Lipkin, M. and Hardy, J. D. Measurement of Some Thermal Properties of Human Tissues. J. Appl. Physiol. 7(2):212-217. Sept., 1954.
17. Crank, J. and Nicholson, P. Proc. Cambridge Phil. Soc. 43:50, 1947.
18. Bruce, G. H., Peaceman, D. W., Rockford, H. H. and Rice, J. D. Trans. A.I.M.E. 198:79, 1953.
19. 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 Science Conference Proceedings, Volume II, (AD-A056437) pp. 267-281, 20-22 June 1978, U. S. Military Academy, West Point, N. Y., also reprinted in USAARL Report No. 78-15, June, 1978.
20. Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. How to Measure the Burn-Preventive Capability of Non-flammable Textiles: A Comparison of the USAARL Porcine Bioassay Technique with Mathematical Models. Burns 5(1)19-29, Sept., 1978.
21. Cooper, T. E. and G. J. Trezek. Correlation of Thermal Properties of Some Human Tissue with Water Content. Aerospace Med. 42(1):24-27, 1971.
22. Rushmer, Robert F., Konrad J. K. Buettner, John M. Short, George F. Odland. The Skin. Science 154(3747)343-348, Oct. 1966.
23. Basar, Erol. The Circulatory Autoregulation, Chap. 4 in Biophysical and Physiological Systems Analysis, Addison-Wesley Pub. Co., Reading, Mass, 1976.

APPENDIX A

BIBLIOGRAPHY - THERMAL PROJECT

Papers:

F. S. Knox III, George D. McCahan, Jr. and Thomas L. Wachtel. Use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. *Aerospace Med.* 45(8):933-938, 1974.

Wachtel, Thomas L., Francis S. Knox III, G. R. McCahan, Jr. Methods of preparing porcine skin for bioassay of thermal injury. *Military Medicine*, July, 1977.

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 Proceedings*, pp. 267-281, 20-22 June, 1978, Volume II, Principal Authors G thru M.

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. How to measure the burn-protective capability of nonflammable textiles: a comparison of the USAARL porcine bioassay technique with mathematical models. *Burns* (5):1:19-29, September, 1978.

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Biomedical constraints on thermal protective flight clothing design: A bioengineering analysis. *Proceedings of AGARD/NATO Aerospace Medical Panel Specialists' Meeting on Operational Helicopter Aviation Medicine*, Ft. Rucker, Alabama, 1-5 May 1978. AGARD Conference Proceedings No. 255 (63):1-11, Dec., 1978.

Abstracts:

Knox, Francis S. III, Thomas L. Wachtel and Stanley C. Knapp. Biomedical constraints on thermal protective flight clothing design: A bioengineering analysis. *AGARD/NATO Aerospace Medical Panel Specialists' Meeting on Operational Helicopter Aviation Medicine*, Fort Rucker, Alabama, 1-5 May 1978.

Knox, Francis S. III, T. L. Wachtel and S. C. Knapp. How to measure the burn preventive capability of nonflammable textiles: A comparison of the USAARL porcine bioassay technique with mathematical models. *5th International Congress on Burn Injuries*, Stockholm, Sweden, 18-22 June 1978. Abstract in Abstract Book.

Reports:

Albright, J., F. Knox, D. R. DuBois and G. M. Keiser. The testing and thermal protective clothing in a reproducible fuel fire environment, phase I report: a feasibility study. March, 1971, USAARL LR 71-3-3-2.

Reports (Continued):

Knox, Francis S. III, George R. McCahan, Jr., Thomas L. Wachtel, Walter P. Trevethan, Andrew S. Martin, David R. DuBois and George M. Keiser. Engineering test of lightweight underwear of the winter flight clothing system: Thermal protection. USAARL Report #71-19. June, 1971.

Albright, John D., Francis S. Knox III, David R. DuBois and George M. Keiser. The testing of thermal protective clothing in a reproducible fuel fire environment, a feasible study. USAARL Report #71-24. June, 1971.

Knox, Francis S. Preliminary results, conclusions and recommendations from the evaluation of helmet flammability - DH-132 and T56-6 helmets. June, 1972, USAARL LR 72-17-3-5.

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.

Knox, Francis S. and Robert W. Bailey. Results, conclusions and recommendations from the evaluation of helmet flammability - DH-132 and T56-6 helmets. May, 1973. USAARL LR 73-9-3-4.

Knox, Francis S. III and Ransom A. Nockton. Data analysis and mathematical modeling based on U. S. Army Aeromedical Research Laboratory's experimental porcine burn - Phase I data. 1 July 1975-30 September 1976. Contract DABT01-75-C-0257. LSU School of Medicine in Shreveport, Dept. of Physiology and Biophysics, Oct., 1976.

Knox, Francis S. III and Ransom A. Nockton. Data analysis and mathematical modeling based on U. S. Army Aeromedical Research Laboratory's experimental porcine burn data. Annual Summary Report, July 1977. USAMRDC Contract DAMD17-77-C-7004. LSU School of Medicine in Shreveport, Dept. of Physiology and Biophysics.

Wachtel, Thomas L., Francis S. Knox III and G. R. McCahan, Jr. A porcine bioassay method for analysis of thermally protective fabrics: a clinical grading system. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama, USAARL Report No. 78-8, June, 1978.

Knox, Francis S. III, Thomas L. Wachtel and George R. McCahan, Jr. Evaluation of four thermally protective fabrics using the USAARL bioassay method. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-9, June, 1978.

Knox, Francis S. III, Thomas L. Wachtel, George R. McCahan, Jr. and Stanley C. Knapp. The effect of fiber and dye degradation products (FDP) on burn wound healing. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-10, June, 1978.

Reports (Continued):

Knox, Francis S. III, Thomas L. Wachtel, Walter P. Trevethan and G. R. McCahan, Jr. A porcine bioassay method for analysis of thermally protective fabrics: a histological and burn depth grading system. U. S. Army Aeromedical Research Laboratory, Ft. Rucker, Alabama. USAARL Report No. 78-11, June, 1978.

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.

Presentations:

Knox, F. S. III. Protective clothing for aviators. Presented at the Third U. S. Army Aviation Accident Prevention Conference, Fort Rucker, Alabama. 18-19 August, 1971.

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.

Knox, Francis S. III. The use of the pig as a bioassay substrate for evaluation of thermal protective clothing and physical sensor calibration. Presented at the American Burn Association 5th Annual Meeting. 6 April, 1973, Dallas, Texas (16mm color, sound film, 20 min.).

Knox, T. (F.S. III), Stanley C. Knapp. Testing for thermal protection, an invited paper. 4th National Flame-Free Design Conference, March 11-13, 1975, San Diego, California.

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.

Knox, Francis S. III, Thomas L. Wachtel, George McCahan and Stanley C. Knapp. The effect of fiber and dye degradation products (FDP) on burn wound healing. Joint Committee on Aviation Pathology, Halton, England, Sept. 6-12, 1976.

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 $3.6 \pm 3\%$ 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 intensities 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 Arrhenius 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 overlaid. 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 Predict Experimentally 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 FIG.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	<ol style="list-style-type: none"> 1) Creates the pig directory FIG.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.
LSTMGRD	Builds a formatted 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 University 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 ITRI (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 ITRI."

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 correction 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 $I = I_0 \exp$

$\frac{\pi}{2}$
(-ax) and the formula $2 \int_0^{\pi/2} \exp(-N \cdot \xi_1) \cdot \cos \theta \cdot \sin \theta \, d\theta$ 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 incinerations. 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.
- N_{xtra} = Number of extra nodes between the surface and node 1 at
220µm
- Blood = Factor to adjust amount of cooling by blood usually set at .001
- DE₁ & DE₂ = $\Delta E/R$ from the Arrhenius relationship for tissue temperatures
from 44 to 50°C or over 50°C respectively
- PL₁, PLN, or PL₂ and PLN₂ = $\log P = \log N + y \log 10$
= 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


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C      ARITHMETIC FUNCTIONS FOR THERMAL CONDUCTIVITY (THKON) AND
C      DENSITY*HEAT CAPACITY
C
0016      THKON(Z) = (THCON(1)*Z+THCON(2))/(ROCON(1)*Z+ROCON(2))
0017      ROCP(Z) = (CPCON(1)*Z+CPCON(2))/(ROCON(1)*Z+ROCON(2))
C
0018      CALL ASSIGN(1,'RENEAU12.DAT')
0019      CALL ASSIGN(2,'SCRCH.TMP')
0020      CALL ASSIGN(3,'PIGBOIL.DAT')
C      SET UP PARAMETERS FOR THIS RUN
C.....
0021      READ(1,901)TEMP10,DENS,G0,BL,AK,BOIL,ABSORB
0022      901      FORMAT(7F10.5)
0023      READ(1,902)JINC,TEMPB,ITIME,ETIME,PCWATR,BLOOD
0024      902      FORMAT(11I0,7F10.5)
0025      READ(1,901)(CP(J,2),J=1,JINC)
0026      READ(1,901)(BK(J,2),J=1,JINC)
0027      READ(1,901)PL2,PLN2,PL1,PLN1,DE2,DE1
0028      READ(1,901)(WATER(I,2),I=1,JINC)
0029      CALL CLOSE(1)
0030      CALL ASSIGN(1,'XKRCH.TMP')
0031      FLUX(1) = G0
0032      FLUX(2) = G0
0033      NFLX = 2
0034      FILNAM(1) = NOFIL
0035      PPL1 = PL1
0036      PPLN1 = PLN1
0037      DDE1 = DE1
0038      NXTRA = 0
0039      NXTRA0 = 0
0040      700      TYPE 910
0041      TYPE 911,TEMP10,DENS,FLUX(1),BL,AK,JINC,TEMPB,ABSORB,BOIL
0042      TYPE 104,PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
0043      IF (NXTRA) TYPE 7003,(XTRA(I),I=1,NXTRA)
0045      7003      FORMAT('0EXTRA NODES: ',8F6.1)
0046      4          TYPE 906
0047      906      FORMAT(1X,'CONTINUE ? Y/N',T15,$)
0048      ACCEPT 220,RESP
0049      IF(RESP.NE.YES) GO TO 290
0051      5          CONTINUE
0052      TYPE 699
0053      699      FORMAT('IFUNCTION *'S'/'01 - REENTER INITIAL VALUES'/
1,' 2 - CHANGE SELECTED INITIAL VALUES'/' 3 - NO CHANGES'/
2,' 4 - EXIT'/'SENDER FUNCTION NO.:')
0054      ACCEPT 801,ANSR
0055      IANSR=ANSR
0056      TYPE 710 ,ANSR
0057      710      FORMAT('0ANSR=',F10.0)
0058      BB = 0
0059      IF(IANSR.EQ.2)BB=1
0061      GO TO (20,80,230,1111)IANSR
0062      20      TYPE 800,TEMP10
0063      800      FORMAT('/// PLEASE PROVIDE THE REQUESTED VALUES: '//
1T5,'TEMP10',G16.8,T15,$)
0064      ACCEPT 801,TEMP10
0065      801      FORMAT(F10.0)
0066      GO TO (200)BB
0067      21      TYPE 802,DENS
    
```

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0068 802 FORMAT(/T5, 'DENS', G16.8, T15, $)
0069 ACCEPT 801, DENS
0070 GO TO (200)BB
0071 22 TYPE 1
0072 1 FORMAT(/ '$FLUX FILE NAME (BLANK IF CONSTANT FLUX): ')
0073 ACCEPT 2, FILNAM
0074 2 FORMAT(5A4)
0075 IF (FILNAM(1).EQ.NCFIL) GO TO 799
0077 CALL ASSIGN(4, FILNAM)
0078 READ(4) ID, TDELTA, NFLX
0079 TYPE 3, ID, TDELTA, NFLX
0080 READ(4) (FLUX(I), I=1, NFLX)
0081 CALL CLOSE (4)
0082 GO TO (200)BB
0083 GO TO 23
0084 799 TYPE 788, FLUX(1)
0085 788 FORMAT(/ '$CONSTANT Q-VALUE = ', G16.8, ' NOW. IT SHOULD BE Q = ')
0086 ACCEPT 801, FLUX(1)
0087 FLUX(2)=FLUX(1)
0088 NFLX = 2
0089 DO 777 I=1, 4
0090 777 ID(I) = IBLNK
0091 GO TO (200)BB
0092 23 TYPE 804, BL
0093 804 FORMAT(/T5, 'BL', G16.8, T15, $)
0094 ACCEPT 801, BL
0095 GO TO (200)BB
0096 24 TYPE 805, AK
0097 805 FORMAT(/T5, 'AK', G16.8, T15, $)
0098 ACCEPT 801, AK
0099 GO TO (200)BB
0100 25 TYPE 806, JINC
0101 806 FORMAT(/T5, 'JINC', I10, T15, $)
0102 ACCEPT 801, JINC
0103 IF (JINC.GT.MAXDIM) JINC=MAXDIM
0104 GO TO (200)BB
0105 820 FORMAT(I10)
0106 26 TYPE 807, TEMPB
0107 807 FORMAT (/T5, 'TEMPB', F10.0, T15, $)
0108 ACCEPT 801, TEMPB
0109 GO TO (200)BB
0110 27 TYPE 808, ETIME
0111 808 FORMAT(/T5, 'ETIME', G16.8, T15, $)
0112 ACCEPT 801, ETIME
0113 GO TO (200)BB
0114 28 TYPE 809, PL1
0115 809 FORMAT(/T5, 'PL1', G16.8, T15, $)
0116 ACCEPT 801, PL1
0117 PPL1=PL1
0118 GO TO (200)BB
0119 29 TYPE 810, PLN1
0120 810 FORMAT(/T5, 'PLN1', G16.8, T15, $)
0121 ACCEPT 801, PLN1
0122 PPLN1=PLN1
0123 GO TO (200)BB
0124 30 TYPE 811, PL2
0125 811 FORMAT(/T5, 'PL2', G16.8, T15, $)
0126 ACCEPT 801, PL2
0127
    
```

```

0128      GO TO (200)BB
0129 31    TYPE 812,PLN2
0130 812   FORMAT(/TS,'PLN2',G16.8,T15,$)
0131      ACCEPT 801,PLN2
0132      GO TO (200)BB
0133 32    TYPE 813,DE1
0134 813   FORMAT(/TS,'DE1',G16.8,T15,$)
0135      ACCEPT 801,DE1
0136      DDE1=DE1
0137      GO TO (200)BB
0138 33    TYPE 814,DE2
0139 814   FORMAT(/TS,'DE2',G16.8,T15,$)
0140      ACCEPT 801,DE2
0141      GO TO (200)BB
0142 34    TYPE 815,ITIME
0143 815   FORMAT(/TS,'ITIME',G16.8,T15,$)
0144      ACCEPT 801,ITIME
0145      GO TO (200)BB
0146 35    TYPE 816,ABSORB
0147 816   FORMAT(/TS,'ABSORB',G16.8,T15,$)
0148      ACCEPT 801,ABSORB
0149      GO TO (200)BB
0150 36    TYPE 817,BOIL
0151 817   FORMAT(/TS,'BOIL',G16.8,T15,$)
0152      ACCEPT 801,BOIL
0153      GO TO (200)BB
0154 7100  TYPE 7005,NXTRA
0155      NXTRAO = NXTRA
0156 7005  FORMAT(/TS,'NO. OF EXTRA NODES ',I4,2X,$)
0157      ACCEPT 7007,NXTRA
0158 7007  FORMAT(I4)
0159      IF (NXTRA.EQ.0) GO TO 7230
0161      IF (NXTRA.GT.8) NXTRA=8
0163      IF (NXTRAO) TYPE 7009,(XTRA(I),I=1,NXTRAO)
0165 7009  FORMAT('CURRENT: ',8F6.1)
0166      TYPE 7011
0167 7011  FORMAT('ENTER NEW VALUES SEPARATED BY COMMAS, OR <CR> IF PROGRAM
1/' IS TO CALCULATE VALUES:')
0168      ACCEPT 7013,XTRA
0169 7013  FORMAT(8F8.1)
0170      IF (XTRA(1)) GO TO 7210

C
C NUMERATOR IN NEXT STATEMENT IS SPECIFIC FOR N-POINT MODEL
C
0172      DXTRA = D2/(NXTRA+1)
0173      DO 7200 I=1,NXTRA
0174 7200  XTRA(I) = DXTRA*I
0175 7210  DO 7220 I=1,NXTRA
0176 7220  XTRALG(I) = ALOG(XTRA(I))
0177 7230  CONTINUE
0178      NXTRAO = NXTRA
0179      GO TO (200)BB
0180 37    TYPE 818,BLOOD
0181 818   FORMAT(/TS,'BLOOD = ',F10.4,3X)
0182      ACCEPT 801,BLOOD
0183      GO TO 200
0184 80    TYPE 600
0185 600   FORMAT(/TS,'PICK A NUMBER',//T10,'1=TEMP10',T30,'8=ETIME'//

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IT10,'2=DENS',T30,'9=PL1',/T10,'3=Q1',T30,'10=PLN1',//
IT10,'4=BL',T30,'11=PL2',/T10,'5=AK',T30,'12=PLN2',//
IT10,'6=JINC',T30,'13=DE1',/T10,'7=TEMPB',T30,'14=DE2',//
IT10,'15=ITIME',T30,'16=ABSORBTIVITY'/
IT10,'17=BOIL',T30,'18=EXTRA NODES'/T10,'19=BLOOD',T30//)
0186      BB=1
0187      ACCEPT 601,INUM
0188      601  FORMAT(12)
0189      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
0190      200  TYPE 210
0191      210  FORMAT(/'ANOTHER CHANGE ? TYPE Y/N')
0192      ACCEPT 220,RESP
0193      220  FORMAT(A1)
0194      IF(RESP.EQ.'YES')GO TO 80
0196      GO TO 700
0197      230  REWIND 1
0198      TYPE 907
0199      907  FORMAT('ENTER MODEL NAME OR DESCRIPTION (80 CHARACTERS)')
0200      ACCEPT 908,DSCRIPT
0201      908  FORMAT(20A4)
0202      WRITE(3,909)DSCRIPT
0203      WRITE(7,909)DSCRIPT
0204      909  FORMAT(' MODEL NAME OR DESCRIPTION: ',20A4)
C
C      ASSIGN LOGICAL UNIT 4 FOR PLOT OUTPUT
C
0205      CALL ASSIGN(4,'PIGBOIL.PLT')
0206      WRITE(4)DSCRIPT
0207      AJ=JINC
0208      Q1 = FLUX(1)
0209      H1=BL/(AJ-1.0)
C
C      INITIALIZE DEPTH NODES D(J)
C
0210      D(1) = -16.
0211      DO 106 I=2,JINC
0212      D(I) = H1*(I-1)*1.E4
0213      106  D(I) = ALOG(D(I))
0214      DTJ = TEMPB/(JINC-1)
0215      DO6J=1,JINC
0216      WATER(J,1) = WATER(J,2)
0217      CP(J,1) = CP(J,2)
0218      BK(J,1) = BK(J,2)
0219      XTIME(J) = 0.
0220      ZTIME(J) = 0.
0221      IFLAG(J) = 0.
0222      JFLAG(J) = 0.
0223      6    T(J) = DTJ*(J-1)+TEMP10
0224      WRITE(4)0.,(T(J),J=1,JINC)
0225      WRITE(3,910)
0226      WRITE(7,910)
0227      910  FORMAT(1H0,55X,'SKIN DIFFUSION DATA'//,55X,' INPUT PARAMETER LIST'//)
0229      WRITE(3,911)TEMP10,DENS,Q1,BL,AK,JINC,TEMPB,ABSORB,BOIL
0229      WRITE(7,911)TEMP10,DENS,Q1,BL,AK,JINC,TEMPB,ABSORB,BOIL
    
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0230 911 FORMAT(1X,52X,8H TEMPI0=,G14.6/54X,5HDENS=,G14.6/54X,3HQ1=,G14.6/
154X,3HBL=,G14.6/54X,3HAK=,G14.6/54X,5HJINC=,16/54X,6HTEMPB=,F8.4/
154X,'ABSORB=',G14.6/54X,'BOIL=',G14.6/)
0231 WRITE(3,104)PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
0232 IF (NXTRA) WRITE(3,7003)(XTRA(I),I=1,NXTRA)
0234 WRITE(7,104)PL2,PLN2,PL1,PLN1,DE2,DE1,ETIME,ITIME,NXTRA,BLOOD
0235 IF (NXTRA) WRITE(7,7003)(XTRA(I),I=1,NXTRA)
0237 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=',14/54X
1,'BLOOD=',F10.4)
0238 WRITE(3,3)ID,TDELT,NFLX,(1,FLUX(I),I=1,NFLX)
0239 WRITE(7,3)ID,TDELT,NFLX,(1,FLUX(I),I=1,NFLX)
0240 3 FORMAT('0FLUX FILE 1.D.: ',4A2,F7.2,14:/' FLUX(I)='
1/(' ',10(15,F8.3)))
0241 JJJJ=0
0242 F(1)=-BK(2,1)/(2.0*H1*H1)-BK(1,1)/(2.0*H1*H1)
0243 G(1)=(BK(1,1)+BK(2,1))/(2.0*H1*H1)+DENS*CP(1,1)/AK
0244 H(1)=0.0
0245 ITR=0
0246 IFLX=1
0247 EITIM1=ITIME+1.
0248 IF (FILNAM(1).EQ.NOFIL) TDELT=AK
0250 FFDG=TDELT/AK
0251 KFDG=FFDG+.0001
0252 TMPMAX=0.
0253 QCONST=ABSORB*60.892
0254 BLUD=0.
0255 M=-1
0256 TIME=0.
0257 ITFLG=0
0258 GO TO 12

C
C STATEMENT 11 AUTOMATICALLY CHOOSES PROPER INTERVAL IN FLUX TABLE
C FOR COMPUTATION OF QT AND QI 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
0259 11 IF (MOD(ITTR,KFDG).EQ.0.AND.IFLX.LT.NFLX) IFLX=IFLX+1
0261 ITR=ITTR+1
0262 P=(ITTR-KFDG*(IFLX-2))/FFDG
0263 QT=(1.-P)*FLUX(IFLX-1)+P*FLUX(IFLX)
0264 QI=QT*QCONST
0265 JJJJ=JJJJ+1
0266 TIME=JJJJ*AK
0267 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
0269 IF (TIME.GE.ETIME) QI=-5.E-4*(T(1)-23.9)
0271 Z(1)=-F(1)*T(2)-((BK(1,1)+BK(2,1))/(2.0*H1*H1)-(DENS*CP(1,1))/AK)
1*T(1)+QI
0272 N=JINC-1
0273 DO10J=2,N
    
```

```

0274      F(J)=-BK(J+1,1)/(2.0*H1*H1)
0275      G(J)=(BK(J,1)+BK(J+1,1))/(2.0*H1*H1)+DENS*CP(J,1)/AK
0276      H(J)=-BK(J,1)/(2.0*H1*H1)
0277      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)
0278      IF (J.GT.3) GO TO 10
0280      Z(J) = Z(J)-1.675*H1/BK(J,1)*BLUD*(T(J)-TEMP10+TEMPB)
0281 10      CONTINUE
0282      F(JINC)=0.0
0283      G(JINC)=(BK(JINC,1)+BK(JINC-1,1))/(2.0*H1*H1)+DENS*CP(JINC,1)/AK
0284      H(JINC)=-((BK(JINC,1)+BK(JINC-1,1))/(2.0*H1*H1)
0285      DT=T(JINC-1)-(TEMP10+TEMPB)
0286      Z(JINC)=(H(JINC)+(DENS*CP(JINC,1)/AK))*T(JINC)
1-H(JINC)*T(JINC-1)-BK(JINC,1)*DT/H1**2
0287      W(1)=G(1)
0288      U(1)=Z(1)/W(1)
0289      DO40J=2,JINC
0290      JM1=J-1
0291      SV(JM1)=F(JM1)/W(JM1)
0292      W(J)=G(J)-H(J)*SV(JM1)
0293 40      U(J)=(Z(J)-H(J)*U(JM1))/W(J)
0294      T(JINC)=U(JINC)
0295      KK=JINC-1
0296      DOS0J=1, KK
0297      KMJ=JINC-J
0298      IF (IFLAG(KMJ).EQ.1) GO TO 203
0300      T(KMJ)=U(KMJ)-SV(KMJ)*T(KMJ+1)
0301      IF (JFLAG(KMJ).EQ.1) GO TO 50
0303      IF (T(KMJ).LT.BOIL) GO TO 50
0305      T(KMJ) = BOIL
0306      IF (KMJ.EQ.1) GO TO 109
0308      Q(KMJ) = BK(KMJ,1)*(T(KMJ)-T(KMJ+1))/H1
0309      GO TO 205
0310 109      Q(KMJ) = QT
0311 205      XTIME(KMJ) = 539.*H1/Q(KMJ)*WATER(KMJ,1)
0312      ZTIME(KMJ) = XTIME(KMJ)+TIME
0313      IFLAG(KMJ) = 1
0314      GO TO 50
0315 203      IF (TIME.LT.ZTIME(KMJ)) GO TO 50
0317      WATER(KMJ,1) = PCWATR
0318      CP(KMJ,1) = ROCP(WATER(KMJ,1))
0319      BK(KMJ,1) = THKON(WATER(KMJ,1))
0320      IFLAG(KMJ) = 0
0321      XTIME(KMJ) = 0.
0322      JFLAG(KMJ) = 1
0323 50      CONTINUE
C
C INTERPOLATE EXTRA TEMPERATURES BETWEEN SURFACE AND 2ND NODE IF CALLED FOR
C
0324      IF (NXTRA.EQ.0) GO TO 7360
0326      IF (T(2).NE.T(1)) GO TO 7320
C
C CONSTANT TEMPERATURE
C
0328      DO 7310 I=1,NXTRA
0329 7310      XTMP(I) = T(2)
0330      GO TO 7360
0331 7320      IF (T(2).NE.T(3))GO TO 7340

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```

C
C LINEAR INTERPOLATION
C
0333 DO 7330 I=1,NXTRA
0334 P = XTRA(I)/D2 ID(1) = 0.
0335 7330 XTMP(I) = (1.-P)*T(1)+P*T(2)
0336 GO TO 7360

C
C 3-POINT LAGRANGE INTERPOLATION FOR EQUALLY SPACED ABSCISSAE
C
0337 7340 DO 7350 I=1,NXTRA
0338 P = (XTRA(I)-D2)/D2 ID(1) = 0. (SURFACE)
0339 7350 XTMP(I) = .5*P*(P-1.)*T(1)+(1.-P**2)*T(2)+.5*P*(P+1.)*T(3)
0340 7360 CONTINUE
0341 IF (ABS(ETIME-TIME).GT..5*AK) GO TO 48
0342 DO 44 I=1,JINC
0343 IF (IFLAG(I).EQ.0) GO TO 44
0344 WATER(I,1) = (ZTIME(I)-TIME)/XTIME(I)*(WATER(I,1)-PCWATR)+PCWATR
0345 CP(I,1) = ROCP(WATER(I,1))
0346 BK(I,1) = THKON(WATER(I,1))
0347
0348 44 CONTINUE
0349 DO 45 I=1,JINC
0350 XTIME(I) = 0.
0351 IFLAG(I) = 0
0352 45 JFLAG(I) = 1
0353 48 CONTINUE
0354 IF (T(1).GT.TMPMAX) TMPMAX=T(1)
0355 ITFLG = -1 ITFLG SET TO 0 IF ANY TEMPERATURE .GE. 44 DEGREES
0356 DO 13 J=1,JINC
0357 IF (T(J).GE.44.) GO TO 14
0358 DW(J) = 0.
0359 GO TO 13
0360 14 CONTINUE
0361 ITFLG = 0
0362 IF (T(J).GE.50.) GO TO 51
0363 PL1 = PPL1
0364 PLN1 = PPLN1
0365 DE1 = DDE1
0366 GO TO 15
0367 51 PL1=PL2
0368 PLN1=PLN2
0369 DE1=DE2
0370 DWLN=PL1+PLN1-DE1/(T(J)+273.)
0371 DW(J) = EXP(DWLN)
0372 13 CONTINUE
0373 WRITE(2)DW
0374 IF (NXTRA.EQ.0) GO TO 7400
0375 DO 7395 J=1,NXTRA
0376 IF (XTMP(J).GE.44.) GO TO 7370
0377 XDW(J) = 0.
0378 GO TO 7395
0379 7370 IF (XTMP(J).GE.50.) GO TO 7380
0380 PL1 = PPL1
0381 PLN1 = PPLN1
0382 DE1 = DDE1
0383 GO TO 7390
0384 7380 PL1 = PL2
0385 PLN1 = PLN2

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0393      DE1 = DE2
0394 7390  DWLN = PL1+PLN1-DE1/(XTMP(J)+273.)
0395      XDW(J) = EXP(DWLN)
0396 7395  CONTINUE
0397      WRITE(1)XDW
0398 7400  CONTINUE
0399      EMTIME = AINT(1000.*(TIME+.00001))/100.
0400      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
0402      IF (ITFLG.AND.TIME.GE.ETIME) GO TO 12
0404      IF (JJJJ.EQ.M*100.OR.JJJJ.EQ.1) GO TO 12
0406      GO TO 11
0407      12 WRITE(3,840)TIME
0408      TYPE 840,TIME,(T(I),XTIME(I),I=1,JINC)
0409 840  FORMAT('0',45X,5HTIME=F10.6:,T4,'T=' .6X,'XTIME='/' .2G12.4)
0410      WRITE(3,842)(XTIME(I),I=1,JINC)
0411 842  FORMAT(2X,'XTIME=',F10.5)
0412      WRITE(3,914)T(1),CP(1,1),BK(1,1)
0413      IF (NXTRA.EQ.0) GO TO 7420
0415      DO 7410 J=1,NXTRA
0416 7410  WRITE(3,914)XTMP(J)
0417 7420  WRITE(3,914)(T(J),CP(J,1),BK(J,1),J=2,JINC)
0418 914  FORMAT(2X,'T=',G16.5:,2X,'CP=',G16.5,2X,'BK=',G16.5)
0419      M=M+1
0420      EM = M
0421      IF (TIME.GE.ITIME.OR.ITFLG.AND.TIME.GE.ETIME) GO TO 100
0423      GO TO 11
0424 100  CONTINUE
0425      REWIND 2
0426      READ(2)DW
0427      DO 17 I=1,JINC
0428 17  SUM(I) = .5*DW(I)
0429      DO 16 J=2,JJJJ-1
0430      READ(2)DW
0431      DO 16 I=1,JINC
0432 16  SUM(I)=SUM(I)+DW(I)
0433      READ(2)DW
0434      DO 88 I=1,JINC
0435 88  W(I) = (SUM(I)+.5*DW(I))*AK
0436      REWIND 2
0437      IF (NXTRA.EQ.0) GO TO 7460
0439      REWIND 1
0440      READ(1)XDW
0441      DO 7430 J=1,NXTRA
0442 7430  SUM(J) = .5*DW(J)
0443      DO 7440 I=2,JJJJ-1
0444      READ(1)XDW
0445      DO 7440 J=1,NXTRA
0446 7440  SUM(J) = SUM(J)+XDW(J)
0447      READ(1)XDW
0448      DO 7450 J=1,NXTRA
0449 7450  XW(J) = (SUM(J)+.5*XDW(J))*AK
0450      REWIND 1
0451 7460  CONTINUE
C
C      SELECT W(J) AND D(J) NEAR W(J) =1
0452      NN = 3
0453      DO 110 J=1,JINC

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0454      JLT1 = J
0455      IF(W(J).GT.1.)GO TO 110
0457      IF(W(J).EQ.1.)GO TO 111
0459      IF (J.EQ.1) JLT1=2
0461      IF (J.EQ.JINC) JLT1=JINC-1
0463      GO TO 112
0464 110    CONTINUE
0465      JLT1 = JINC          I EXTRAPOLATE
0466      NN = 2
0467 112    WRITE(3,120)(W(K),K=JLT1-1,JLT1+1)
0468      WRITE(7,120)(W(K),K=JLT1-1,JLT1+1)
0469 120    FORMAT(/(1X,'W=',E20.5))
0470      WRITE(3,121)(D(K),K=JLT1-1,JLT1+1)
0471      WRITE(7,121)(D(K),K=JLT1-1,JLT1+1)
0472 121    FORMAT(/(1X,'D=',E20.5))
0473      IF (NXTRAO.EQ.0.OR.JLT1.GT.2) GO TO 1005
0475      TYPE 7015
0476 7015  FORMAT('BW=1 LIES ABOVE NODE 2. INTERCOLLATING VALUES OF D AND W' /
1. ' COMPUTED FROM INTERPOLATED VALUES OF D AND TEMPERATURE' /)
0477      WRITE(3,7015)
0478      WRITE(7,7015)
0479      WRITE(1)D(1)
0480      WRITE(2)W(1)
0481      DO 7470 J=1,NXTRA
0482      WRITE(1)XTRALG(J)
0483 7470   WRITE(2)XW(J)
0484      DO 7480 J=2,JINC
0485      WRITE(1)D(J)
0486 7480   WRITE(2)W(J)
0487      REWIND 1
0488      REWIND 2
0489      DO 7490 J=1,JINC
0490      READ(1)D(J)
0491 7490   READ(2)W(J)
0492      REWIND 1
0493      REWIND 2
0494      NXTRAO = 0
0495      GO TO 7460
0496 1005   CONTINUE
0497      NXTRAO = NXTRA
0498      IF (W(JLT1+1).EQ.0..AND.NN.EQ.3) NN=2
0500      CALL DEPTH(D(JLT1-1),W(JLT1-1),NN,TD,IERR)
0501      IF (IERR.EQ.0) GO TO 102
0503      TYPE 1002
0504      WRITE(3,1002)
0505      WRITE(7,1002)
0506 1002   FORMAT('0ERROR IN SUBROUTINE 'DEPTH'. EXITING.' /)
0507      GO TO 290
0509 102    CONTINUE
0509      IF (NN.EQ.2.AND.JLT1.EQ.JINC) GO TO 1000
0511      GO TO 1020
0512 111    TD=EXP(D(J))
0513 999    FORMAT(/(1X,'THRESHOLD DEPTH = ',G20.4)
0514      GO TO 1020
0515 1000   WRITE(3,1001)MAXDIM
0516      WRITE(7,1001)MAXDIM
0517 1001   FORMAT(/(1X,'THE MODEL BLEW UP: DAMAGE > 1 AT NODE ',I2/)
0518 1020   WRITE(3,101)(W(1),I=1,JINC)
    
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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(/'SDO 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. ' ''KRCM.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 TCPLT AND THEN (7,11)RASM 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
BI	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
PLN1	011664	REAL*4	VARIABLE
DDE1	011670	REAL*4	VARIABLE
NXTRA	011674	INTEGER*2	VARIABLE
NXTRAO	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
KNJ	012026	INTEGER*2	VARIABLE
ABS	000000	REAL*4	PROCEDURE
DNLN	012030	REAL*4	VARIABLE
EXP	000000	REAL*4	PROCEDURE
EMTIME	012034	REAL*4	VARIABLE
AINI	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
DEPTN	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

```

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 = 3
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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