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Effects of Workplace Thermal Conditions On Safe Work Behavior

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The effect of workplace thermal conditions on worker safety has not previously been adequately investigated, due in part to the difficulty of defining a suitable safety performance measure. This report describes a study conducted in two industrial plants to determine if a correlation exists between the safety-related behavior of workers and workplace thermal conditions. Both heat exposure measurements and behavioral observations were taken over a 14-month period, for a total of over 17,000 observations. The results indicate that temperatures below and above those typically preferred by most people have a significantly detrimental effect on the safety-related behavior of workers. This is demonstrated by an index based on the ratio of observed unsafe behaviors to the total number of observed behaviors. The relationship between this index of unsafe behavior and the ambient temperature formed a U-shaped curve. The minimum unsafe behavior index occurred within the zone of preferred temperature (approximately 17°C to 23°C, WBGT). Other factors such as metabolic workload and time during the shift also had significant effects on worker safety-related behavior.

The safety of workers is influenced by many interacting factors. One factor of concern is workplace thermal conditions. Some evidence suggests that an optimum range of thermal conditions exists within which people demonstrate the best performance in terms of error rates, learning time, and production values (Poulton, 1972). Outside of this range, an individual's performance deteriorates. Unfortunately, the evidence to support this relationship is not predicted on safety-related performance. The need to clarify how workplace thermal conditions affect unsafe acts and accident risk prompted this study.

Some investigators have attempted to determine the relationship between workplace thermal conditions and worker safety using injury experience as a measure (Farmer, Chambers, & Kirk, 1933; Osborne, Vernon,

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& Muscio, 1922; Powell, Hale, Martin, & Simon, 1971). Although these investigations were unable to account for possible effects of all covariates, they did provide support for the theory that the relationship between injury rates and air temperature is a U-shaped curve. Other outcome measures have been found to have a U-shaped relationship to thermal conditions, including perceived thermal comfort (Humphreys, 1981) and the performance of sedentary tasks (Ellis, 1982; Ramsey & Morrissey, 1978).

In order to study the relationship between worker safety and thermal exposure, meaningful measures of both variables are needed. Parameters traditionally used as measures of occupational safety are based directly on injury experience. These measures are not generally suitable for occupational safety research because (1) numerous factors can affect the reporting of their occurrence, (2) not all occurrences are documented, and (3) they are rare events in a statistical sense. Rockwell (1959) and Tarrants (1980) describe a more sensitive measure, based on behavioral observations, which has been used in several recent occupational safety studies (Komaki, Barwick, & Scott, 1978; Komaki, Heinzmann, & Lawson, 1980; Smith, Anger, & Uslan, 1978; Zohar, 1980; Zohar, Cohen, & Azar, 1980). The measure is based on the premise that for every fatality or serious injury there is a larger number of minor injuries and, correspondingly a much larger number of unsafe acts and hazardous opportunities (Ramsey, 1973).

This measure is based on the observation of behaviors and conditions resulting from behaviors that are correlated with injury risk. The technique involves defining those behaviors and conditions that are unsafe for specified operations and then making random observations of those operations. Being observed causes some change in worker behavior; nevertheless, it is well documented that this is a transient change that disappears after repeated observations (Barnes, 1980).

In addition to having a measure of safety behavior, a measure of heat exposure is needed that accounts for all characteristics of the thermal environment (temperature, radiation, humidity, and air velocity). The thermal index recommended by the National Institute for Occupational Safety and Health (1972) for use in hot environments, the Wet Bulb Globe Temperature (WBGT), was selected for this study. The WBGT is based on simple measurements of environmental conditions. Although experts in thermal stress argue about which index is best for use in the workplace, in the two plants in this study the most advocated indices correlated quite well with each other (Beshir, Ramsey, & Burford, 1982).

METHOD

This study was conducted using indoor work tasks at two industrial plants: a metal products manufacturing plant and a foundry. A wide variety of industrial work tasks and work stations were observed, including welding, crating, painting, machine tool operation (e.g., turning, tapping, milling, boring, grinding, drilling), shipping and receiving, pattern making, thermal and chemical core making, mold shaking, pin machining, milling, shot tumbling, and casting.

Prior to the data collection period, a taxonomy of unsafe worker behaviors and data sheets were developed for each of the two plants (Ramsey, Burford, & Beshir, 1982). The data sheets facilitated the systematic recording of the following items: observer, day of the week, time of observation, date, outside ambient temperature conditions, machine/work station number, observed safe or unsafe behaviors and conditions, estimated employee workload at the time of the observation, and a set of thermal measures.

Observers made daily trips to the plants, and both plants received approximately the same number of visits throughout the study. Observers carried the temperature measurement equipment to each work station during each trip to the plant. The time of the visit was chosen at random. Each trip to a plant included two separate data collection walks through the plant. The data were collected over a 14-month period from July 1, 1981 through the end of August of the following year at the rate of approximately 60 observations per day.

At the first data collection point, the tripod with the mounted equipment was placed close enough to the worker to ensure accurate meas-

urement of his or her thermal environment, but not so close that it interfered with the worker's activities. The wet-bulb wick was then wetted, and the monitor was allowed to stabilize for 5–15 minutes depending on the temperature. Subjects were observed for approximately 30 seconds to characterize their work behavior according to the taxonomy of unsafe behaviors. After data were collected at the first station, the next station was chosen at random to avoid any bias. At the end of the first walk, the observer waited for about 10 minutes before commencing the second walk. After completion of a 30-day pilot study, workers displayed little concern or apparent behavior change in the presence of an observer.

The study data were collected by three observers. In order to maintain consistency in unsafe behavior definitions among observers, a file of definitions and examples was prepared for each unsafe behavior category. This file provided the observers with common definitions of unsafe worker behavior. Prior to actual data collection, each observer received training in the definitions of unsafe behavior categories and the proper evaluation of metabolic workload rate. In addition, during the study each observer conducted a joint visit with another observer at least once a month. During joint visits, the observers made independent observations of safety behavior and environmental conditions. The data were compared at the end of each walk in order to provide corrective feedback and to ensure consistency in defining unsafe behaviors, reading the instruments, and estimating metabolic workload. A complete description of the experimental procedure and the taxonomy of behaviors is reported in Ramsey, Burford, and Beshir (1982).

The independent variables were ambient temperature, metabolic workload, job risk group, period of the day, and day of the week. The dependent variable was a measure of unsafe behavior. These variables are described more specifically below.

Independent Variables

Ambient temperatures. The WBGT was used to measure environmental heat stress. A heat stress monitor was mounted on a tripod and carried by the observer to measurement locations throughout the plants. The monitor provided a direct reading in degrees Celsius of the WBGT indoor and outdoor dry-bulb temperature, natural wet-bulb temperature, and globe temperature. The WBGT indoor scale was used in this study because all of the observed jobs were indoors. Three Reuter-Stokes instruments were used in this study, one model RSS-211A and two model RSS-211D. Three sets of instruments were necessary because of repeated electronic circuit failures. All instruments used in the study were calibrated after any repair, however, and then periodically recalibrated in an environmental chamber.

The calibrations were performed in an environmental chamber over a range 10–35°C WBGT by comparing the instruments with a standard WBGT tree as recommended by NIOSH (1972). Over 99% of the field measurements were within this range. A comprehensive calibration was conducted monthly, and a simple calibration check was made weekly. The difference between the standard WBGT tree and the field collection instruments did not exceed 1°C for the different heat measures.

Metabolic workload. The thermal equilibrium of a worker is affected not only by the heat of the environment but also by the metabolic heat generated as a result of the work task. It is difficult to accurately measure this metabolic heat without interfering with job performance and behavior. For this study a table (Ramsey, 1978) was used to estimate metabolic rate. The table categorizes activities into three metabolic workload (M) levels: (1) light ($M \leq 200$ Kcal/h); (2) moderate ($201 \leq M \leq 300$ Kcal/h); and (3) heavy ($M \geq 301$ Kcal/h).

Job risk group. Although there is a risk of traumatic injury associated with every job in industry, some jobs involve more risk than others. For instance, a person operating a numerically controlled machine would be exposed to less risk, by the very nature of the job, than a person working as a member of a pouring crew in a foundry. Hence, an observer studying the safety behavior of these two workers should take into account the in-

herent risk in each job to prevent the risk factor from masking the effects of temperature on safety behavior.

After a short period of data collection, this risk phenomenon became apparent due to the high variability in unsafe work behavior among the different jobs in the study. Consequently, the jobs were categorized based on the preliminary data and on a judgmental assessment of the general level of risk. Three job risk categories were established based on this pre-study proportional data: (1) low risk ($p < .05$); (2) moderate risk ($.05 \leq p \leq .1$); and (3) high risk ($p \geq .1$). At the end of the study, the proportion (p) of unsafe behavior observations to total observations was determined for each job in order to verify that the jobs that had been assigned to a specific risk level group at the beginning of the study in fact met the criteria for that group.

Period of the day. Another independent factor is the day or shift, which potentially reflects the effects of fatigue and time-at-work on behavior. Four periods were used to classify observations: (1) early morning, (2) late morning, (3) early afternoon, and (4) late afternoon. The lunch break was used to distinguish between morning and afternoon observations. The mid-morning and mid-afternoon breaks, which were taken at slightly different times at the two plants, were used to distinguish between the early and late sessions of the morning and afternoon.

Day of week. The day of the week (Monday, Tuesday, Wednesday, Thursday, or Friday) was considered as an independent variable in order to evaluate its influence on behavior.

Dependent Variable

An unsafe behavior index (UBI) was the dependent variable in this study. The observational data were initially expressed as a proportion (p), defined as the ratio of the number of unsafe observations to the total number of observations. When proportions or percentages are used as the response variable, the data are binomial, variances are related to means, and the basic assumptions of analysis of variance do not hold. In order to make the observed data amenable to regression and analysis of variance, the proportional data of this study were transformed as the arc sin square root of p ($\sin^{-1} p$) (Davies, 1954).

The UBI then is defined as the transformed proportion for use in subsequent statistical analysis:

$$UBI = \sin^{-1} p$$

It should be noted that the UBI is an increasing function of the proportion of unsafe behavior. Therefore, any statistical conclusion drawn concerning UBI will apply to p.

Injury occurrence was originally considered as a potential dependent variable for this study. The actual number of injuries was very small, however, and data on the thermal conditions at the time of the incidents were limited. These deficiencies were not found in the behavioral data selected for analysis.

RESULTS

Determining the relationship between thermal conditions as an independent variable and unsafe work behavior as a dependent variable was the main objective of this study. However, the interactive influences of the other independent variables (metabolic workload, job risk, and period of the day) are also important in interpreting the results.

The statistical technique of analysis of variance (ANOVA) was first used to test the hypothesis that the following variables and their respective levels affect the UBI:

1. Temperature: (1) cold ($T < 15°C$ WBGT); (2) cool ($15° \leq T$ 20°C WBGT); (3) comfort ($20° \leq T \leq 25°$ WBGT); (4) warm ($25° \leq T \leq 30°C$ WBGT); and (5) hot ($T \geq 30°C$ WBGT);
2. Workload: (1) light, (2) moderate, and (3) heavy;
3. Job risk level: (1) low risk, (2) moderate risk, and (3) high risk;
4. Period of the day: (1) early morning, (2) late morning, (3) early afternoon, and (4) late afternoon); and
5. Variable interactions.

The results are shown in Table 1. All of the independent variables and their interactions have significant effects ($p < .01$) on worker

TABLE 1
ANALYSIS OF VARIANCE FOR UBI

SOURCE OF VARIATION	*df*	*SS*	*F*
Temperature (T)	4	5.5541	8.00*
Workload (WL)	2	62.5540	180.18*
Job risk	2	86.0051	247.72*
Period	3	6.4299	12.35*
T × WL	8	17.2991	12.46*
T × Job risk	8	1.1563	0.83
T × Period	12	1.3574	0.65
WL × Job risk	4	11.3721	16.38*
WL × Period	6	4.2196	4.05*
Job risk × Period	6	9.4126	9.04*

*$p < .01$.

safety behavior with the exception of the temperature × job risk and temperature × period interactions. These effects will be discussed in the order of their appearance in Table 1.

Since temperature, workload, and the temperature × workload interaction were significant, a regression analysis of these variables with UBI was also conducted. For the regression analysis, values of p were computed for each degree Celsius WBGT within the measured range of ambient temperatures rather than for only the five temperature levels used in the ANOVA. The linear regression model did not correlate as well as did the second order quadratic model:

$$UBI = A + B(T) + C(T^2)$$

where

T is temperature in degrees Celsius WBGT units, and

A, B, C, are constants.

The regression models for the relationship between the UBI and ambient temperature at the three different levels of workload are shown in Figure 1 and Table 2. The 29 data points (29 UBI values) for light work in Table 2 were determined from 12,379 observations while the 25 data points for each of the moderate and heavy workloads were determined from 4595 and 818 observations, respectively.

At temperature levels in the thermally neutral range and warmer, the heavy workload tasks have the highest UBI, followed by the moderate, and then the light workload tasks. In the cooler environments, however, this pattern is not consistent. (See Figure 1 and

FIGURE 1
UBI AS A FUNCTION OF WBGT:
PREDICTED SECOND ORDER REGRESSION
FOR THREE DIFFERENT WORKLOADS

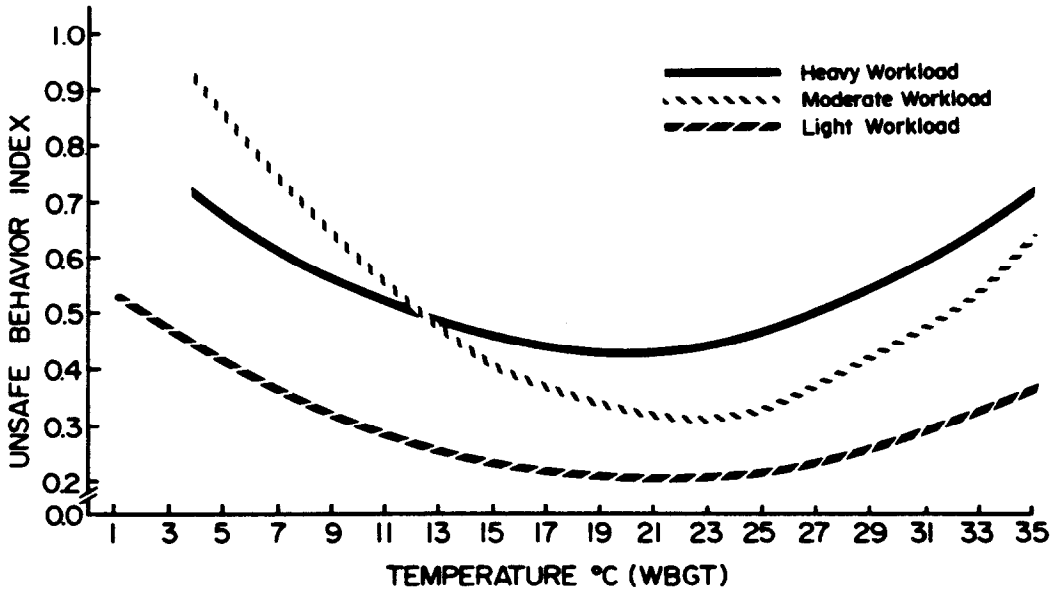


TABLE 2
RELATIONSHIP BETWEEN UBI AND
AMBIENT TEMPERATURE FOR DIFFERENT WORKLOAD GROUPS

WORKLOAD	NUMBER OF OBSERVATIONS	NUMBER OF DATA POINTS	UBI = A + B(T) + C(T²) A	B	C	F	R	C.V.
Light	12379	29	0.5829	−0.0341	0.0008	13.64*	0.7155*	27.35
Moderate	4595	25	1.2526	−0.0839	0.0019	9.53*	0.6731*	40.79
Heavy	818	25	0.8889	−0.0456	0.0012	4.94*	0.5567*	26.15

*$p < .01$.

the ambient temperature × workload interaction in Table 1.)

Figure 1 also shows that the minimum UBI occurs in the 17° to 23°C WBGT range for light, moderate, or heavy workloads. This range coincides with or is slightly below the range specified as thermal comfort for light or sedentary work activities. Beshir and Ramsey (1981) found the comfort temperatures for light workload to be 22°C WBGT, and Humphreys (1981) reported numerous studies with preferred air temperatures between 17° and 26°C dry bulb. Table 2 shows the coefficients of correlation (R) for the relationship between the UBI and temperature for each workload level. These values of R are significant ($p < .01$) based on the number of observations (Edwards, 1967).

As previously mentioned, the risk level of each job was estimated at the beginning of the study and verified at the end of data collection. The results of a second order quadratic regression model indicate that, for each of the three job risk levels, the UBI increases as the ambient temperature either increases or decreases from the midrange values. Also, the high-risk group has the highest UBI followed by the moderate-risk group and then the low-risk group. This hierarchy was expected since job risk levels were originally assigned according to their proportions of unsafe behaviors in the preliminary data.

The ANOVA indicates that the period of the day has a highly significant effect ($p < .01$) on UBI. Figure 2 shows an increase in the UBI throughout the four periods of the day. As the day progresses, time-on-task also increases as does the potential for fatigue build-up. Since the WBGT temperature also increases in the same direction, both fatigue and temperature may explain the observed increase in UBI.

Figure 3 shows the workload × job risk interaction effect on UBI. For each job risk group, the higher metabolic workload levels correspond to higher values of UBI. It should be noted, however, that the high risk-heavy workload combination yields a UBI that is disproportionately higher than the other combinations.

The relationship between UBI and the workload × period of the day interaction is shown in Figure 4. The UBI does not show a period effect for light workload, but does increase throughout the day under moderate workload. The UBI is highest under heavy workload conditions, except during period one. A possible explanation for this observation is that many of the heavy workload jobs in the foundry and plant have cooler temperatures during period one and thus lower UBI. This inconsistency more likely resulted, however, from the small data set (only 30 observations) for the period one and heavy workload combination.

FIGURE 2
RELATIONSHIP BETWEEN THE UBI AND
PERIOD OF THE DAY AND WBGT

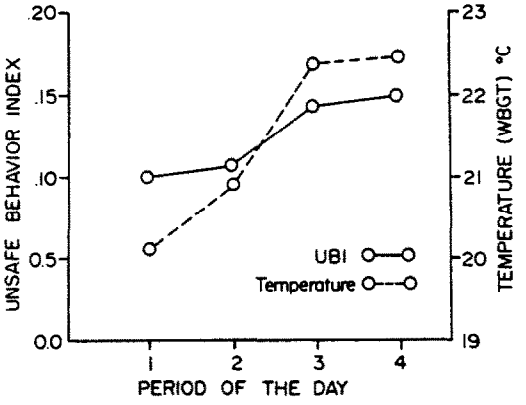
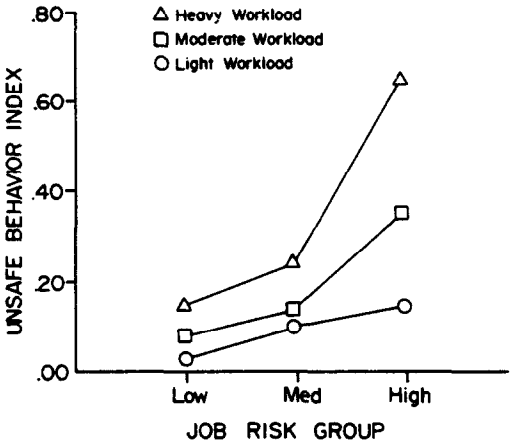


FIGURE 3
RELATIONSHIP BETWEEN UBI AND
JOB RISK GROUP AND WORKLOAD



The interaction of job risk group × period of the day (Figure 5) shows UBI increasing very little during the day for low-risk jobs, but increasing substantially for the high-risk jobs. Safety behavior on the low-risk jobs was apparently influenced very little, or not at all, by the time of day. This is the same relationship observed for light workload (Figure 4). In both instances the nature of the work is such that the build-up of fatigue is less likely than for the other combinations of risk or workload. This supports the premise that behavior is adversely affected by the length of time on the task or fatigue. On the other hand, the temperature which is increasing during the day does not have a noticeable affect on UBI for these light workload or low job risk conditions.

FIGURE 4
RELATIONSHIP BETWEEN UBI
AND THE INTERACTION OF
WORKLOAD AND PERIOD OF THE DAY

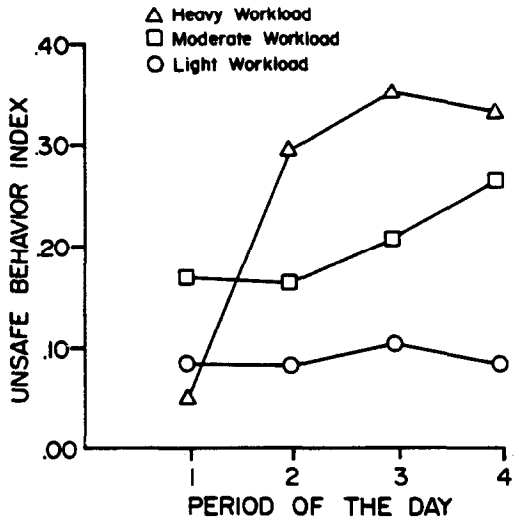
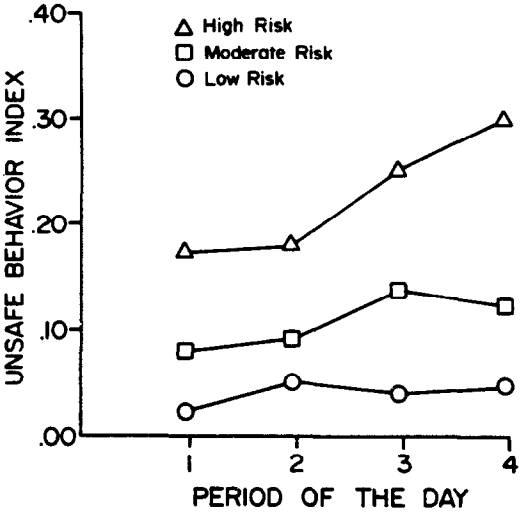


FIGURE 5
RELATIONSHIP BETWEEN UBI
AND THE INTERACTION OF
JOB RISK GROUP AND PERIOD OF THE DAY



The analysis of variance performed on the variable day of the week showed no significant difference in UBI among the different days.

The second order regression models for the relationship between UBI and ambient temperature for the data sets obtained by each observer were also determined. The model obtained for each data set (i.e., for each observer) showed the same pattern shown in Figure 1, that is, a U-shaped relationship with the minimum UBI occurring in the range of 17° to 23°C WBGT. This supports the consistency of observations made by the different observers, as well as the persistence of the U-shaped curve phenomenon.

The total number of observations in this study was 17,841, with 16,107 being reported as safe and 1,734 as unsafe. Thus, according to the definitions of this study, about 90% of the observed worker behaviors were safe and about 10% were unsafe.

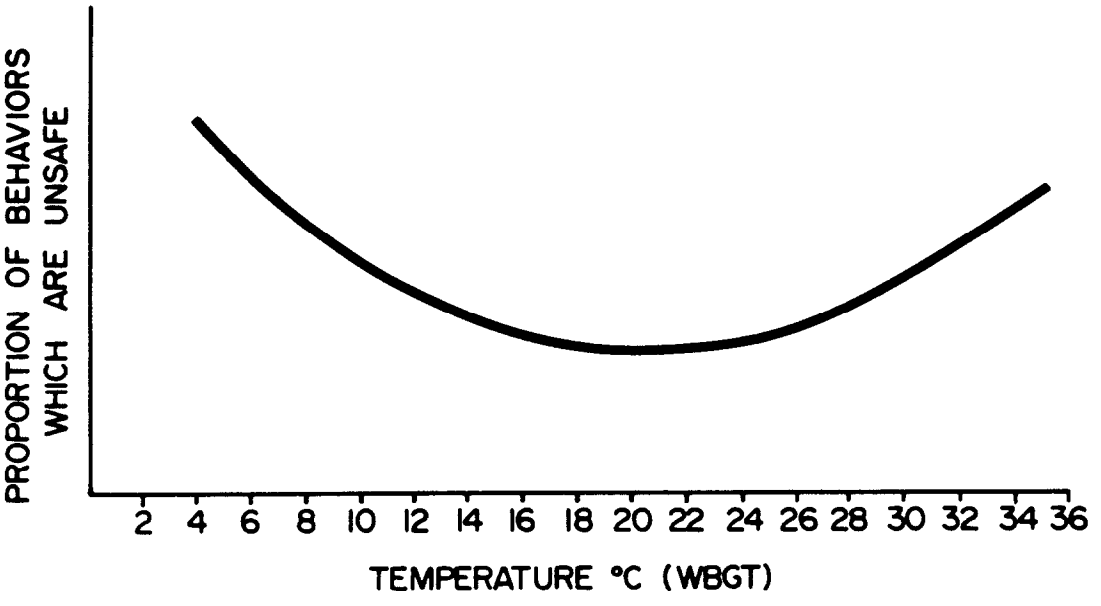
DISCUSSION

The results obtained from this study are most directly relevant for industrial environments similar to those observed, i.e., metal products manufacturing plants and foundries. Whether similar relationships exist in other workplaces is a question that is unanswered by this study, although there are no obvious reasons for expecting different relationships in other work environments. The data for this study were collected over a 14-month period so that there was a wide array of seasonal weather conditions and indoor temperatures. The clothing worn by the workers ranged from short sleeved shirts and cotton trousers to overalls and jackets, but was directly related to the need of the workers to adjust their personal microclimates as a function of temperature and metabolic work load. The U-shaped character and the tendency for all three curves of Figure 1 to reach minimum UBI in the same general range suggest that this ability to regulate clothing allows a similar comfort zone for light, moderate, and heavy work. A possible explanation for the crossover of the heavy and moderate work curves in Figure 1 is that heavy work generates enough heat in the body to counteract the negative effect of the colder environment, thus reducing the UBI.

The U-shaped relationship between UBI and temperature is reflective of similar U-shaped (or inverted U-shaped) curves used to describe: (1) performance efficiency as a function of both environmental conditions and arousal (Poulton, 1972); (2) rate of accidents as a function of stress level (Salvendy, 1982); and (3) human performance as a function of arousal (Surry, 1969). This study provides the first objective indication that the relationship between job behavior and the workplace thermal level follows a similar pattern.

The behavioral observation technique proved very useful as a research tool. It facilitated the collection of relatively large amounts of data that were more sensitive than the outcome measures traditionally used in safety studies.

FIGURE 6
GENERAL RELATIONSHIP BETWEEN
THE PROPORTION OF UNSAFE WORK
BEHAVIORS AND THERMAL CONDITIONS



CONCLUSIONS

The significant observations and conclusions drawn from the results of this investigation are:

1. Ambient temperature has a statistically significant effect on the unsafe behavior index (UBI) used in this study. This relationship is a U-shaped curve, with minimum UBI values occurring in the preferred temperature zone of 17° to 23° WBGT. An increase in the UBI occurs when ambient temperature increases above or decreases below this range. A generalized curve depicting the relationship between the proportion of unsafe work behaviors and temperature is shown in Figure 6.

2. The level of metabolic workload is significantly related to the UBI, with higher workload levels associated with higher values of UBI. The U-shaped relationship between temperature and UBI occurs for each workload level (light, moderate, or heavy).

3. Grouping machines and work tasks into different job risk groups (low, moderate and high) allows the assessment of differential effects associated with each group. The U-shaped pattern of the UBI versus temperature relationship was consistent for each of the job risk groups.

4. The UBI values during the morning were significantly lower than those observed in the afternoon. Further research is required to determine if this is due to fatigue or other variables.

5. The U-shaped (or inverted U-shaped) curve is commonly used to describe human perceptual-motor performance as a function of increasing levels of environmental stimulation or arousal. The findings of this worksite study suggest that the thermal environment has influences on safety behavior similar to those found in laboratory studies of the relationship between environmental temperature and human performance.

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