HUMAN TOLERANCE LIMIT TO ELEVATED TEMPERATURE: AN EMPIRICAL APPROACH TO THE DYNAMICS OF ACUTE THERMAL COLLAPSE

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Charles R. Crane, Ph.D.

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Federal Aviation Administration
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Civil Aeromedical Institute
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Human Tolerance Limit to Elevated Temperature: An Empirical Approach to the Dynamics of Acute Thermal Collapse

Fire in the environment of an aircraft accident significantly increases the probability of serious injuries and death for those who otherwise would survive. Heat and the toxic gases that result from burning of fuel and thermal degradation of nonmetallic materials are the two agents primarily responsible for this increased risk. This report addresses the relationship between environmental temperature and that human response most closely associated with the potential for escape from a thermally hazardous environment, namely physical incapacitation (or thermal collapse). Elsewhere (1), the author has discussed human tolerance limits for toxic systemic gases.

There are situations in which humans are expected to perform satisfactorily while exposed to an elevated-temperature environment. As a result of such needs, there have been many experimental and theoretical

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(1) Charles R. Crane, "Human Tolerance Limits to Systemic Toxic Gases" Memorandum Report No. AAC-114-78-1, April 14, 1978.

studies that attempted to define thermal tolerance limits in terms of performance decrements, personal comfort, or tissue injury. Most of these studies have involved relatively long exposure periods--hours, days, or even weeks.

Less numerous are experimental studies of the acute situation, i.e., studies that subject humans to temperatures that cause thermal collapse in a relatively short time. Possibly this is so because such studies are not so relevant to the work situation. Even in the few high-temperature studies, the tolerance limits have usually been defined in terms of performance decrements, personal discomfort or pain, or occasionally skin burns of moderate severity.

Exposure-response relationships developed for the chronic and the acute situations have been characterized by their detailed use of theoretical concepts, involving complete thermal balance equations for the human body, radiant emissivity and absorptivity factors, effects of clothing, humidity, activity level, metabolic rate, and other factors.

Acute exposure of humans to thermal environments of sufficient intensity to result in thermal collapse has been the subject of relatively few experimental investigations. This is not surprising because intense pain and potentially serious tissue burns may occur before incapacitating hyperthermia. This is illustrated almost daily by fire victims who, during escape from burning environments suffer severe burns and intense pain, yet most importantly, they escape the hazardous environment <u>by their own actions</u> in spite of the pain and tissue damage. Obviously, then, identification of a thermal tolerance limit related to loss of escape potential from a post-crash fire situation must go beyond those limits that produce pain and even serious burns.

The rationale of the present approach was derivation of the simplest and most direct relationship that could be based on the few pertinent empirical studies that were located in the scientific literature. The results of this effort should provide, at the least, a working foundation that could be utilized as a first approximation of the effect of the thermal component on survivability in a post-crash fire. The accuracy of an empirically derived relationship should be open to improvement as better data become available from additional studies.

A search--significant, but not exhaustive--of the more readily available literature yielded four experimental data points for human heat tolerance limits that the author felt were appropriate to the endpoint in question, i.e., physical collapse from a thermal overload. The measured thermal parameter was air temperature, the subjects were "healthy adult males," and the clothing was "usual business dress" (1 Clo).

A least-squares linear regression technique was utilized to fit an equation to the four data points, presented in Table 1. The derived equation is:

$$t_c = Q_o/T^{3.61} \tag{1}$$

where, t_c is time-to-thermal collapse, in minutes,

T is air temperature, in ^oC, and

$Q_o = 4.1 \times 10^8$.

Q_o is the statistically derived proportionality constant; it is a quantity related to the number of calories that the body could absorb before incapacitation.

After this relationship (Eq. 1) was derived, an additional four data points were found in the literature. Plotting these four new points on a graph of the original equation (Eq. 1) revealed that two fell on the original line and the remaining two were near it. With this apparent satisfactory fit of additional points to the curve, no attempt was made to derive a new relationship using all eight points. The four additional points are presented in Table 2, and the graph of Equation 1 is presented in Figure 1.

Equation 1 can be used to calculate a predicted time-to-collapse for a person exposed to an air temperature of $T^{o}C$. The exposure, however, must be to a constant air temperature of the chosen magnitude. This constraint, which is imposed by the experimental protocol that produced the original data, places a severe limitation on the utility of this relationship (Eq. 1) in the context of people involved with real fires, for in such situations the air temperature is not constant.

The author's treatment of this problem was as follows:

Since Q_o is the proportionality constant that relates an air temperature to the time that can be spent in that environment before collapse, consider Q_o as a heat factor related to the number of calories that a body must absorb from the environment to produce thermal collapse. However, for a time interval t_1, such that the product $t_1 \cdot T_1^{3.61}$, is less than 4.1×10^8, thermal collapse is not produced, but that product, which we will call Q_1, represents the heat load added to the body by that exposure. Now change the temperature to T_2, and expose for an additional interval, t_2; the body would increase its heat content by an additional, $t_2 \cdot T_2^{3.61} = Q_2$ heat units. If this process is continued until the sum of all the Q_i's equals Q_o, i.e., 4.1×10^8, then thermal collapse results and the total exposure time-to-collapse would be the sum of all the individual exposure times, t_i. Therefore, during a changing temperature exposure, if we select successive intervals of time that are sufficiently short we can consider the temperature to be constant over that time interval, and we can accumulate those successive increments of Q.

So,

$$t_c = t, \text{ when} \sum T^{3.61} \Delta t = Q_o = 4.1 \times 10^8 \qquad (2)$$

or,

$$t_c = t, \text{ when } Q_o - \sum T^{3.61} \Delta t = 0. \qquad (2a)$$

If T is a known function of t, then

$$t_c = t, \text{ when } Q_o - \int T^{3.61} dt = 0. \qquad (3)$$

For experimental tests, T can be measured continuously with suitable transducers and Equation 2a can be used to indicate the scenario time at which thermal incapacitation would be predicted.

A program, in BASIC, that can be used on a simple programmable calculator, such as the Hewlett-Packard

9830, equipped with a plotter, was written to illustrate the application of Equation 2 (or Eq. 3). Figure 2 illustrates the theoretical situation for which environmental temperature, T, is constant. As exposure time at temperature T ($140^{o}C$) increases, the changing value, $Q_o - Q_i$, is plotted along with the value of T. This value, $Q_o - Q_i$, represents the body's reserve heat capacity, that is, the difference between the amount of heat already absorbed by the body and the amount that results in incapacitation. The third plotted value is the predicted time remaining before incapacitation occurs, which would be synonymous with remaining escape time. This predicted time, at any instant during the exposure, is, however, based on the presumption that the temperature will remain constant at its present value. Remaining escape time and body heat reserve values will go to zero simultaneously. The elapsed scenario time at which these parameters become zero is therefore the actual escape time for that thermal profile, and is equal to the value of t_c that one would obtain if Eq. 1 were solved directly.

Figure 3 illustrates the more realistic fire for which T changes with time. The same three parameters are plotted as a function of scenario time, and again we see that the predicted remaining escape time goes to zero as the body heat reserve goes to zero. We see also in this plot that the parameter, "predicted remaining escape time," at $t < t_c$ is an erroneously optimistic estimate of the actual escape time. This occurs because calculation of that value at any given scenario time (and temperature) assumes the temperature will remain constant thereafter. As a consequence, this particular parameter has no real value in a scenario that involves a changing temperature. It has been left in the plot, however, for illustrative purposes, and also as a check on the proper operation of the program's algorithm, for it and the heat reserve plot should simultaneously go to zero.

Figure 4 (a,b,c, and d) illustrates the effects of different temperature-time profiles on the values of t_c.

It should be reemphasized that the use of a value of 4.1×10^8 for Q_o signifies that the exposed individual is a healthy, male adult, dressed in a particular way. The value of Q_o would surely be different for individuals of other ages, body sizes, states-of-health, types of attire, etc. However, if these limitations are borne in mind, this derived relationship should at least approximate the real situation.

Many laboratories are currently conducting research that attempts to predict the thermal behavior of materials in a full-scale situation with measurements derived from small-scale experiments. The ultimate criterion of full-scale performance, either real or predicted, is the length of time that potential victims would have available for escape. In the thermal context this would be the time-to-thermal-collapse, t_c. The use of various criteria for predicting t_c has been an impediment to the evaluation of results from different laboratories, and in some instances may even have led to an erroneous assignment of relative merit among some materials.

It was the thought, that availability of a simple, yet workable, relationship for predicting t_c might lead to more common usage, that prompted the effort reported here. A more general utilization should also result in earlier and more accurate improvements in the basic relationship.

TABLE 1

Experimental Values of Endurance Time at Various Environmental Air Temperatures[1]

Air Temperature, °C	Time-to-Collapse Min
50	300
105	25
120	15
200	2

[1]These values were used to derive Equation 1.

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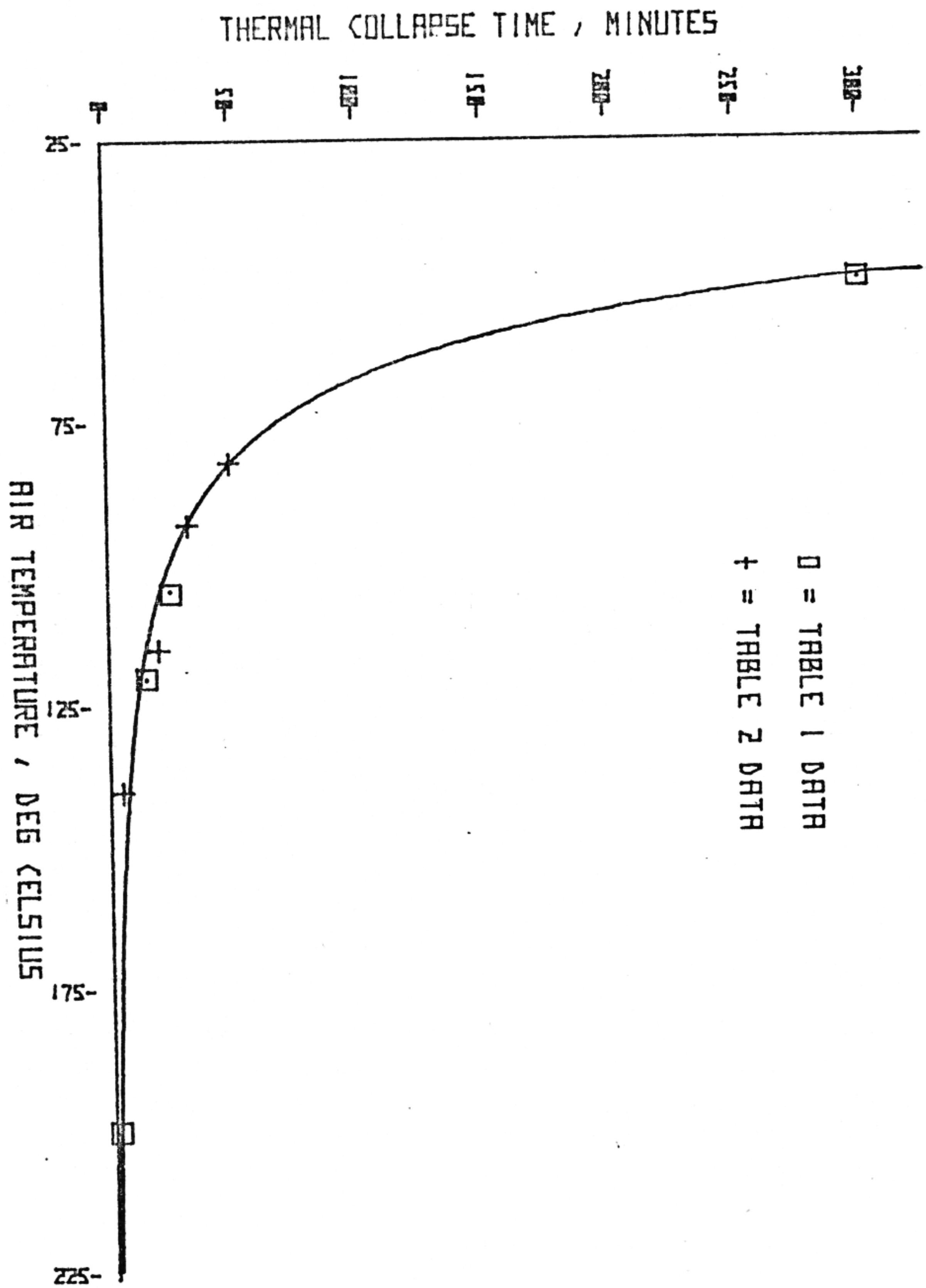
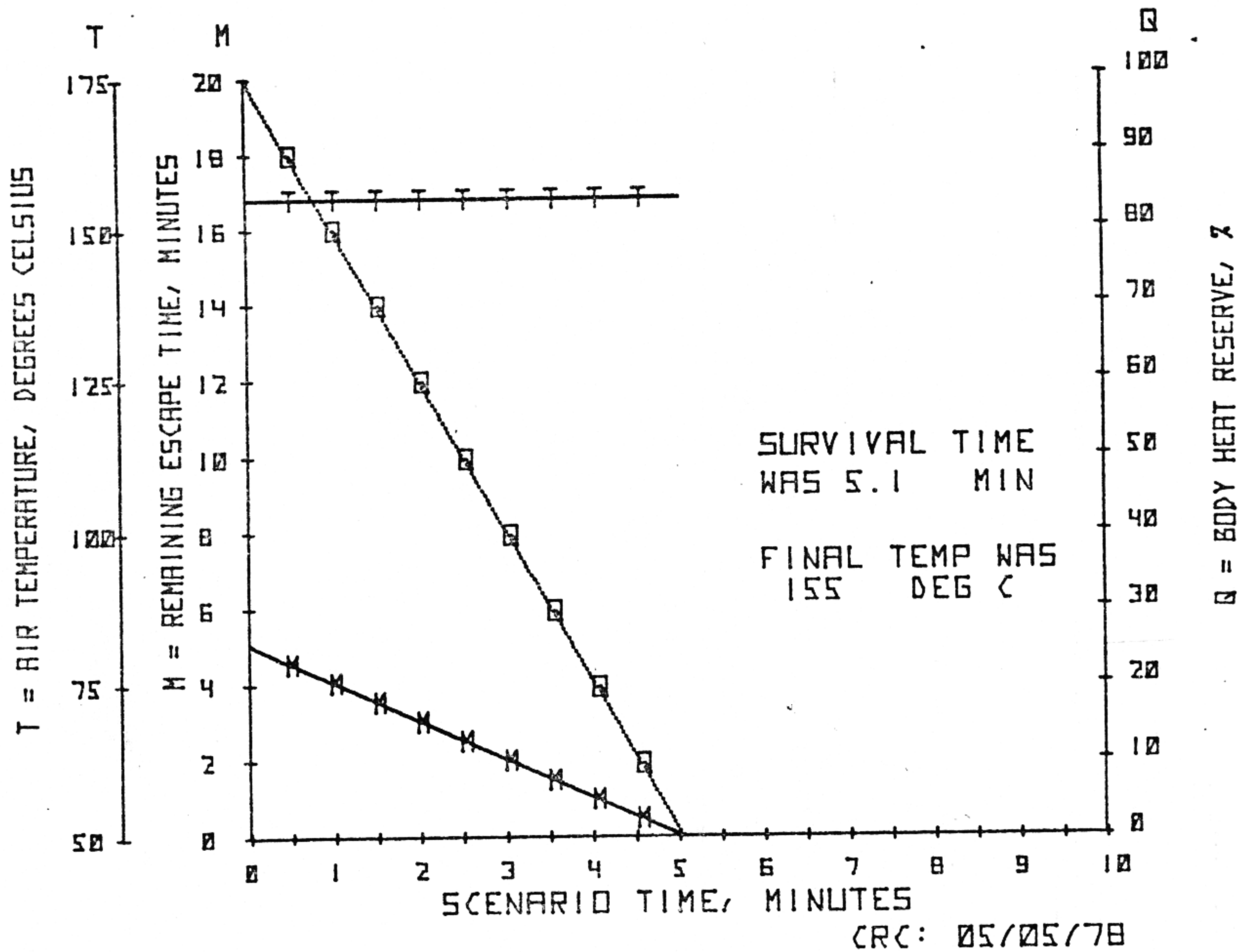
TABLE 2

Additional Experimental Values for Thermal Endurance[2]

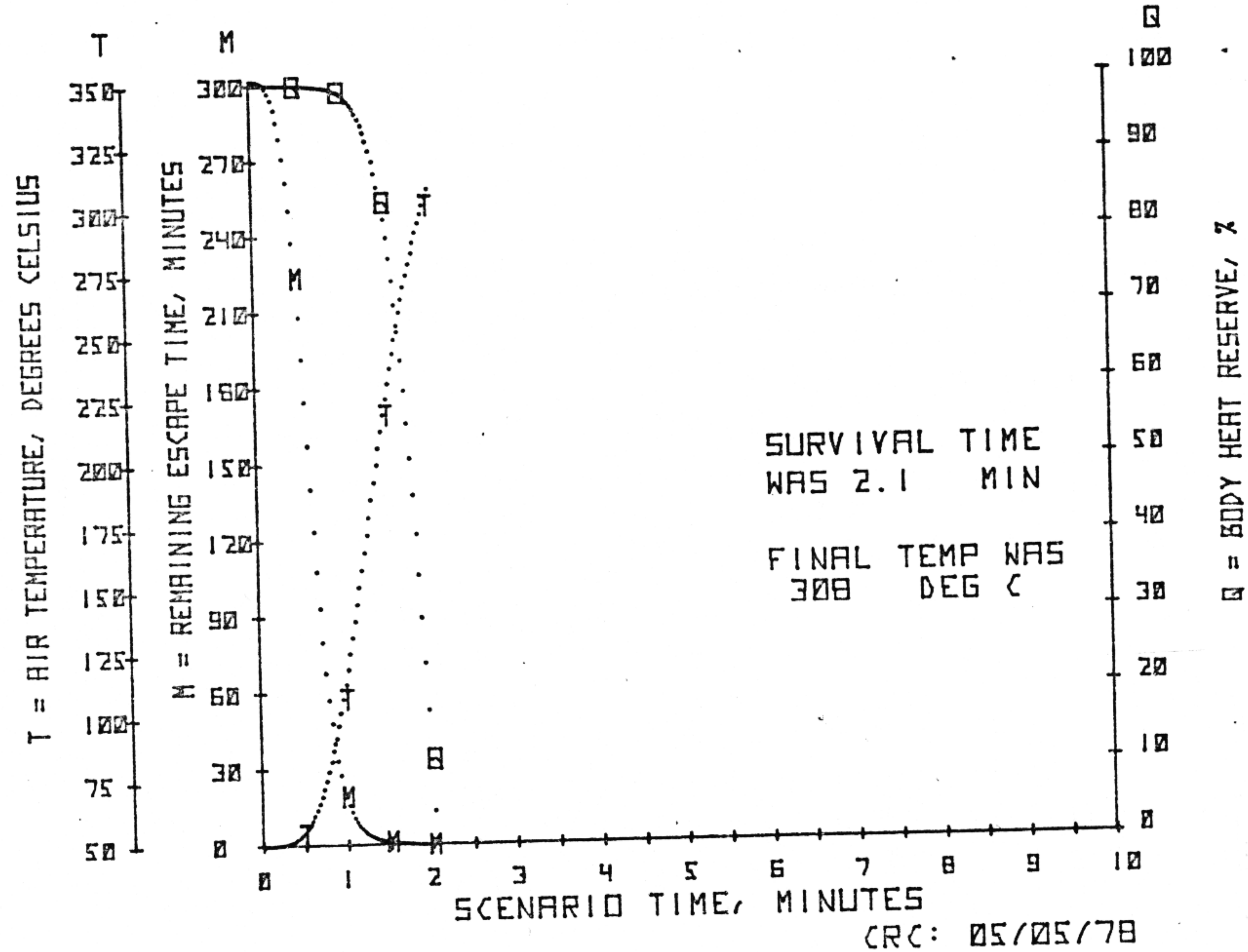
Air Temperature, °C	Time-to-Collapse Min
82	49
93	32
115	20
140	5

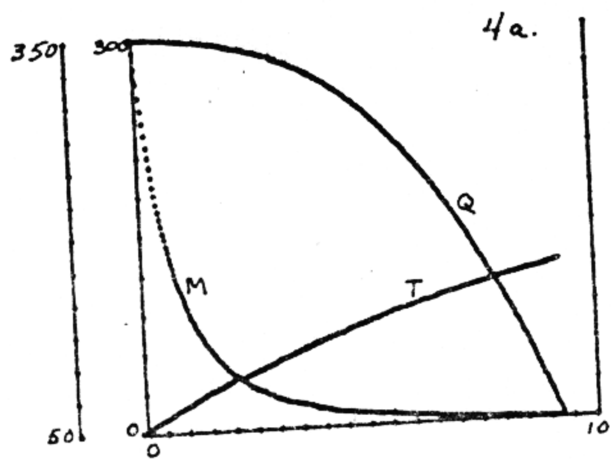
[2]These values are plotted on Figure 1, but were not used in the derivation of Equation 1.

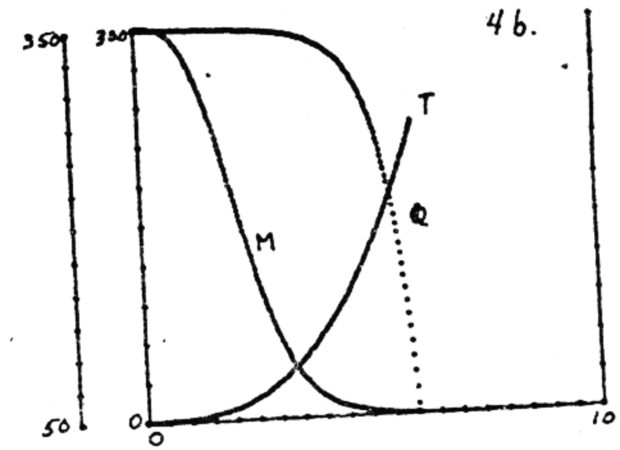

THERMAL COLLAPSE TIME / MINUTES
0
50
100
150
200
250
300
25-
75-
125-
175-
225-
AIR TEMPERATURE / DEG CELSIUS
□ = TABLE 1 DATA
+ = TABLE 2 DATA



T
M
Q
T = AIR TEMPERATURE, DEGREES CELSIUS
M = REMAINING ESCAPE TIME, MINUTES
Q = BODY HEAT RESERVE, %
175
150
125
100
75
50
20
18
16
14
12
10
8
6
4
2
0
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
SCENARIO TIME, MINUTES
SURVIVAL TIME
WAS 5.1 MIN
FINAL TEMP WAS
155 DEG C
CRC: 05/05/78


T = AIR TEMPERATURE, DEGREES CELSIUS
M = REMAINING ESCAPE TIME, MINUTES
Q = BODY HEAT RESERVE, %
SCENARIO TIME, MINUTES
SURVIVAL TIME
WAS 2.1 MIN
FINAL TEMP WAS
308 DEG C
CRC: 05/05/78


4a.
350
300
50
0
0
10
M
T
Q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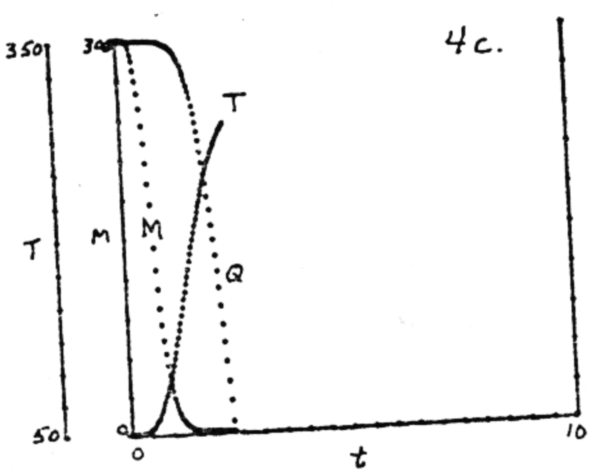
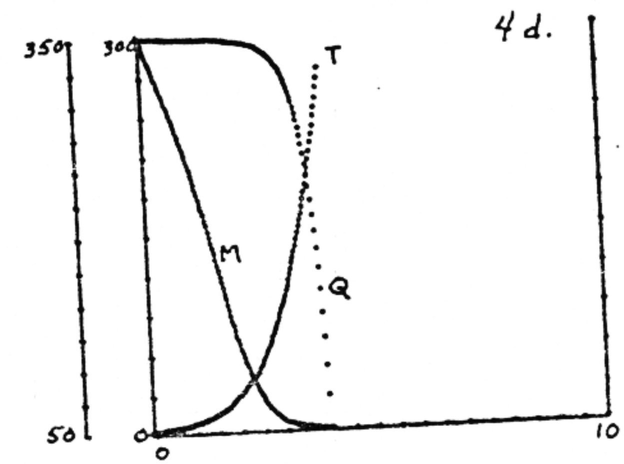
350
300
50
0
0
10
M
T
Q


4c.
350
300
50
0
0
10
T
M
M
T
Q
t


4d.
350
300
50
0
0
10
M
T
Q