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16. Abstract

Skin temperature is a sensitive index of the effect of the thermal environment on the seminude man. Skin temperatures and tolerance times from several studies have been utilized in an attempt to establish a relationship between 1) final skin temperature and tolerance time and 2) skin temperature during the early minutes of exposure and final skin temperature. The number of subjects during each exposure ranged from five to ten. Exposure temperatures ranged from -4° to 113°C (25° to 235°F). Air movement ranged from about 50 to 880 ft/min. Many criteria were used to fix tolerance time: for hot exposure we used T_r = 102.5, HR = 180 beats/min, nausea, etc.; for cold exposures we used toe temperatures below 4.4°C (40°F) and subjective evaluations. A relationship exists between final temperature and tolerance time and between final skin temperature and skin temperature at ten minutes of exposure. Final skin temperature (at tolerance) in hot and cold environments can be predicted from the skin temperature at ten minutes. Tolerance time may also be estimated from the ten minute skin temperature.

17. Key Words
Tolerance, Heat, Cold, Human, Thermal Exposure, Skin Temperature, Prediction of Tolerance

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USE OF SKIN TEMPERATURE TO PREDICT TOLERANCE TO THERMAL ENVIRONMENTS

I. Introduction.

The effects of the environment on man have been receiving a great amount of attention during the last several years. Because of advanced technology in aviation and space activities, more interest is being generated concerning the effects of the thermal environment on man. The two areas of interest in aviation activities center around performance capabilities and physiological tolerance, especially in hot environments, such as those presented during failure of the ventilation system of high performance aircraft. What has been needed is a definitive means of predicting performance capabilities and tolerance times of people in hostile environments. In our laboratories we have recently completed two studies evaluating performance during time-temperature profiles simulating air conditioning failure in-flight aboard a high-altitude, high-speed aircraft. A single-parameter predictive index would have facilitated the study through simplification and would have obviated multiple temperature measurements. This paper represents an attempt to use a single physiological criterion to predict tolerance time in all thermal environments.

The possibility of using a single physiological measure to predict tolerance time for humans in all thermal environments has long intrigued workers in the field. Attempts to use deep body temperature, skin temperature, sweat rate, heart rate, and oxygen consumption as indexes have allowed only partial success in predicting tolerance. During exposure to hot environments, heart rate, sweat rate and deep body temperature have been used with varying degrees of success as predictors of tolerance while heat production, skin temperature and deep body temperature have been used during cold exposures. Perhaps the single measure which has shown the most promise over a wide range of thermal environments has been deep body temperature.

Many workers have shown rectal temperature to be very sensitive to increases in environmental temperature but not as sensitive to decreases in ambient temperature[1-7]. During exposure to cold environments, rectal temperature actually increases during the first 30 or 40 minutes of exposure[1-7].

Adolph, in the mid-1940's recognized that skin temperature was a sensitive measure of the effect of cold environments in man[1]. Later, we showed that skin temperature could be predicted for a wide range of cold environments and that there was a relationship between final skin temperature and tolerance time[6].

The purpose of this paper is two-fold: (1) to show that skin temperature is a reliable and sensitive measure of the effect of hot and cold environments on man, and (2) to show that skin temperature during the first minutes of exposure can be used to predict final skin temperature and tolerance time.

II. Methods.

Data from studies conducted over several years in the author's laboratory[4 6-12] and in other laboratories[2] have been used for the present paper. Subjects in these studies were used for a variety of purposes, but all were lightly clothed or seminude and all were wired for the measurement of skin temperatures. Subjects (5 to 10 per environment) were exposed usually in groups, but sometimes singly, to environments which ranged in temperature from −4° C. (25° F.) to 113° C. (235° F.), in air movement from about 50 to 880 ft/min and in vapor pressure from less than 20 mm Hg to about 72 mm Hg. Only group means are used in this paper. Tolerance was established according to a variety of criteria. For termination of hot exposures, we used rectal temperature 39.2° C. (102.5° F.), heart rate 180 beats/min, nausea, hyperventilation tetany or the decision of a physician. These criteria were applied either singly or in any combination. For cold exposures we used toe temperature 4.4° C. (40° F.), exhaustion, or the decision of a physician. In the event the tolerance limit was not reached, the exposures were terminated at 120 minutes or longer.

III. Results and Discussion.

Skin temperature responds rapidly and sensitively when an individual is exposed to an environment warmer or colder than a "neutral" environment. Figure 1 shows mean skin temperature plotted against time for a number of representative exposure conditions. We pointed out in an earlier paper that during exposure to hot environments at least 75% of the total change in skin temperature occurred during the first 15 minutes of the exposure[11]. Subsequently, we examined data from other studies we had performed in cold environments and established that essentially the same degree of change took place during the first ten minutes of exposure. This characteristic of the rapid change in skin temperature was mentioned by Adolph in 1946[1] when he pointed out that equilibrium mean skin temperature during exposure to cold was nearly established after ten minutes of exposure.

The second characteristic of the change in skin temperature is that the final skin temperature is a function of the exposure conditions. Final skin temperature during cold exposure is a func-

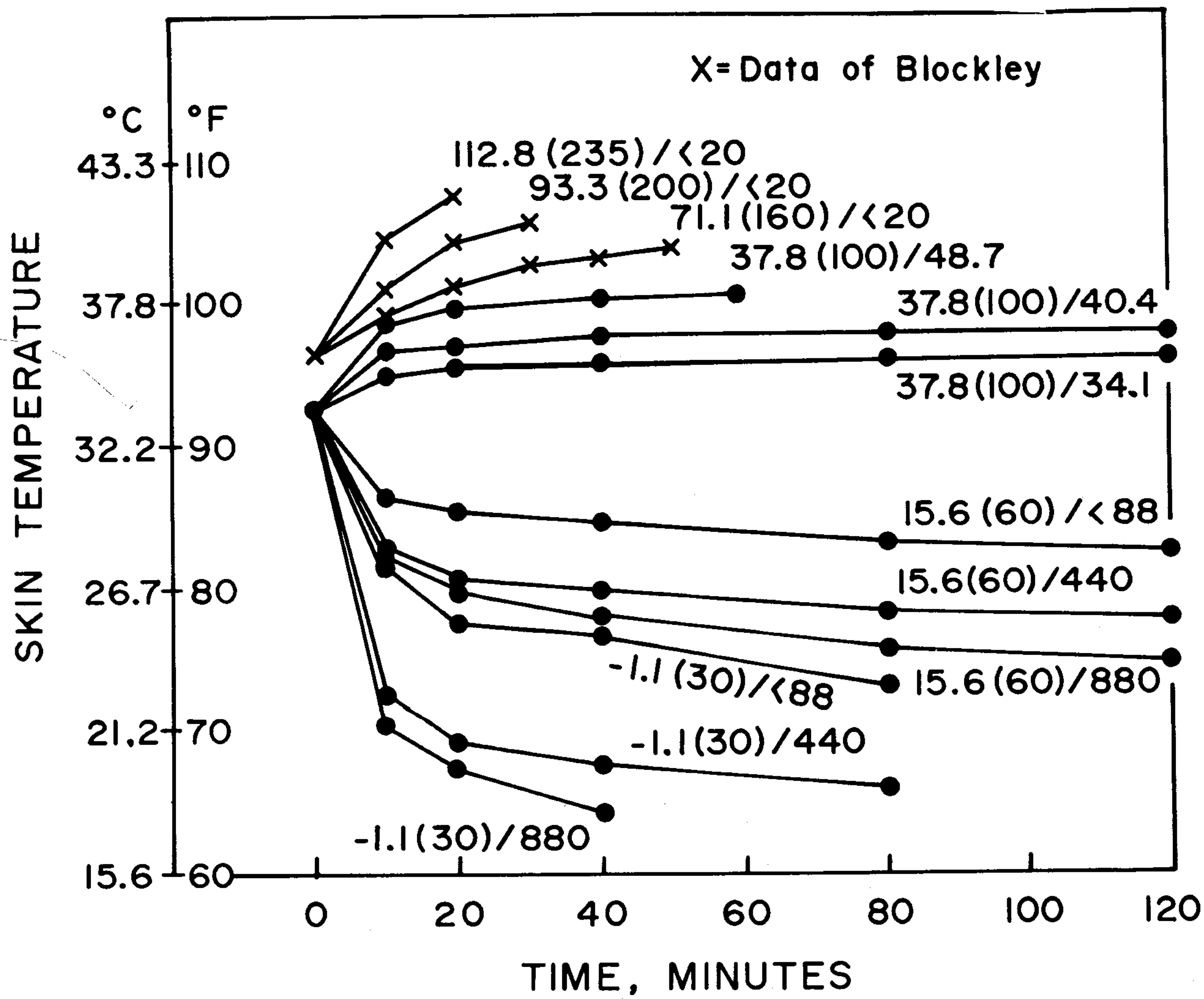

FIGURE 1. The relationship of skin temperature to time during exposure to hot and cold environments. Representative conditions are illustrated. (Data of Blockley, 2).

tion of air movement and ambient temperature and during heat exposure it is, in addition, a function of ambient humidity. Table I shows final skin temperature for some representative hot and cold exposures. It is apparent that for a given dry bulb temperature during cold exposure final skin temperature is lower with higher air movements. As would be expected, skin temperature is lower when ambient temperature is lower. During exposure to high temperature increasing humidity and air movement increase final skin temperature at a given ambient temperature. Increasing ambient temperature without increasing humidity or air movement also increases final skin temperature.

Table I.—The relationship of skin temperature at tolerance to the exposure conditions. Skin temperature is a function of air movement and humidity as well as ambient temperature.

Ambient Conditions			Final Skin
Dry Bulb °C (°F)	Vapor Pressure mm Hg	Air Movement ft/min	Temperature °C (°F)
−4.0 (25)	1.6	<88	21.8 (71.3)
−4.0 (25)	1.6	440	17.6 (63.6)
4.4 (40)	3.1	<88	23.8 (74.8)
4.4 (40)	3.1	440	21.4 (70.5)
4.4 (40)	3.1	880	19.0 (66.2)
15.6 (60)	6.6	<88	28.2 (83.0)
15.6 (60)	6.6	440	25.7 (78.2)
15.6 (60)	6.6	880	23.9 (75.0)
37.8 (100)	40.4	264	36.5 (97.7)
37.8 (100)	48.7	264	38.1 (100.6)
43.3 (110)	19.6	264	36.1 (97.0)
43.3 (110)	49.1	264	38.7 (101.7)
42.8 (109)	63.6	264	40.8 (105.5)
48.3 (119)	44.8	264	38.0 (100.4)
48.9 (120)	50.5	264	39.5 (103.2)
48.3 (119)	71.9	264	41.2 (106.1)
60.0 (140)	<20	40	38.9 (102.0)
71.1 (160)*	<20	40	40.2 (104.4)
93.3 (200)*	<20	40	40.8 (105.4)
112.8 (235)*	<20	40	41.9 (107.4)

* Data of Blockley[2].

Tolerance times were determined for all of those exposures during which the subjects were terminated before the scheduled time was complete. Table II lists tolerance times for a variety of exposures. These times varied from hours for the mild exposures to about 20 minutes for the most severe hot or cold exposures. These data show that tolerance time is not determined solely by dry bulb temperature; air movement and humidity also have an influence on tolerance.

Table II.—The relationship of tolerance time to the exposure conditions. Tolerance time is a function of air movement and humidity as well as ambient temperature. Tolerance times are given to the nearest five minutes.

Ambient Conditions			
Dry Bulb °C (°F)	Vapor Pressure mm Hg	Air Movement ft/min	Tolerance Time minutes
−4.0 (25)	1.6	<88	>120
−4.0 (25)	1.6	440	40
−1.1 (30)	2.1	440	80
−1.1 (30)	2.1	880	60
4.4 (40)	3.1	<88	>120
4.4 (40)	3.1	440	>120
4.4 (40)	3.1	880	80
15.6 (60)	6.6	<88	>120
15.6 (60)	6.6	440	>120
15.6 (60)	6.6	880	>120
37.8 (100)	40.4	264	>120
37.8 (100)	48.7	264	60
43.3 (110)	19.6	264	>120
43.3 (110)	49.1	264	60
42.8 (109)	63.6	264	20
48.3 (119)	44.8	264	65
48.9 (120)	50.5	264	45
48.3 (119)	71.9	264	20
60.0 (140)	<20	40	90
71.1 (160)*	<20	40	70
93.3 (200)*	<20	40	35
112.8 (235)*	<20	40	25

* Data of Blockley[2].

We noted the fact that tolerance time and change in skin temperature are related to the several environmental factors in the same way. For example, increasing the humidity during exposure to a hot environment increases the total change in skin temperature and decreases the tolerance time. During cold exposure, increasing the air movement at a given temperature increases the total change in skin temperature and decreases the tolerance time.

Figure 2 shows tolerance time plotted against final skin temperature for all exposures. Final skin temperatures in the approximate range 37.8° C. (100° F.)–21.1° C. (70° F.) are associated with tolerance times of 120 minutes or greater. Tolerance times less than 120 minutes are obtained when skin temperatures are greater than 37.8° C. or less than 21.1° C. and the decrease in time is proportional to the increase or decrease in skin temperature. Figure 2 indicates that tolerance time will be essentially "zero" when skin temperature approaches 46.1° C. (115° F.) and 15.6° C. (60° F.). The upper value, 46.1° C. agrees well with studies showing that the thermal pain threshold is around 45.6° C. (114° F.). These studies indicate that the tolerance limit is achieved within seconds to a minute or two when surface temperature reaches 45° C.[3 5 13]. The lower limit (15.6° C.) is not as simple to define. In an earlier study[6] we showed that tolerance time was 60 minutes when skin temperature was 17.2° C. (63° F.). Estimates of time below this skin temperature indicated a tolerance of about 20 minutes when skin temperature reached 15.0° C. (59° F.). Therefore, it appears that the value 15.6° C. in the present paper for "zero" tolerance may be about two degrees too high.

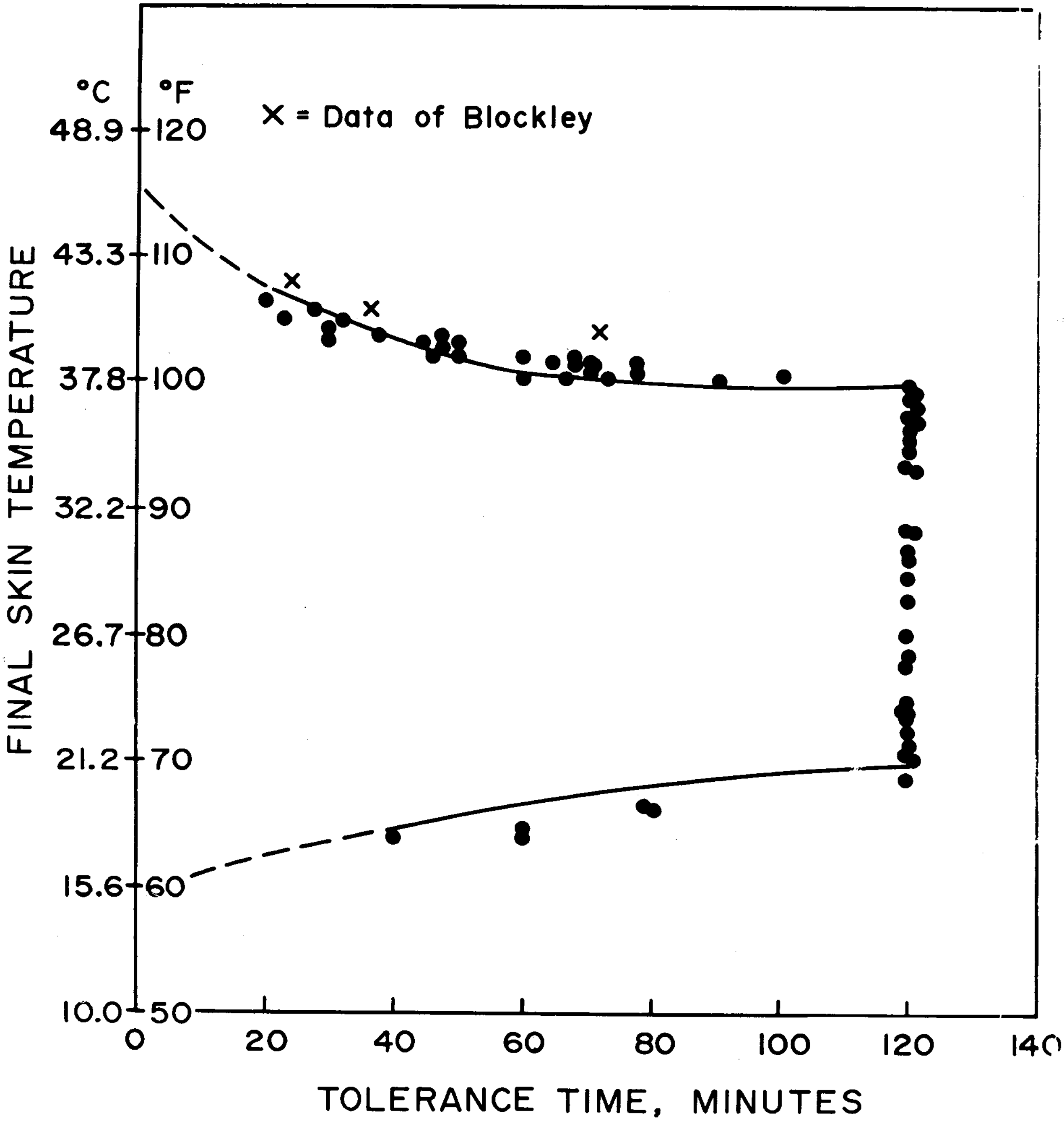

FIGURE 2. The relationship of tolerance time during exposure to hot and cold environments to the final skin temperature achieved. Dashed portion of the curves are extension beyond the limits of the data (Data of Blockley, 2).

A relationship between skin temperature at ten minutes of exposure and skin temperature at the tolerance limit is depicted in Figure 3. When environmental conditions are essentially thermally "neutral" for the seminude, resting mean skin temperature does not change during the course of the exposure and therefore skin temperature at ten minutes of exposure ($T_{s_{10}}$) is the same as final skin temperature (T_{s_f}). As the environmental conditions deviate from the "neutral" situation, $T_{s_{10}}$ and T_{s_f} deviate from the neutral T_s (33.8° C., 93° F.).

When subjects are exposed to cold environments $T_{s_{10}}$ is always higher than T_{s_f}. However, as the conditions become more extreme, and tolerance time decreases, $T_{s_{10}}$ approaches the T_{s_f} value. When the conditions are so severe that tolerance time is ten minutes, then $T_{s_{10}}$ will equal T_{s_f}. The same situation occurs when subjects are exposed to hot environments except that

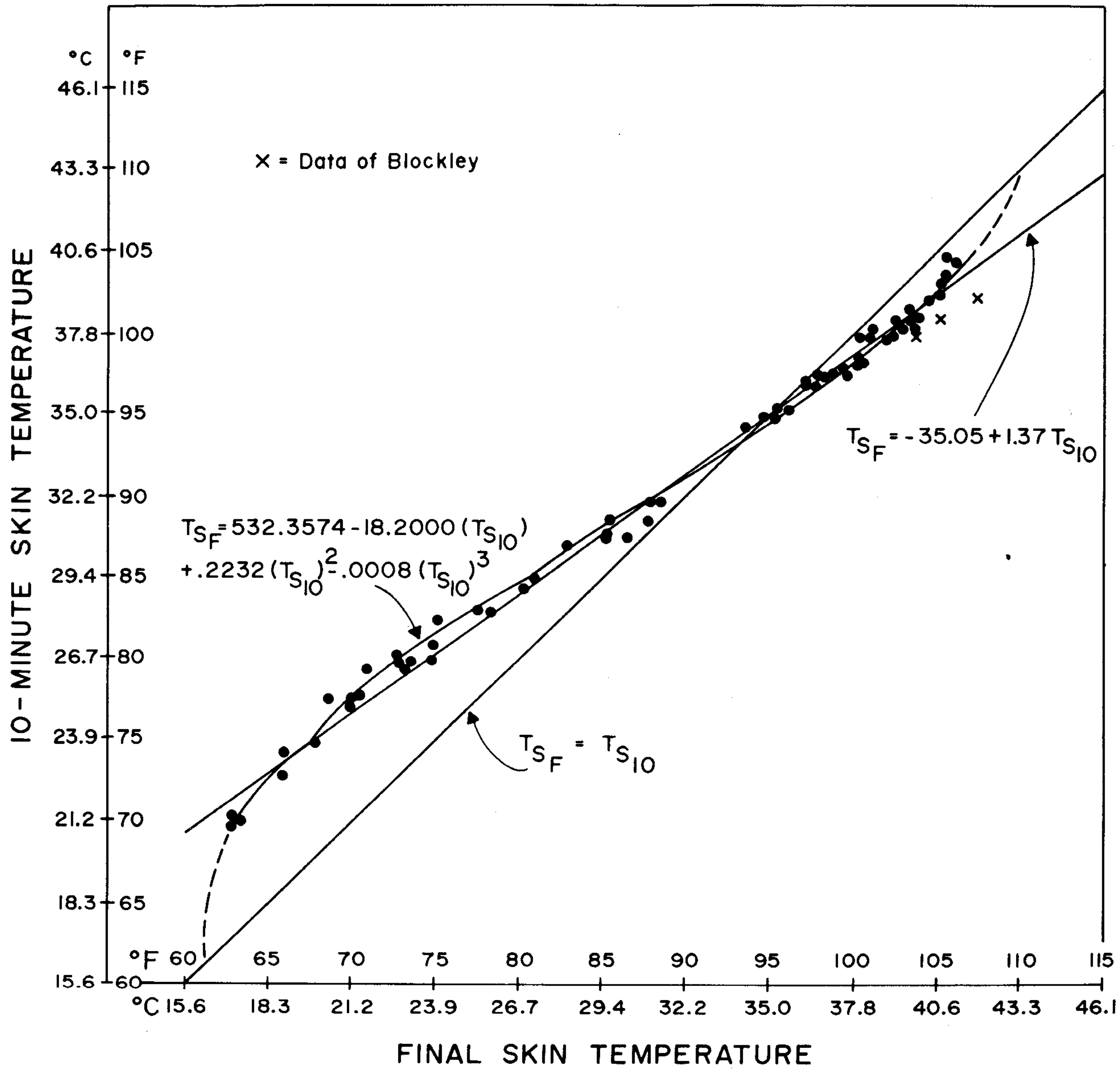

FIGURE 3. The relationship between final skin temperature (at tolerance) and skin temperature at 10 minutes of exposure. Dashed portion of curves are extensions beyond the limits of the data (Data of Blockley, 2).

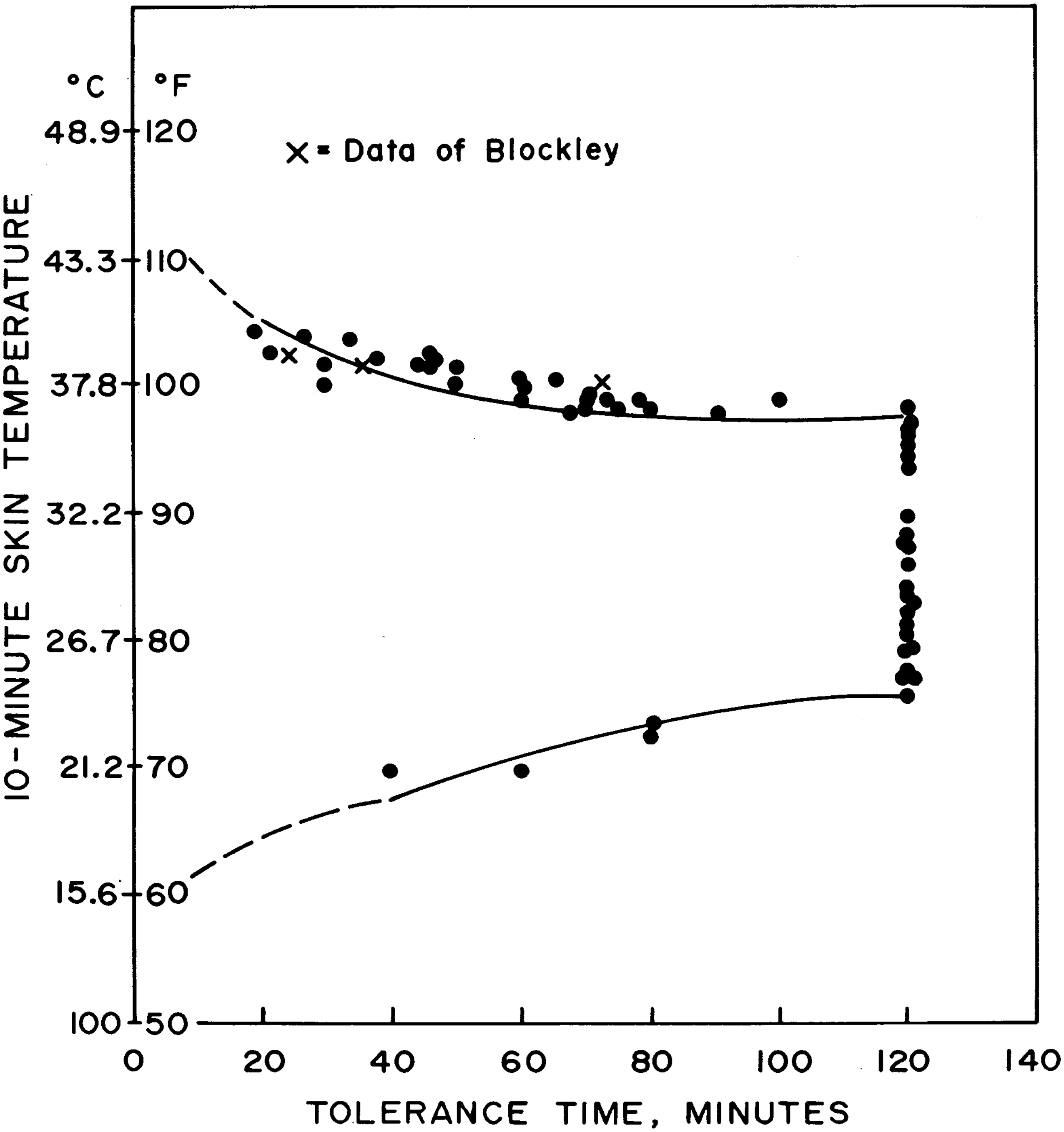

FIGURE 4. The relationship of skin temperature at 10 minutes of exposure to tolerance time. Dashed portions of the curves are extensions beyond the limits of the data (Data of Blockley, 2).

$T_{s_{10}}$ is always lower than T_{s_f} until tolerance time is ten minutes. The dashed portions of the curve represent extrapolations beyond the available data. Figure 3 also indicates that the relationship between $T_{s_{10}}$ and T_{s_f} is essentially linear for the range $T_{s_{10}}$ =23.9° C. (75° F.)−37.8° C. (100° F.). An expression was derived to fit the data so that T_{s_f} could be calculated from $T_{s_{10}}$ within this range. The regression is shown in Figure 3. However, as indicated above, the ratio $T_{s_{10}}/T_{s_f}$ approaches unity as tolerance time approaches ten minutes. Therefore, a cubic expression was derived which would take this fact into consideration. This expression has essentially the correct values for the "neutral" T_s and for $T_{s_{10}} = T_{s_f}$ at both the hot and cold extremes. This equation is also indicated in Figure 3.

We have established that final skin temperature and tolerance time are related and we have shown that skin temperature at ten minutes of exposure is related to skin temperature at the tolerance limit. Therefore, skin temperature at ten minutes can be used to predict tolerance time for both hot and cold exposures. Figure 4, which is patterned after Figure 2 shows the relationship of $T_{s_{10}}$ to tolerance time. If $T_{s_{10}}$ is between the limits of 25.0° C. (77° F.) and 36.4° C. (97.5° F.) tolerance time is at least 120 minutes. Beyond these limits tolerance time decreases in proportion to the increase or decrease in $T_{s_{10}}$ values. Tolerance time would decrease to ten minutes when $T_{s_{10}}$ increases to 43.3° C. (110° F.) or decreases to 16.4° C. (61.5° F.).

The very good agreement between skin temperature and tolerance time is remarkable because several criteria were used to determine tolerance including subjective evaluations as well as several objective measures. It would thus appear that skin temperature is the one physiological measure which responds to all environments in a predictable and sensitive manner, at least under the conditions of these studies. This measure can be a very useful tool to those who have an interest in the effects of the thermal environment on man's ability to perform in, and tolerate physiologically, that environment. More work is required to determine the effects of workload, clothing, equipment and other factors on this prediction model.

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