TOLERANCES TO THERMAL EXTREMES IN AEROSPACE ACTIVITIES

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It is presumed that all participants in aerospace activities are protected from the hazards of the space environment. The protection takes the form of a self-contained space suit, or a system in which the individual lives in a cabin or capsule without a protective suit, or some combination of the two. The primary and most immediate hazards to the space voyager are associated with extremes of pressure and temperature. Also, in both civil and military aviaion there are potential high temperature problems. High performance aircraft (Air Force fighters, SST) can experience surface temperatures in excess of 260° C. (500° F.). In the event of a failure of the cooling system, crewmembers and passengers could be exposed to very high temperatures. This is not meant to minimize other potential physical hazards of aerospace activities such as radiation and meteor strikes. It is possible, although unlikely, that a thermal threat could occur in conjunction with a partial loss of suit or cabin pressure. However, attempts to separate and ascribe the physiological events of such a dual exposure to the individual stresses would be difficult at best. This paper will concern itself only with some aspects of physiological tolerance to the thermal threats of aerospace activity and in addition will consider only problems of excessive heat since these are more prevalent than problems associated with cold exposure. This is attested to by the fact that space suits are designed for heat elimination rather than for conservation or production of heat. Hardy[5] in an excellent paper stated that "shading or cooling will have to be provided for the astronaut in the space environment near the earth or moon and that this problem will be greater as one goes near the sun." However, situations may occur in which moderately low temperatures may be a problem. The flight of Apollo 13 indicated that under certain unique emergency situations moderate discomfort could occur because of temperatures in the range 4–10 C. (40–50° F.).

The temperatures of the atmosphere are indicated in Fig. 1 for reference. It is seen that at altitudes above 300,000 ft. the temperature rises very rapidly. However, temperature at extreme altitude or in space does not have the same meaning as temperature in our atmosphere. Ambient temperature in our atmosphere is the net result of convective and radiative heat exchanges between the temperature sensing device and its surroundings, while in space the temperature is the net result of radiative exchange only. The heat sources in space near earth are the earth, sun and moon and the heat sink is outer space. The point to be made here is that heat exchanges between man's suit or cabin and his environment in space must be accomplished by radiation alone. Thus, special problems of heat exchange are imposed on the astronaut. Man in space may be faced with several types of thermal stress depending on the kind of failure of his protective equipment or the kind of environmental situation with which he is confronted. Before categorizing and describing the types of physiological tolerances the space traveler may be faced with, it should be emphasized that physiological tolerance is a rather extreme circumstance and the individual approaching physiological tolerance is probably well beyond any ability to perform complex duties which might help him to improve his condition. Fig. 2 illustrates this. This figure shows the marked differences in tolerance times for impaired performance and for physiological tolerance. Performance deteriorates, for comparable exposure conditions at much earlier times than does physiological function. In addition, the more complex the performance, the earlier the deterioration. The physiological tolerance curves shown here are based primarily on data relating to body temperature and to heat storage. It is apparent now that there is no one clear cut criterion which can be used to determine physiological tolerance to all thermal stresses.

There are at least three kinds of physiological tolerance to thermal stress and each of these has characteristics which separates it from the others. Also, each of these tolerances could be important in space activities depending on the exposure conditions of the astronaut. Table 1 lists the three types of tolerance and the environmental conditions which might produce each. There does not seem to be much question that there is a differentiation of the physiological events prominent in the deterioration of tolerance for these three categories, as well as some differentiation of the tolerance times. However, it is to be expected that, because of individual variation and other variables, there will be some overlap of tolerance times, as well as overlap of the physiological determinants of tolerance. For purposes of simplification, only seminude or lightly clothed, resting or sedentary men will be considered in this analysis.

There may be some question concerning these three categories of physiological tolerance, especially because of the 2nd and 3rd categories. Those workers who are firmly committed to the idea that rate of heat storage is the ultimate determinant of tolerance may not agree that other factors can determine tolerance under essentially identical exposure conditions.

TABLE 1.—Tolerance Times for Three Types of Physiological Limitations During Exposure to Hot Environments

Type of Thermal Tolerance	Ambient Conditions Dry Bulb, °C (°F) Vapor Pressure, mm Hg	Tolerance Time Minutes
Pain Limited	100(212)—260(500) Low (<20)	<1—15
Heat Load Limited	55(130)—110(230) Low (<20)	25—>180
Systems Limited	37(98)—55(130) High (45—70)	20—140

Pain Limited Tolerance.

Pain limited tolerance can occur by exposure of skin areas to direct radiation of sun, by skin coming into contact with hot objects or by exposure to radiation other than solar, for example, hot walls of the capsule. Webb's[12] presentation of information on pain limited heat exposures in 1963 illustrated very well not only the range of tolerance times for pain limited exposures, but also that there is a transition region where pain limited exposures may overlap with heat storage limited exposures (Fig. 3). Exposures which are pain limited occur only when the exposure temperature is very high or when the heat flux is high. Webb's temperatures were on the order of 115 (238) to 260° C. (500° F.). However, pain may be incurred by contact with objects at a much lower temperature than is necessary to cause pain by radiation. In our experience contact with metal objects at temperatures around 71° C. (160° F.) causes discomfort[7] and temperatures probably not much higher would cause pain. The statement is made that subjects in the UCLA[1 2] studies exposed to temperature above 100° C. (212° F.) spent considerable time protecting hot spots, blowing on knuckles, etc. It could be construed that tolerance was reached when the subjects attempted to protect themselves from the environment. However, the point to be made here is that at very high temperatures there is no question that pain is the determiner of tolerance. Hardy[5] has estimated that in space near the earth and moon, radiation from the sun (about 2.0 gm cal/cm^2/sec) is enough to cause pain on exposed skin surfaces. Hardy[5], Buettner[3], Webb[12] and others have found that skin temperatures around 45° C. (113° F.) are always associated with pain. Recovery from pain limited exposures is rapid if burns have not been incurred.

Heat Load Limited Tolerance.

The second category of tolerance limit is heat storage and is probably the most commonly described and used. Most exposures to heat are in reality heat storage limited and therefore there is some justification for so much preoccupation with this category. This type of limit could be achieved in the space situation in several ways. Failure of the cooling system would be a prime avenue, or heat loading by excessive exposure to thermal radiation could be another.

Many workers have espoused the idea that limitation on exposure to heat can always be defined in terms of heat storage. Blockley[1 2] and his co-workers have been serious advocates of this concept. Fig. 4 shows the data of Blockley (solid line) and others on tolerance times modified from Taylor[10]. Taylor states that at lesser temperatures factors of judgment enter into the interpretation of tolerance. He also states that nausea, air hunger, tingling of extremities should be considered in evaluation of tolerance. I have taken the liberty of drawing in a curve (dashed line) through the data of McConnell[8], Taylor[9 10], Webb[11] and some of my own[7]. If we assume that various factors are involved in tolerance, then we might reach the following conclusion: At temperatures roughly above 80° C. (176° F.) tolerance is determined by a single factor since all points fall on the curve relatively well. At temperatures below 80° C. several factors are probably involved in tolerance since the various points show considerable scatter. Blockley and Webb both indicate that at temperatures above about 71° C. (160° F.) and below the pain threshold, exposures are terminated primarily because of heat storage. Thus, Blockley's data gives one curve based on heat storage and the data of the others gives another curve based on heat storage and other limitations.

Systems Limited Tolerance.

The third type of tolerance is indicated as being systems limited for want of a better term. Not much attention has been paid to this category primarily because very special environmental conditions are required to elicit the response. My reason for listing this type of tolerance is that the conditions of space exploration are conducive to this type of failure. As indicated earlier, very high humidities combined with moderately high temperatures are required. This condition can be obtained in the space situation because we are dealing essentially with a closed environment; either a space suit or a capsule. Thus, if for any reason, there is a decrease in the capacity to remove moisture from the environment surrounding the voyager coupled with a decrease in the capacity to remove heat, the conditions will be suitable for a systems limited tolerance. A systems limited tolerance is manifested by (1) excessive heart rate or (2) extreme hyperventilation or (3) nausea, vomiting, dizziness, etc., either singly or in combination. Fig. 5 shows a subject who was removed from the chamber because of a systems failure. He had hyperventilated to the point where he exhibited intense carpopedal spasm and had no control of his extremities. However, excessive body temperature or heat load is not associated with this tolerance. When a systems limited tolerance occurs, it does so before an excessive heat load is built up. Those individuals who do not exhibit a systems limited tolerance will then eventually incur a limiting heat load. Table 2 shows the tolerance times, the ambient conditions and the percent of subjects removed from the chamber because of systems failure[4 6].

TABLE 2.—Tolerance Times for Systems Limited Exposures. Ambient Conditions Are Expressed as "WD" Index (0.15 Dry Bulb +0.85 Wet Bulb)

Ambient Conditions	Mean Tolerance Time	Subjects Terminated for Systems Failure
"WD" Index	Minutes	%
98	142	30
100	78	35
101	73	25
102	72	30
103	67	30
104	60	22
105	46	40
106	44	90
107	41	53
108	28	55
109	20	100
111	27	89
115	19	80

The tolerance times listed here include the time for some subjects to incur a limiting heat load. An important point to be noted is that tolerance because of systems limitations range from about 20 minutes to about 140 minutes but by far the greater percentage of removals occurred with times less than 60 minutes. At the milder conditions (longer tolerance times) there is a considerable overlap with conditions which produce high heat loads and thereby limit tolerance in that way. However, when humidity is lower than for system limited tolerances, then higher dry bulb temperatures are required in order to reach tolerance. For example, temperatures around 48° C. (118° F.) with low humidity can be tolerated indefinitely without incurring systems limitations or heat load limitations.

The tolerance time curves for the three types of limits are summarized in Fig. 6 for quick reference. The interesting relationship of tolerance times for the three types of exposure is evident from the figure. Pain limited exposures last from a few seconds to minutes and occur when air temperatures are very high (above 100° C., 212° F.). Heat storage limited exposures may last from minutes to hours depending on the dry bulb temperature and humidity.

Very high temperatures (around 100° C., 212° F.) can be tolerated for about 30 minutes when humidity is low (<20mm Hg), while temperatures below about 55° C. (131° F.) and low humidity can be tolerated for several hours. Systems limited exposures are of relatively short duration and are terminated because of extreme hyperventilation, excessive heart rate, vomiting, dizziness, etc. High humidity with moderately high temperatures induces this tolerance.

Additional work is required to determine more fully the factors involved in tolerances to hot environments. The three types of limits presented here are arbitrary and certainly improvements can be made on them. The important point to be made is that a single criterion for tolerance to hot environments is not justified. The tolerance time and type of limitation will be determined by the type of hot environment encountered.

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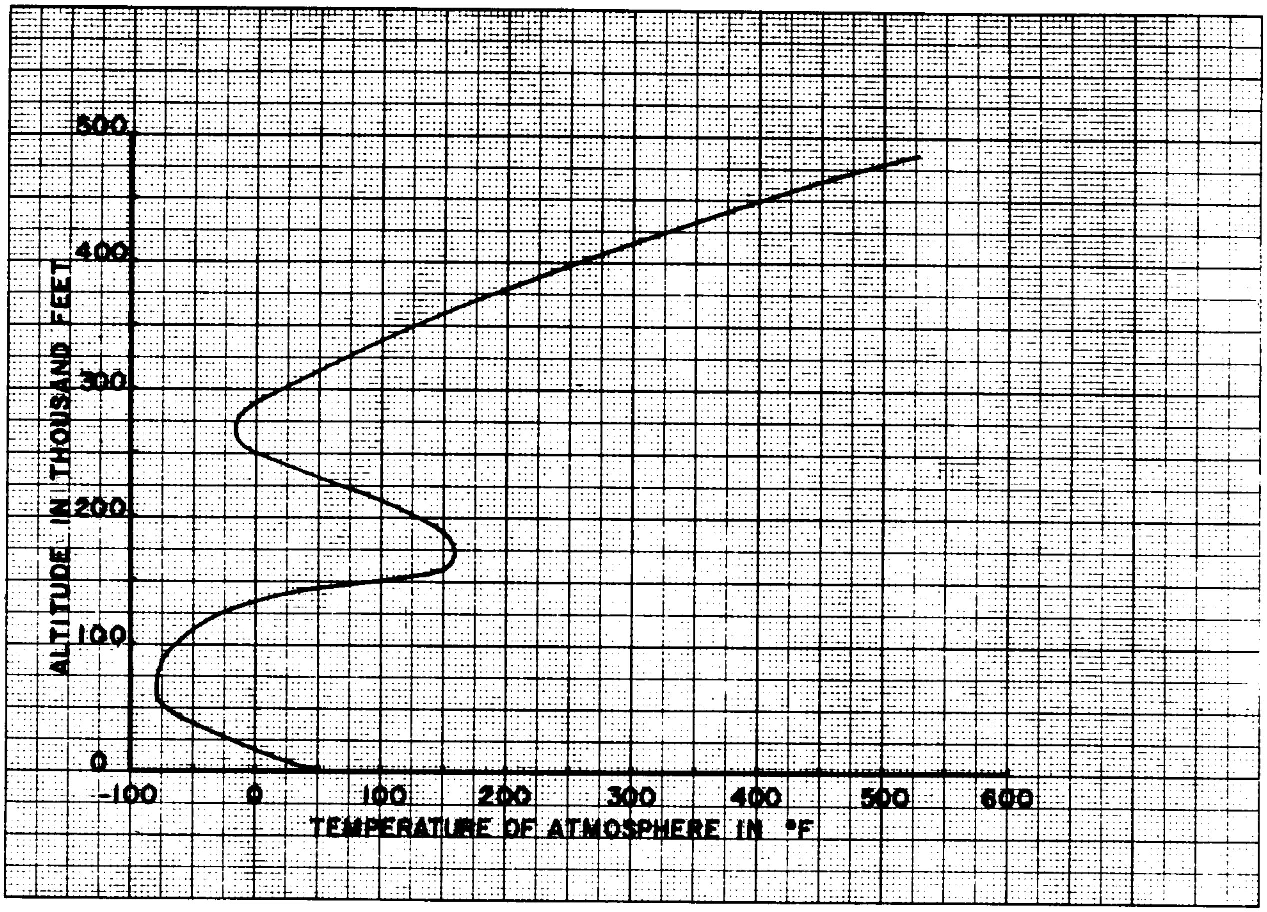

FIGURE 1. The temperatures of the atmosphere for sea level to 500,000 feet.

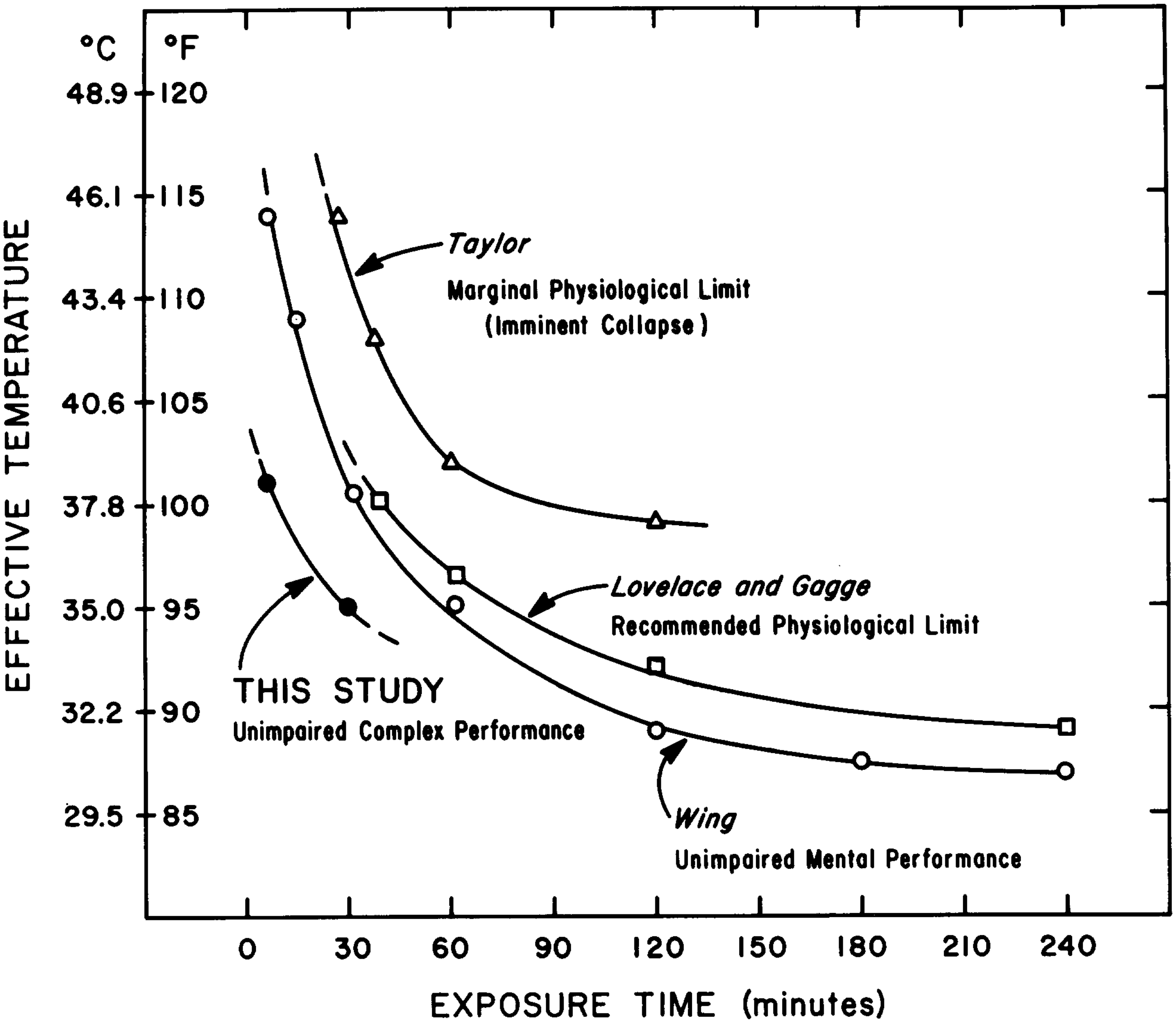

FIGURE 2. Physiological and performance limits in hot environments (modified from Wing[13]).

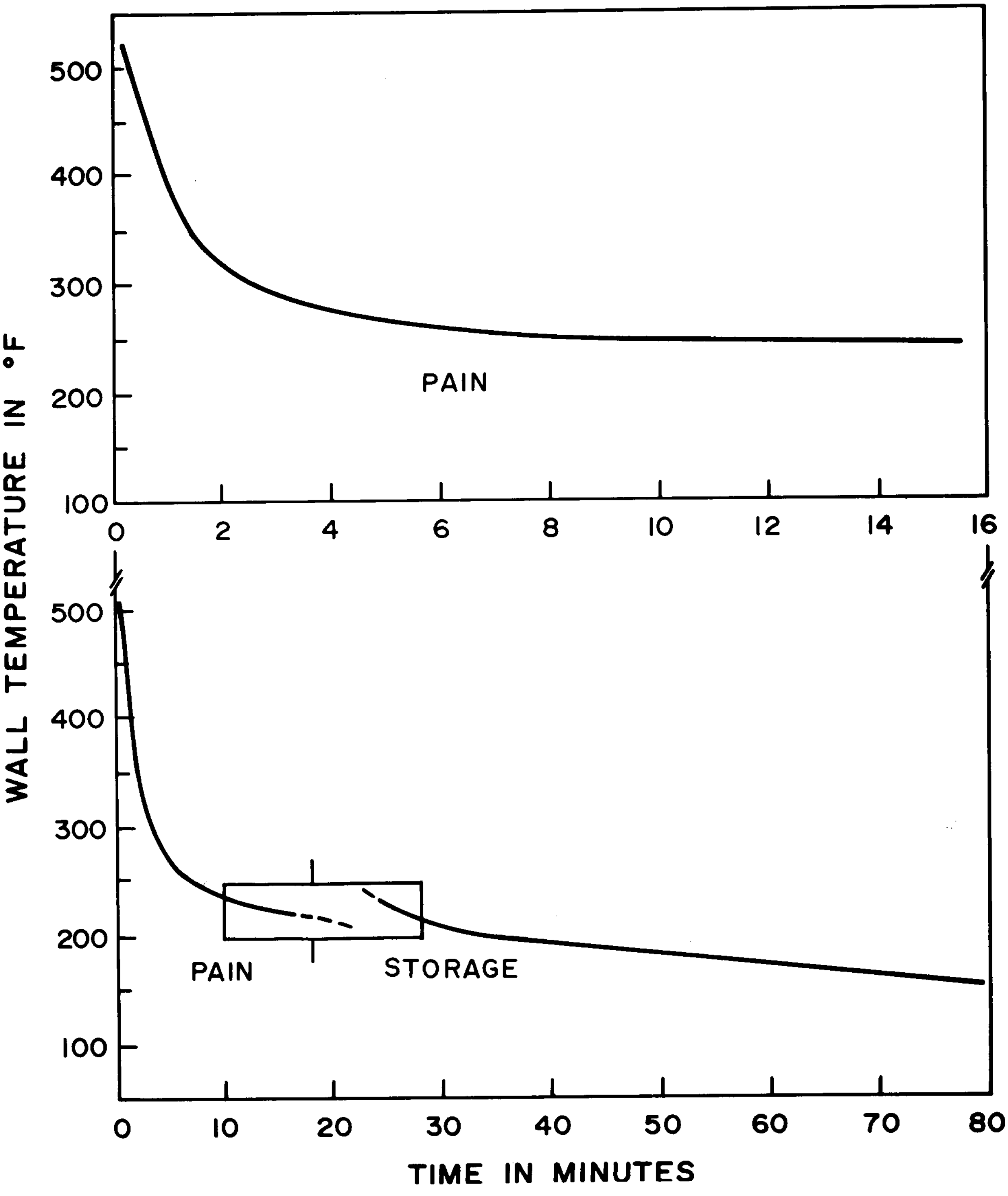

FIGURE 3. Tolerance times for pain limited heat exposures (top panel) and curves showing transition areas between pain limited and heat storage limited exposures (bottom panel) (from Webb[12]).

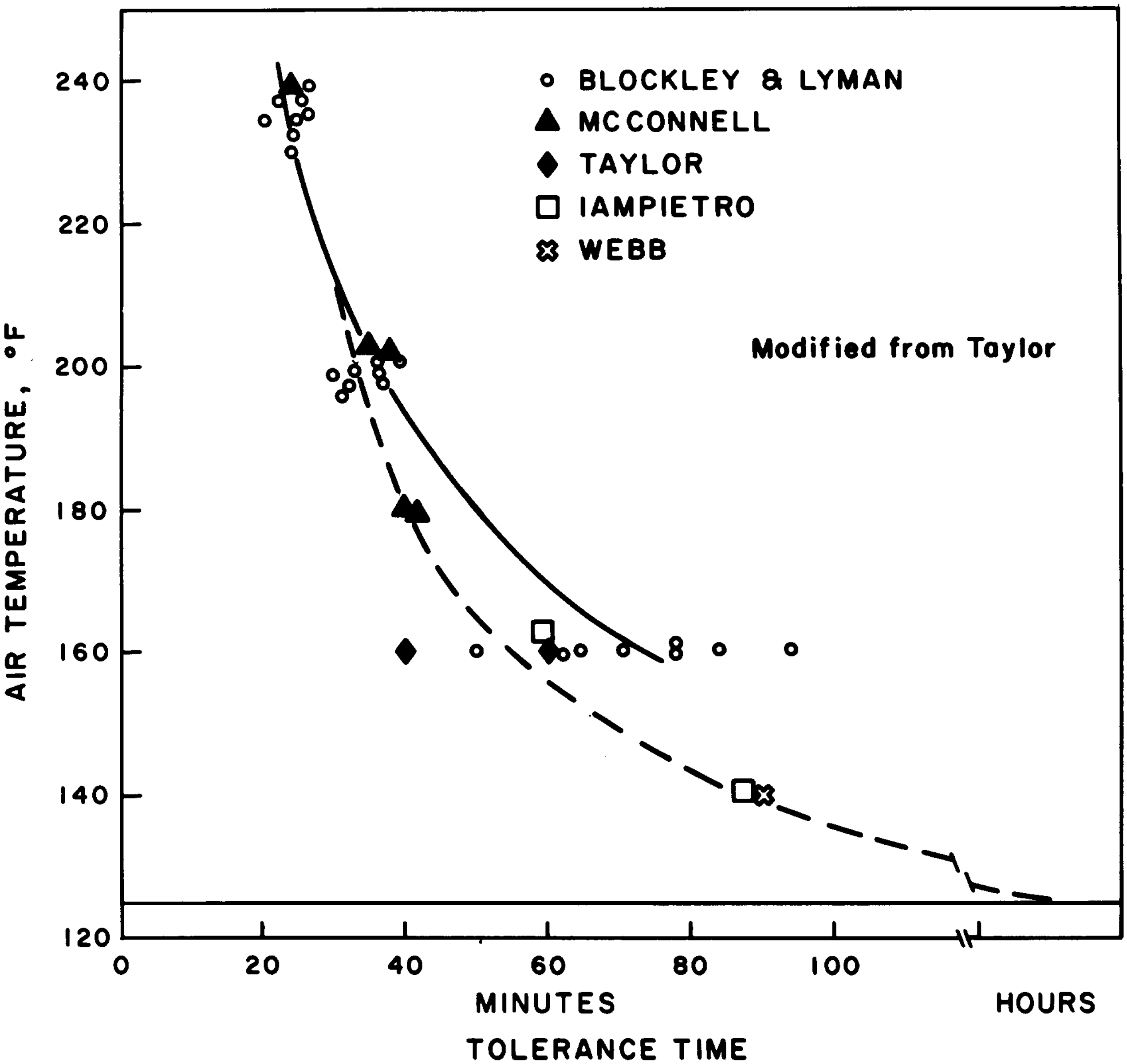

FIGURE 4. Tolerance times for heat storage limited exposures (solid curve). Dash curve represents tolerance limits which do not conform to the heat storage curve (modified from Taylor[10]).

FIGURE 5. Subject exhibiting one form of systems limited tolerance (carpopedal spasm) (from Iampietro[6]).

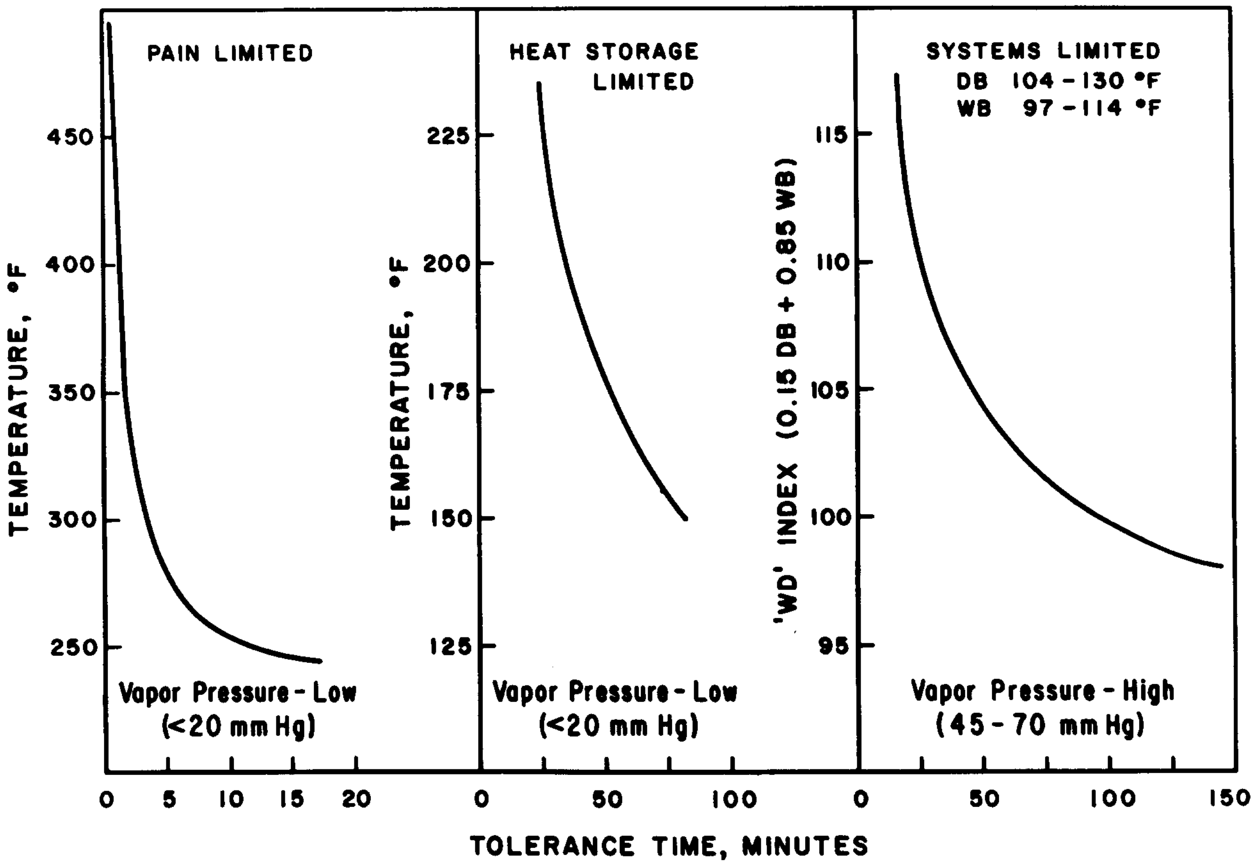

FIGURE 6. Summary graph of tolerance times for three types of physiological limits and the conditions which elicit each tolerance.

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