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LIMITS OF BEHAVIORAL EFFICIENCY FOR WORKERS IN HEAT STRESS *

P.A. Hancock ** and M. Vercruyssen

Department of Safety Science and Human Factors Department, Institute of Safety and Systems Management, University of Southern California, Los Angeles, CA 90089-0021 (U.S.A)

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ABSTRACT

This paper describes three zones which differentiate the limits of human behavioral efficiency in heat stress. They are: (1) a zone of thermal intolerance, (2) a zone which identifies the upper thermal tolerances for unimpaired cognitive and neuromuscular performance, and (3) a zone of thermal equilibration. Description of the boundaries to these zones through concurrent identification of time/intensity specifications and physiological criteria allows their broad application across both traditional industrial industrial conditions and activity in unusual occupational environments (e.g., those requiring enclosed garment useage), where contemporary indices based on physical values of the ambient surround are of restricted applicability. It is suggested that these criteria, based upon performance change, can be used to augment current heat stress standards which are founded upon physiological evidence of impairment.

INTRODUCTION

There are many occasions in which workers may be exposed to heat stress. Extremes of heat are associated with work in equatorial or desert regions, activity in a variety of aerospace endeavors, or work in heavy industry where heat sources are openly exposed and usually a by-product of the production process. Milder levels of heat stress are experienced in continental or tropical climates and in confined space operations where cooling is unavailable. In addition, recent energy conservation measures have dictated that many occupational environments be maintained at ambient levels approaching or violating the thresholds of the thermal comfort envelope (Fanger, 1970). The origin of interest in temperature and its effects on human behavior is founded in antiquity (cf., Sanctorius, 1614), but it is the necessity to operate efficiently and safely in these diverse and often arduous conditions which drives contemporary concerns for the problems imposed by heat stress (Hancock, 1984a; Kerslake, 1972; Ramsey, 1983).

With respect to behavioral capabilities there are four factors of particular concern. We wish to know how variation in the thermal environment affects the comfort, health, safety, and productiv-

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** To whom all correspondence should be addressed.

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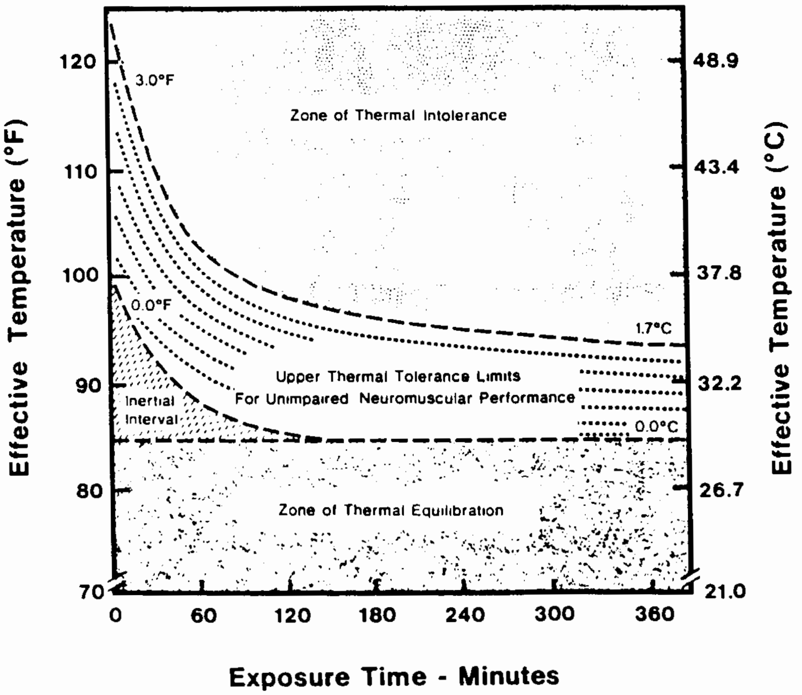

Fig. 1. Using the axes of exposure time and stress intensity, three major zones of worker performance efficiency are distinguished. The heat stress axis is expressed in terms of Effective Temperature (ET). The zone of thermal intolerance describes a region of complete performance cessation due to physiological failure. The zone of thermal equilibration describes a ceiling level of ambient conditions which are insufficiently severe to disturb deep body temperature and thus curtail performance efficiency. Embedded between these zones are isodecrement contours which describe the upper thermal tolerance limits for unimpaired cognitive and neuromuscular performance. Precise details for differing task characteristics are described in the text. The boundaries and contents of each zone can be described in terms of dynamic change to the core body temperature of the exposed individual which permits their use for occupations where traditional indices cannot accurately assess the heat load imposed on the worker. The inertial interval, which reflects the resistance of human core temperature to sudden change, completes the present picture.

ity of the exposed individual. This overall relationship is liable to be somewhat complex (Poulton, 1977) and a formal statement of the multiple interactions between these factors exceeds the scope of this paper. Rather, this work aims at a more modest goal, namely to outline the effects of the heated environment on the behavior of the exposed worker, with particular focus on change in performance efficiency. This is accomplished initially through the development of three thermal performance zones which are illustrated in Fig. 1.

These zones are constructed with reference to elevated environmental temperature. The comparable changes that may be anticipated in cold conditions are not examined in detail here. However, it is reasonable to infer that a mirror image of the illustrated zones should occur, with some variation due to the more complex effects of cold exposure (e.g., the mechanical interference to performance due to shivering, and the transient *increases* in core temperature upon immediate exposure to cold conditions; Burton and Edholm, 1955). In the sections which follow, support for the composition and thresholds of each performance zone is established. The practical importance of this description to current industrial problems is evaluated. The relationship between these limits and those recommended in the recent revised criteria for occupational exposure to heat (NIOSH, 1986) is examined.

THERMAL INTOLERANCE LIMITS

For several decades experimenters have sought a single description of human tolerance to thermal extremes and a measurable physiological or behavioral parameter to index and predict such limitation. This exploration has met with varied success and is the subject of continuing, practially-oriented efforts (cf., Goldman, 1984). Independent of influential variants such as age, gender, somatotype, and state of acclimatization unanimity among researchers has been somewhat limited. For example, Iampietro (1970) described tolerance in terms of pain, heat load, and system limits. This latter category consists of heat-related incapacitation through behavioral distress which precedes limitation due to heat accumulation. Evidence for this tripartite distinction led to his suggestion that a single tolerance criterion was unjustified, as limiting functions vary according to the type and severity of environment encountered, i.e., exposure limitations could fluctuate between the three identified categories dependent upon the specific operating conditions. Evidence of these various types of limitation can be seen in the several different approaches which have been advocated. A synopsis of works around this topic can be found in the comprehensive and informative review by Kobrick and Fine (1983).

Tolerance to the extremes of any stress depends upon the dynamic adaptability of the organism involved. The human ability to withstand excessive thermal stress may be divided generally into social, behavioral, or physiological restrictions. Each of these represent one locus along a single adaptability continuum and are not simply discrete forms of limitation. Subjective tolerance and pain limits are largely behavioral in origin, while heat-load and body temperature measures belong mostly to the physiological portion of the continuum. The system-limited tolerance of nausea, vomiting, dizziness, and extreme hyperventilation are also physiological in nature but lie more toward the behavioral portion of the continuum than the classic heat-load limits. Such symptoms can also result from orthostatic heat intolerance in which core temperature may remain at a relatively low level (Shvartz, 1987). As yet, relatively little evidence concerning social limitations has percolated into the literature on work standards (ACGIH, 1987). However, a number of traits such as increased irritation, intolerance of co-workers, and frustration can have a significant influence on safety and productivity in heat stress and other occupational environments which prove stressful to the worker. Some information on such general effects can be found in the work of Frese (1987) and Karasek, Russell and Theorell (1982) while information concerning the actions of heat stress specifically can be found in the review work of Bell (1981; see also Bell and Greene, 1982).

The *core* and *deep* body temperature of the individual has most commonly been used as the criterion for heat tolerance (Goldman et al., 1965). Although core temperature can be measured at several locations, the rectal value is usually presented as the most stable site. However, it has been demonstrated that differing values may be observed even at one site depending upon the measurement technique employed (Mitchell, 1977). The typically advocated physiological ceiling for core temperature is centered around a value of 39.2°C (102.6°F) measured while under the influence of a driving heat load. As with all single-point measures, deep body temperature has certain inherent limitations. First, due to its intrinsic inertia, it is relatively slow to respond to sudden external changes making it of restricted value in exposures to exceptionally high temperatures. Use of deep body temperature as a measure in these cases could result in a potentially dangerous underestimation of an individual's approach toward physiological collapse. It has been shown that other measures such as heart rate and skin temperature provide superior indicators of heat tolerance in hot and humid conditions (Iampietro and Goldman, 1965). Also, as temperature is a distributed physiological parameter, one single site cannot represent the temperatures of differing bodily locations. This is important when the worker may be exposed to specific heat sources, e.g., radiant heating, where the exposed side of the body may differ markedly from the unexposed area. In occupational settings, the long term effect of such differential heating is largely unknown. In addition, many industrial occupations require prolonged standing in the heat. In these conditions, orthostatic heat tolerance can assume a greater role in terminating an individual's exposure to heat, rather than simple heat storage alone. Under such conditions, heart rate and skin temperature would provide a superior indicator of incipient collapse (Shvartz et al., 1975). Despite these objections, core temperature remains a useful overall measure and is the only metric that has been related to both physiological and performance limitations as elaborated in this paper. The lack of acceptance of rectal temperature in the applied occupational environment is an important drawback. To counter this problem, core temperature assessment at the tympanic site (i.e., the deep portion of the auditory meatus) should be considered a more acceptable measurement location in actual work conditions.

The physiological tolerance limit, as proposed in Fig. 1 represents a dynamic increase of 1.67 ° C (3.0 ° F) in core temperature above a resting level for the sedentary worker. This threshold is supported by both empirical studies and reviews of the literature (Gorodinskii et al., 1968; Kaufman, 1963). This limit is a slightly conservative one compared to the alternative modal tolerance value of 39.2 ° C indicated previously, and so provides an intrinsic safety cushion should the present performance zones be used to augment current industrial standards (see NIOSH, 1972; 1986). It is acknowledged that core temperature alone is not as comprehensive in its assessment abilities as composite measures (i.e., a compound of core and skin temperature assessment; Bell et al., 1965; Bell and Walters, 1969; Craig et al., 1954; Goldman et al., 1965; Iampietro, 1971; Iampietro and Goldman, 1965; Shvartz and Benor, 1972) nor is it as quick to respond to changes in the environment as other physiological parameters (e.g., heart rate, skin temperature, etc.). However, to provide consistency across zonal limits and to present an acceptable common measure, deep body temperature is currently the best single measure. In future descriptions of limitations of human performance efficiency in hot conditions, it may be possible to derive a fuller synthesis concerning change in capability based on more complete empirical evidence of both core temperature and other physiological responses. Such developments await more thorough experimental work and a fuller understanding of human thermo-physiological and behavioral response under heat stress. There are a variety of additional approaches to heat tolerance which range from voluntary participant withdrawl from the stressful environment, to pain-induced limitations (Hardy, 1953; Webb, 1963). However, the focus of the present work is upon the limitations of behavioral efficiency in heat stress and it is to this performance-based evidence that we now turn.

PERFORMANCE LIMITS

While environmental limits and physiological response have been used traditionally to dictate occupational restriction to thermally stressful environments (NIOSH, 1972; 1986), it is often the performance of the exposed worker which is more important than simple medical considerations in setting safe tolerance times. This is because *if the worker is unable to perform the task which has been set forth or, if errors rise to an unacceptable level, continued work in the stress no longer serves any useful purpose, and may prove positively harmful to the exposed individual and their co-workers*. Typically, these performance limits are encountered prior to the limits of physiological functioning. The above statement is inherent in Fig. 1, which illustrates that an individual's performance breakdown occurs a considerable period before the absolute physiological threshold for heat tolerance.

The early NIOSH (1972) limit for performance under heat stress was a transcription of the threshold suggested by Wing (1965) from a review of a variety of experimental studies on temperature and performance. The change of heat stress index on the axis from Effective Temperature (ET), as expressed by Wing (1965), to Wet Bulb Globe Temperature (WBGT) (NIOSH, 1972; Fig. 1) without any form of correction for radiant heat was, most probably, an incorrect assumption. In order to achieve an accurate translation between these indices, further empirical investigation is needed. However, independent of such consideration this NIOSH threshold was criticized by Hancock (1981a) on the basis of both factual and interpretational errors made by Wing in his original work. A more recent synthesis on performance indicated that such limits are task dependent. For example, Hancock (1981a) established that simple mental performance was relatively invulnerable to heat and decrement was only observed in this type of performance as participants approached physiological tolerance. However, as the complexity of the task increased and involved more fine psychomotor control, a lower heat stress level was sufficient to interrupt successful performance (Hancock, 1982). It has been suggested that the attentional *resources* demanded by the task are a key factor in determining performance breakdown. Hancock (1986a; Hancock and Chignell, 1985) suggested that stress competes for and drains such resources so that performance efficiency declines, with more attention-demanding tasks suffering earlier and more substantively than comparable but less attention-demanding tasks (Hancock, 1986b).

In an overall view, performance limits were tied to increases in deep body temperature such that physiological tolerance is identified with a dynamic increase of 1.67°C (3.0°F) in deep body temperature of the sedentary worker. Performance breakdowns in mental, psychomotor and dual task performance were associated with uncontrolled rises of 1.33°C (2.4°F), 0.88°C (1.6°F) and 0.22°C (0.4°F) in deep body temperature, respectively (Hancock, 1982). Psychomotor tasks typically require the execution of some skilled neuromuscular action by the individual as evidenced in tracking-type tasks, while dual-task performance usually requires such fine motor coordination in conjunction with an additional performance task. In an extension to the above view, it has been demonstrated that vigilance, or the ability to sustain attention over long periods, is particularly vulnerable to the effect of heat (Hancock, 1984b). Within this category of performance, any dynamic disturbance to deep body temperature, either an uncontrolled increase (Bell et al., 1964; Benor and Shvartz, 1971) or decrease (Kissen et al., 1964) is sufficient to degrade performance efficiency (see also Grether, 1973; Hancock, 1986b). It is these limitations that are represented by the dashed lines in the zone of upper tolerance limits for unimpaired neuromuscular performance, as given in Fig. 1, although their representation is illustrative and more accurate details of specific contours are given in Hancock (1982, 1987). It is these limitations that have been reproduced in a number of recent texts concerning human performance limits under stress (Kantowitz and Sorkin, 1983; Konz, 1983; Sanders and McCormick, 1987).

The above observations are concerned with the upper tolerance limits in each type of performance category. However, this does not preclude fluctuations in performance efficiency below such limits which may be represented by either facilitation or reduction in capability. Gradations of performance change were indicated by Ramsey and Morrissey (1978) who described a number of decrement contours in differing neuromuscular and cognitive task categories. Numerous factors may influence performance fluctuation both within and between zones. For example, the *motivation* of the worker to perform and the relative *skill* level of that individual are considered important influences (Hancock, 1986c). Both gender and race also appear to be sources of individual difference for performance under heat stress. For example, Meese et al., (1984) found in a study of 1000 black and white male and female factory workers, that the white female participants performed less well under moderate heat stress compared to each of the other groups. Further, immediate exposure to an heated environment has been shown to produce a transient increase in perceptual efficiency (Poulton and Kerslake, 1965). In relatively brief exposures to transient extreme heat as represent in Fig. 1, the role of acclimation and acclimatization remains a poorly explored area, particularly with reference to its effects on performance (see NIOSH, 1986, Section X, for a synopsis of this and other experimental areas of interest). However, in simple pragmatic terms subjects perform better on a task after an initial and critical exposure to the stress (Hancock, 1984a). This is an important observation for those concerned with safety and training of operators for work in hot industrial environments.

While research concerning the physiological effects of heat and analysis of human comfort in differing thermal environments have been both systematic and productive, the study of performance has been much more sporadic. With few theoretical formulations to guide experimental efforts, little in the way of an overall perspective has emerged. The traditional behavioral arousal construct has been used to account for performance change (Poulton, 1977) but its validity has recently been questioned (Hancock, 1984a), and a number of its theoretical and experimental foundations have foundered under more recent concerted attack (e.g., Hancock, 1986c; Hancock and Chignell, 1985; Hockey and Hamilton, 1983; Sanders, 1983). In contrast to the failure of the unitary behavioral arousal explanation, contemporary views of human attentional capacity appear to offer a more fruitful theoretical alternative (Kahneman, 1973; Wickens, 1980; Schneider and Shiffrin, 1977). Regardless of the theoretical explanation, a review of the stress literature in general, and the information on heat in particular, indicates that performance effects are contingent upon: (1) the research methodology employed, (2) the nature of the performance task involved, (3) the obvious and more subtle physical characteristics of the stress experienced, (4) the baseline state of the exposed individual, and (5) the interactional effects of co-occuring stresses in the workplace (Hancock, 1985; Vercruyssen and Noble, 1985; Wilkinson, 1969). The current consensus of data supports the position expressed in Fig. 1, where upper tolerance limits for prescribed tasks are embedded between thermal intolerance on the one hand and a zone of thermal equilibration on the other. The basis of this latter zone is examined below.

ZONE OF THERMAL EQUILIBRATION

At the outset it should be noted that this is not the first description of this zone. The zone of thermal equilibration as expressed in Fig. 1 is coincident with the prescriptive zone proposed by Lind (1963a, b), and later summarized by Jokl (1982). The temperature limit described is for an individual expending energy up to 180 kcal/h which represents a sedentary level of seated work. This zone is a region where the core temperature remains *largely* stable in response to the ambient thermal surroundings. The combination of ambient temperature and exposure time are insufficient to perturb the thermal homeostasis of the exposed worker. At relatively mild levels of physical activity, i.e., 180-200 kcal/h the upper boundary to this region is approximately 30.0° F, ET (86° F). As work level increases, the threshold of the upper bound is reduced, so narrowing the zone of equilibration as dictated by the physiological mechanisms of thermoregulation (see Dukes-Dobos and Henschel, 1973; and Lind, 1963a for elaborated discussion with respect to setting heat tolerance standards based upon such effects). Lind's original experiment dealt with measures of physical performance rather than more cognitive aspects of work as discussed here. The zone of thermal equilibration is significant as it defines an area where cognitive performance should show little decrement while equilibrium is maintained. This resurrection of a concept originally defined as *physiological adequacy* (Connell, 1948) is an important consideration for those promulgating work-related stress tolerance standards which combine the factors of physiological and behavioral response.

Contained within this zone of thermal equilibration is the region of thermal comfort expressed, for example in the work by Rohles et al., (1980). This area, with a lower bound of 20.0° C ET (68° F ET) and upper bound of 26.1° C ET (79° F ET) describes the region where 94% of the population will be thermally comfortable while engaged in sedentary or near-sedentary activity (see also Rohles, 1980). While the prescriptive zone, described by Lind (1963a; see also Konz, 1983), was based on objective measurements of deep body temperature, the thermal comfort zone was developed using 1600 subjects indicating perceived comfort when exposed to a number of temperature-humidity combinations for three hours. It is the range of this comfort zone and its violation by energy conservation measures which pose an important challenge for the assessment of temperature-sensitive productivity rates in occupations where typically, heat stress is *not* identified as a particular problem (e.g., office work). How small perturbations from comfort impact sedentary workers in terms of health, safety, and productivity remains, in large part, an open question.

Inertial Interval

To complete the present description an addendum is required, which we have labelled the *inertial interval*. It is necessary to include this element, as the core or deep body temperature of the worker resists sudden change irrespective of the intensity of the heat stress exposure. As can be seen from Fig. 1 the inertial interval, like the identified major zones, covaries with environmental heat load, such that high ambient temperatures produce only a brief inertial interval which increases in temporal duration as heat level is reduced. This asymptotes at the ceiling of the equilibration zone where the temperature is 30.0° C ET (86° F ET).

APPLICATION TO INDUSTRIAL PROBLEMS

Having derived and supported the zonal differentiation expressed in Fig. 1, it is important to consider some inherent limitations of this description and also to elaborate its use in solving practical industrial problems. The primary limitation of the present description is the use of Effective Temperature (ET) as an index of heat stress. Unlike other indices which are founded upon *physical* elements of the environment (e.g., WBGT), the ET scale uses the perceptions of the exposed individual as a basis for thermal assessment. For use in industrial conditions, it is more appropriate to use physically-based indices. It may be possible to translate the present limits to a WBGT scale, but this has to be accomplished by a transformational algorithm, or by direct experimental observation, *not* through assumed linear equivalence between the two scales as indicated in the NIOSH (1972) criteria document.

Despite this concern, the expression of human performance limits in terms of *dynamic* change in deep body temperature allows a number of practical applications. Principal among these is the personal monitoring of individuals who may be exposed to high risk situations. One current and pre-eminent example is the use of semi-permeable and impermeable garments which are employed in activities such as hazardous-waste disposal. In such operations, the *physical* values of the environment alone cannot specify tolerance criteria. Rather, it is the interactional effects between the ambient thermal conditions, the microclimate generated in the enclosed garment, and the baseline state of the exposed worker that become key factors in deriving safe exposures times. Component functions of such an interaction may be simulated using a number of thermoregulatory models (Hancock, 1981b; Kwon and Ramsey, 1986). However, prediction from such models typically simulate the response of fit, healthy, male workers whose stature closely approximates a postulated "standard man" (Dubois and Dubois, 1915). Even in simple versions of such models, variation between workers due to factors such as age, gender, somatotype, fitness, and acclimation can cause wide variation in predicted safe tolerance times. Therefore, users of semi-permeable and impermeable garments in response to occupational exposure to hazardous environments including, hazardous waste disposal, nuclear power plant employees, fire-fighters, chemical plant workers, and security personnel, should employ the present heat tolerance descriptions expressed in terms of dynamic changes to the core body temperature of individual exposed.

There are a variety of work-related circumstances where voluntary withdrawl from the heat is not feasible (consider for example work in confined spaces, or self-contained micro-environments, e.g., enclosed and/or pressurized garments). Several studies have examined the physiological reactions and tolerance limits when wearing fire-fighting equipment (Duncan et al., 1979; Lemon and Hermiston, 1977; Myhre et al., 1979; Reischel and Stransky, 1980), and chemical protective clothing (Mihal, 1981; Raven et al., 1979; Smolander et al., 1985; Tanaka et al., 1978). A few studies have even quantified the interaction of a variety of permeable and impermeable clothing and respirator ensembles, at several levels of work intensity on work tolerance (White and Hodous, 1987) and subjective reactions (White et al., 1988). These studies point to the considerable differences in the physiological limits for performing physically-demanding work when the micro-environments varies. For instance, at room temperature, working at 290 kcal/h (7.7 METS), the maximum work time was only 3.1 minutes when wearing fire-fighter turnout gear, 11.7 minutes in a chemical impermeable garment, and 89.2 minutes in cotton work clothes, before test termination due to either heart rate reaching 90% of maximum, a rectal temperature of 39 °C, or skin temperature equalling or exceeding the rectal temperature value. White and her associates have completed subsequent experiments which examine physiological and subjective responses of working while wearing these garments in cold, neutral, and hot ambient environments. However, nearly all the studies mentioned were designed to assist in recommending federal standards for worker tolerance and failed to monitor change in performance capability on tasks requiring cognitive operations as an additional indicant of impaired functional capacity. Nevertheless, it is reasonable to postulate that the zones of behavioral efficiency described in the present work can also apply to these conditions, and can be helpful in setting such closely allied federal standards.

These performance limits do not replace the recommended criteria for exposure to heat (see NIOSH, 1986, Figs. 1 and 2). This is because the metabolic load of exercise is a chief consideration of the latter limits, but is not specifically incorporated into Fig. 1 of this paper. Whether performance fails at the same levels of deep body temperature change when considerable physical effort is involved is an open empirical question. However, it may be that an increase to a steady state in deep body temperature caused by exercise, becomes the new *floor* level from which the dynamic changes described here must then occur. This is suggested by the earlier observations of Lind (1963a, b). In practice, these unimpaired performance limits should be considered liberal rather than conservative interpretations of current knowledge. They should be recognized as *tolerance* limits, not the limits for *safe* functioning. The relationship between temperature, safety, and performance is not a clear one, although the work of Jokl (1982), Ramsey et al., (1982), and Ramsey and Morissey (1978) is suggestive of the greater fragility of safety over tolerance for simple work accomplishment in the heat (see also Ramsey et al., 1986). Therefore, caution should be exercised in the application of the proposed limits. To complete a picture on performance in heat more information is needed on repetitive exposure effects (NIOSH, 1986) and a theoretical base for much of our present knowledge (see also Hancock, 1987).

CONCLUSIONS

The present paper has described three zones which elaborate the limits of performance when working in elevated temperatures. These should be considered as an *augmentation* to, not a replacement for recent criteria founded upon largely physiological concerns (NIOSH, 1986). The advantages and disadvantages of the present approach are evaluated with respect to application in practical industrial conditions where individuals are required to perform in heat stress. Although no theoretical base for these limits is elaborated here, our recent work on stress (Hancock and Chignell, 1985) provides a rationale for the limits given. The long-term effects of repetitive heat exposures and their impact on health and safe work activity remain largely unresolved issues (but see Redmond et al., 1979). As advocated in the recent criteria (NIOSH, 1986), more understanding is needed concerning these issues to ensure a safe and healthy working enviroment when individuals are required to operate in hot conditions. One avenue through which to garner such knowledge is through performance assessment as advocated in this paper.

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