EVALUATION OF HEAT STRESS: AN EXPERT SYSTEM BASED MODEL

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ABSTRACT

Since the problem of evaluation of heat stress is difficult because of utilizing a variety of sometimes contradictory heat stress indices, an intelligent knowledge base system is naturally suited for solving these types of problems. Therefore, the purpose of this paper was to develop an expert system for heat stress evaluation. The present system uses an expert system shell written in VP-EXPERT. It is implemented on IBM families of microcomputers. The knowledge based system allows the user to simulate a variety of environmental conditions for maximum efficiency of working conditions. The system is easy to be used through detailed explanations using on-line assistance implemented within the system. A consultation session that illustrates the system capability is included.

INTRODUCTION

Heat-induced occupational illness, injuries, unsafe acts, and reduced performance occur in a hot environment, and in situations in which the total heat load (the sum of heat generated in the body plus the heat gained from the environment) exceeds the capacities of the body to maintain normal body functions without excessive strain [1]. Several researchers [2-7] were engaged in a series of extensive field studies of heat stress in several types of heat-exposed industries. Hyper-tension, higher plasma renin concentration, higher heart rate, higher core and skin temperatures, lower hemoglobin value, and impaired endurance were the adverse health effects associated with the exposure of industrial workers to heat stress. The adverse health effects can be controlled by the proper application of engineering and work practice controls, worker acclimatization, worker training, medical supervision, and proper use of heat-protective clothing.

Unfortunately, the evaluation of heat stress is a particularly difficult problem since a variety of heat stress indices may lead to contradictory conclusions [8-9]. In addition, there are many situations where very stressful environments are created by the demands of particular industries. For example, miners are subject to hot working conditions partly due to the increase of temperature with depth, and partly due to lack of ventilation. Textile workers are subjected to hot, humid conditions in order to maintain optimum conditions for cotton weaving. Steel, coke, aluminum, etc., workers are subject to intense radiative loads from open hearth furnaces and refractory ovens. In many industrial companies, such conditions may exceed the climatic stresses found in the most extreme naturally occurring climates.

Ramsey and Chai [10] have examined the inherent variability in heat-stress decision rules. They concluded that the use of a simplified set of decision rules can basically serve the same purpose of conducting highly accurate thermal evaluation. Freivalds [11] tried to develop an expert system for heat stress evaluation using FORTRAN language. As a matter of fact, what he developed was just a program to calculate most of heat stress indices. In addition, no advices were included in the program in a condition of heat stress predicted. Therefore, the goals of this paper were: 1) to assist in solving the user's problem of choosing the appropriate heat stress index, 2) to recognize the important factors toward the problem solution, and 3) to provide the user with the suitable heat stress preventive measures.

THERMOREGULATION

The ability to maintain heat balance within very narrow limits, around 37 °C, is one of the human characteristics and other mammals. To keep this body temperature almost constant, it is required a state of the balance of heat exchange between the worker and his environment. When heat exchange is balanced, the following equation is applied:

$$E = MET \pm R \pm C \pm K \qquad (1)$$

where E = heat lost by the body through evaporation, water vapor diffusion, and respiration process, MET = heat gained of metabolism (total metabolism minus external work performed), R = heat gained or lost by the body due to radiation, C = heat gained or lost by the body due to convection, and K = heat gained or lost by the body due to conduction through the clothing. In addition to the conduction heat, heat lost by respiration and by water vapor diffusion are negligible values relative to the values of other terms.

INDICES FOR ASSESSING HEAT STRESS

Corrected Effective Temperature (CET)

Houghten and Yaglou [12] developed the effective temperature (ET) as the first subjective index of heat stress using the parameters of dry-bulb temperature, wet-bulb temperature, and air movement.Bedford [13] proposed the use of the globe temperature instead of the dry-bulb temperature to make allowance for radiant heat; the scales then became known as the Corrected Effective Temperature Scales (CETS). Because the effective temperature scale does not take metabolic heat production into account, it may not give a true evaluation of heat stress where moderate or heavy work is being performed in a hot environment. Similar simulation techniques to those ones in Freivalds [11] had been done to develop the following relationships:

$$CETS = 40\,(f_{TG})\,(f_{TWG})\,(f_v)\ ^\circ C \qquad (2)$$

where

$$f_{TG} = -0.4983 + .051985 * (T_G) - .041304 * T^2_G + .01246 * T_G^3 \qquad (3)$$

$$f_{TWG} = \frac{1}{(T_G/10)^{2.5}(.0115 * ((T_{WB}/10)^{2.5} - 31)^2 + 27)} \qquad (4)$$

$$f_v = LOG(-.48 * (\frac{TG}{LOG(((LOGV_{AIR} - 1.301)^2 + 1) * (T_G/10)^{2.5}})^{0.5} + 4.15) \qquad (5)$$

T_G = globe temperature, °C.
T_{WB} = wet-bulb temperature, °C.

The World Health Organization [14] has recomme as unacceptable for heat-unacclimatized individ values that exceed 30 °C for sedentary activities °C for moderate work, and 26.5 °C for hard w For the fully heat-acclimatized individuals, tolerable limits are increased about 2 °C.

Predicted Four-Hour Sweat Rate

McArdle et al. [15] devised empirically the Predi Four-Hour Sweat Rate (P4SR). It is based upon amount of sweat produced in four hours and can applied to relatively wide ranges of combination dry-bulb temperatures, wet-bulb temperatures, gl temperatures, and air movement. In additi allowance can be made for the amount of cloth worn and the work effort expended. Based simulations similar to those ones used in develop CETS, the P4SR is initiated and then adjusted metabolic rate:

$$P4SR = 5\,e^{(-1000/f_{TG}} + 1.5\,LOG\,(.0000011\,e^{(T_{WB}/10)^{2.5} + .8)} - \frac{.025\,(f_{TWG} + 32)}{(TWB/10)^{2.5}} - \frac{(f_v - 1)}{(LOGV_{AIR} - 1.301)^2} + 0.25 + 0.002\,(MET/S_A - 54)\ \text{liter/4h}$$

where MET = metabolism load (kcal/hr.), S_A surface area of the body (m^2),P4SR = Predicte Four-Hour Sweat Rate. In terms of limits of physica performance, McArdle et al. [15] considered a P4S value of 4.5 liter/4h. to be the 8-hour limit abov which an increasing number of workers will fin conditions beyond their endurance. Furthermore, th rise in rectal temperature can be predicted b multiplying P4SR by 0.4. The maximum allowable ris in rectal temperature is limited to 1 °C [1].

Wet Bulb Globe Temperature Index (WBGT)

The Wet-Bulb Globe Temperature Index (WBGT) was formulated by Yaglou and Minard [16]. The WBGT combines the effect of humidity and air movement in terms of natural wet bulb temperature (T_{NWB}), radiation temperature (T_G), and air temperature (T_{DB}) as a factor in outdoor situations. If there is a radiant heat load, the T_G reflects the effects of air velocity and air temperature [1]. Leithead and Lind [17] have recommended that the WBGT Index should not be used at high levels of climatic heat stress. However, the American Conference of Governmental Industrial Hygienists proposed Threshold Limit Values (TLV's) for heat stress utilizing the WBGT Index [18],

For outdoor conditions it is calculated as:

$$WBGT = 0.2 T_G + 0.1\ T_{DB} + 0.7\ T_{NWB}\ °C \qquad (7)$$

For indoor conditions the formula is modified to:

$$WBGT = 0.3\ T_G + 0.7\ T_{NWB}\ °C \qquad (8)$$

The maximum limit for WBGT Index depends on the metabolic rate and the ratio of rest to work periods per working hour as indicated in the following relationships:

For unacclimatized workers:

$$WBGT_{max} = 36.5125 - 0.01775\ MET - 0.098\ WTIME\ °C \qquad (9)$$

For acclimatized workers:

$$WBGT_{max} = 36.9 - 0.0145\ MET - 0.07533\ WTIME\ °C \qquad (10)$$

Where WTIME = working time in minutes in each working hour.

Heat Stress Index (HSI)

The Heat Stress Index (HSI) was developed by Belding and Hatch [19]. Their index combines the environmental heat (radiation and convection, R and C) and metabolic heat (MET) into an expression of stress in terms of energy requirement for evaporation of sweat (E_{REQ}), and it is calculated from heat balance equation:

$$E_{REQ} = MET \pm R \pm C\ \text{kcal/h.} \qquad (11)$$

where

$$C = 7.0\ \alpha\ V_{AIR}^{0.6}\ (T_{DB} - T_{SK})\ \text{kcal/h.} \qquad (12)$$

$$R = 6.6\ \alpha\ (T_R - T_{SK})\ \text{kcal/h.} \qquad (13)$$

$$T_R = T_G + \alpha\ 1.8\ V_{AIR}^{0.5}\ (T_G - T_{DB})\ °C \qquad (14)$$

Maximum evaporative capacity (E_{max}) is described as:

$$E_{max} = 14.0\ \alpha\ V_{AIR}^{0.5}\ (p_{sk,s} - p_a)\ \text{kcal/h.} \ldots (15)$$

where

C = convection heat exchange, kcal/h.
α = constant value for clothing effect, 1.0 for clothed subject and 1.667 for nude subject.
V_{AIR} = air velocity, m/s.
T_{DB} = dry bulb temperature, °C.
T_{sk} = mean weighted skin temperature; °C, the ISO-Working Group on the Thermal Environment [20] recommended the use of 36 °C for T_{sk} on the assumption that most workers engaged in industrial hot jobs would have a T_{sk} very close to this temperature.
R = the rate of radiant heat exchange, kcal/h.
T_R = the mean radiant temperature, °C.
E_{max} = maximum water vapor uptake capacity, kcal/hr.
$p_{sk,s}$ = saturated water vapor pressure at 36 C, skin temperature, 45 mmHg.
p_a = partial water vapor pressure at ambient air temperature, (mmHg.).

Maximum water vapor heat capacity (E_{max}) is limited to 650 grams/hour for an unacclimatized person and 1040 grams for an acclimatized one. At the same time, for a full work shift (8-hour) the total sweat output should not exceed 3250 grams for an unacclimatized person and 5200 grams for an acclimatized one [1]. Each Kilogram of sweat evaporated from the skin surface represents a loss of approximately 580 kcal depending on mean skin temperature and subject acclimatization [1,3].

The ratio: $$\mathrm{HSI} = (100 \times E_{REQ}) / E_{max} \qquad (16)$$

indicates the level of heat stress, with a value of 100 being considered the maximum value that can be tolerated for working hours a day. Allowable exposure time (AET), in hours, can be calculated from the rate at which the body stores the excess heat gain.

$$\mathrm{AET} = W_e\, H_c\, \Delta T \,/\, (E_{REQ} - E_{max}) \text{ hour} \qquad (17)$$

where W_e = weight of the person (kg.), H_c = heat capacity of human body 0.827 kcal/kg. °C, and ΔT = increase in core temperature in °C.

SYSTEM DEVELOPMENT AND VALIDATION

The heat stress knowledge domain, being based on a variety of equations, utilizes VP-EXPERT shell from Paperback Software International [21]. The knowledge base contains all advices that shell expert system can display on a given material, as well as the information that it needs to construct equations and decide what advice to display. The data base sections are divided to control, explanation, and advice logic rules. The purpose of control logic rules is to control where the consultation is and where will it go next. In addition, it assigns the values of user answers to the data base variables. The examples of such rules are: IF RELATIVE_HUMIDITY > 75% OR V_AIR>2.5 THEN CET< >UNKNOWN; IF METABOLIC_RATE>3 THEN CET< > UNKNOWN; and IF CLOTHING_CLO> =2 THEN WBGT< >UNKNOWN. The explanation logic rules are designed to display messages at any time the users press How or Why keys, or type HELP when they are confused to understand the given question. The following example is a sample of the explanation rules: IF ENVIRONMENT_ CONDITION = HELP THEN DISPLAY "This question has been asked to determine the solar radiation load on the worker. Therefore, please enter either indoor or outdoor conditions." The advice rules express the conclusion that has been reached through the consultation execution such as: IF HEAT_STRESS = YES AND DRY_BULB_TEMP>36 AND V_AIR> =1.5 THEN DISPLAY "Both dry bulb temperature and air velocity should be decreased"; IF HEAT_STRESS = YES AND DRY_BULB_TEMP>36 AND V_AIR<1.5 AND CLOTHING_CLO>1.0 THEN DISPLAY bulb temperature should be decreased, and laye clothing should be taken off"; and IF HEAT_STR = YES AND GLOBE_TEMP>36 THEN DISP "Place shielding or barriers around the heat sour

The hierarchical structure of the expert system been fully developed. It consists of main progra subprograms, and 6 subroutines written and com in BASICA. It has 397 rules, 49 parameters, an conditional paragraphs of advice. The main sourc information for the development of the knowledg were taken from NIOSH [1], Freivalds [11], Bed [13], McArdle et al [15], Yaglou and Minard ACGIH [18], Belding and Hatch [19], Goldman Grandjean [23], McCullough et al [24], Avellini [25], Henschel [26], and Ramadan [27].

The following variables were used in the develop of various data bases: 1) type, age, condition, we and height of the worker (estimated values are off in the system using regression models [28], 2) typ clothing that is worn, 3) whether indoor or out conditions, 4) energy expenditure rate of worker, 5 speed, 6) dry bulb temperature, 7) natural and for wet bulb temperatures, 8) globe temperature, working shift in hours, and 10) work/rest sched The given information was extracted and translated rules and qualifying conditions which are utilized consultation shell to generate advice. Once information needed to evaluate the environme conditions are obtained the system determines wh index is the most appropriate to be implemented to particular environmental conditions. Then, it calcula 1) all heat-stress indices, 2) increase in core b temperature, 3) amount of sweat released, and decrement in physical work output in a form working time limit; if there is any. The syst prompts the user for response with suggested in format. The system checks the user input consistency in units and whether the inputs are wit rational limits. In addition, all rules were set based metric system. The system provides a br explanation, any time the user be confused abo particular prompt. The period of knowledge acquisiti lasted about 7 months; development of data bas required 5 months. Subsequently, the system w validated through numerous consultations with t experts in the field.

CONSULTATION SESSION

An unacclimatized, 95 percentile female worker (40 years of age) who performs skimming dross from molten bars of aluminum. The worker stands at the task. Manipulation of a ladle involves moderate use of shoulder and arm muscles. Short-sleeved shirt and trousers were worn. The environmental conditions were reported as:

dry bulb temperature = 47.8 °C, forced wet bulb temperature = 30.5 °C,
globe temperature = 71.7 °C, natural wet bulb temperature = 32.9 °C.

Air was forced from an overhead duct at 275 meter per minute. Would this particular set of conditions result in a heat stress ? and if so, what should other control measures be taken to prevent heat injuries ? Exhibits 1 & 2 show the information presented as inputs and outputs that appear to the user during a consultation session with the developed expert system.

CONCLUSION

The basic knowledge base for heat stress evaluation has been developed. The present system can be included as one of the lower level models within a general ergonomics expert system. The prediction of heat stress measures using such models is one of the safest and most practical approaches used by task designers and medical professionals. It should be noted that the use of expert system in heat stress evaluation has its advantages and its limitations. The advantages include the model's ability to obtain quantitative data on the effect of heat stress parameters on the human body responses without having the worker to be in hazardous conditions. The major drawback is that results obtained from these types of models are dependent on the assumptions made in developing the model and in how realistic do these assumptions duplicate the complex structure of the environmental conditions and function of human systems imposed to these conditions. Therefore, in the interpretation of the results one should be quite familiar with the assumptions and limitations of the models used. The system outputs however still can provide very useful approximation of heat stress values that otherwise would not be available. These values can be used in conjunction with the guidelines of job analysis and design. The recent widespread use of microcomputers permits an analyst to more freely use such models to study the cost associated with using different types of heat stress protective measures to select the available cheapest-effective method. Finally, with the wide availability of the microcomputer the author suggest that the use of the proposed system can have an impact on operator's performance and on the prevention of costly workplace injury.

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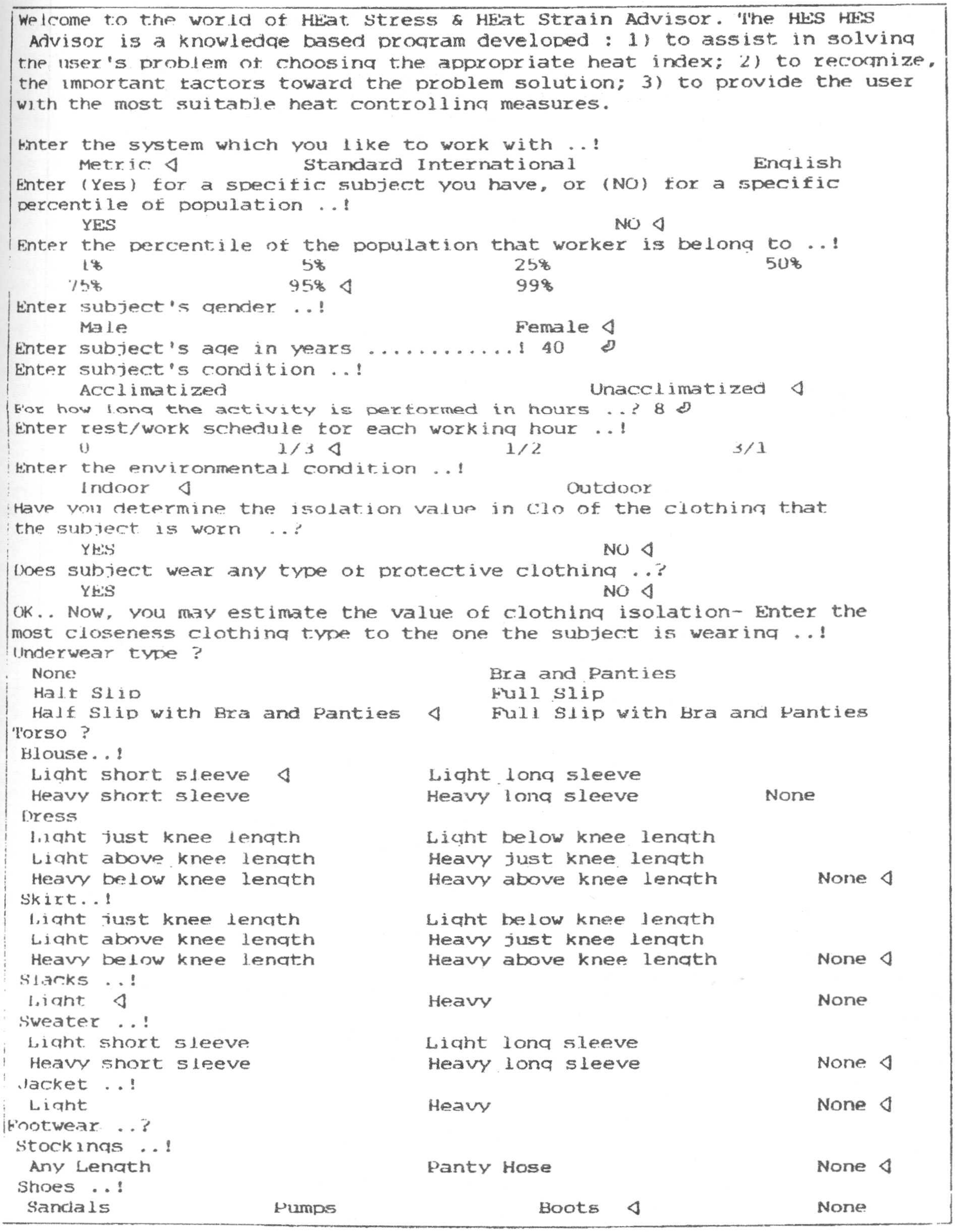

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Welcome to the world of HEat Stress & HEat Strain Advisor. The HES HES
 Advisor is a knowledge based program developed : 1) to assist in solving
the user's problem of choosing the appropriate heat index; 2) to recognize,
the important factors toward the problem solution; 3) to provide the user
with the most suitable heat controlling measures.

Enter the system which you like to work with ..!
    Metric ◁              Standard International                English
Enter (Yes) for a specific subject you have, or (NO) for a specific
percentile of population ..!
    YES                                         NO ◁
Enter the percentile of the population that worker is belong to ..!
    1%                 5%              25%                50%
   75%                95% ◁            99%
Enter subject's gender ..!
    Male                                 Female ◁
Enter subject's age in years ...........! 40  ↵
Enter subject's condition ..!
    Acclimatized                               Unacclimatized  ◁
For how long the activity is performed in hours ..? 8 ↵
Enter rest/work schedule for each working hour ..!
    0                 1/3 ◁              1/2                 3/1
Enter the environmental condition ..!
    Indoor  ◁                                Outdoor
Have you determine the isolation value in Clo of the clothing that
the subject is worn  ..?
    YES                                        NO ◁
Does subject wear any type of protective clothing ..?
    YES                                        NO ◁
OK.. Now, you may estimate the value of clothing isolation- Enter the
most closeness clothing type to the one the subject is wearing ..!
Underwear type ?
  None                                  Bra and Panties
  Half Slip                             Full Slip
  Half Slip with Bra and Panties   ◁    Full Slip with Bra and Panties
Torso ?
 Blouse..!
  Light short sleeve  ◁            Light long sleeve
  Heavy short sleeve               Heavy long sleeve           None
 Dress
  Light just knee length           Light below knee length
  Light above knee length          Heavy just knee length
  Heavy below knee length          Heavy above knee length         None ◁
 Skirt..!
  Light just knee length           Light below knee length
  Light above knee length          Heavy just knee length
  Heavy below knee length          Heavy above knee length         None ◁
 Slacks ..!
  Light  ◁                         Heavy                           None
 Sweater ..!
  Light short sleeve               Light long sleeve
  Heavy short sleeve               Heavy long sleeve               None ◁
 Jacket ..!
  Light                            Heavy                           None ◁
Footwear ..?
 Stockings ..!
  Any Length                       Panty Hose                      None ◁
 Shoes ..!
  Sandals             Pumps               Boots  ◁                 None
```

Exhibit 1. show print out of the model input data

```
Have you measured the energy metabolism for the activity the subject
performed ?
   Yes                                  No ◁
Ok... Now, you may estimate the metabolism value by choosing the most
appropriate activity close to the performed one.  This operation will
be executed through two steps. First, choose the worker body position
and movement during work most of the time.   Second,  enter from  the
given list  the most relevant number  close to the type of work  that
subject performed ..!
Body-position ..?
     Sitting                            Standing  ◁
     Walking                            Walking uphill

Work type ..?- It is allowed to enter three relevant values, one at a time,
               for an accurate description of the activity. In a case of
               one entry data, enter zeros for the rest choices ..!

      1. light, hand work.
      2. moderate, hand work.
      3. heavy, hand work.
      4. very heavy, hand work.
      5. light, one arm work.
      6. moderate, one arm work.
      7. heavy, one arm work.
      8. very heavy, one arm work.
      9. light, both arm work.
     10. moderate, both arm work.
     11. heavy, both arm work.
     12. very heavy, both arm work.
     13. very light, whole body work.
     14. light, whole body work.
     15. moderate, whole body work.
     16. heavy, whole body work.
     17. very heavy, whole body work.
You may enter now...! HELP     ↵

This question has been asked to determine average values of metabolic rate
during different activities.  Such examples are given below :
(1) light work (up to 200 kcal/h. or 800 Btu/h.): e.g., sitting or standing
    to control machines, performing light hand or arm work,
(2) moderate work (200-350 kcal/h. or 800-1400 Btu/h.): e.g., walking about
    with moderate lifting and pushing, or
(3) heavy work (359-500 kcal/h. or 1400-2000 Btu/h.): e.g., picking and
    shovel work.
In addition, there are some other activity examples are given below:
* Light hand work: writing, hand knitting
* Heavy hand work: typewriting
* Heavy work with one arm: hammering in nails (shoemaker, upholsterer)
* Light work with two arms: filing metal, planing wood, raking of a garden
* Moderate work with the body: cleaning a floor, beating a carpet
* Heavy work with the body: railroad track laying digging, barking trees.
You may enter now...!   9  ↵
You may enter now...!  13  ↵
You may enter now...!   0  ↵
Enter air velocity in meter per second .....! 4.58  ↵
Enter globe temperature in °C ...............! 71.7  ↵
Enter dry bulb temperature in °C ............! 47.8  ↵
Enter natural wet bulb temperature in °C ...! 32.9  ↵
Enter forced wet bulb temperature in °C ....! 30.5  ↵
```

Cont.' Exhibit 1. show print out of the model input data

```
 >>>>>>>>>>>>>>>>>  HEAT STRESS EVALUATION FOR GIVEN DATA   <<<<<<<<<<<<<<<<
Dry Bulb Temperature                 =  47.8   °C
Forced Wet Bulb Temperature          =  30.5   °C
Natural Wet Bulb Temperature         =  32.9   °C
Globe Temperature                    =  71.7   °C
Mean Radiant Temperature             = 166.8   °C                (Calculated)
Air Speed                            = 4.58     meter/second
P.W.V. Pressure @ A. Air Temp.       = 25       mm.Hg.           (Calculated)
Subject Gender                       = Female
Subject Age                          = 40 years
Subject Height                       = 1.71 meter.               (Estimated)
Subject Weight                       = 90.0 kg.                  (Estimated)
Surface body area                    = 2.0893  square meter      (Estimated)
Body fat as % of body weight         = 28.1 %                    (Estimated)
Subject Condition                    = Unacclimatized
Working Period                       = 8 hours
Ratio of Rest/Work in Min./Min.= 15/45
Environmental Condition              = Indoor
Clothing Isolation                   = 1.326 Clo                 (Estimated)
Metabolism Rate                      = 5.5 kcal/min.             (Estimated)
 >>>>>>>>>>>>>>>>>>>>  CALCULATED HEAT STRESS INDICES    <<<<<<<<<<<<<<<<<<
Corrected Effective Temperature Scale (CETS) = 36.1     °C
Predicted Four-Hour Sweat Rate (P4SR)        =  4.8     liters
Wet Bulb Globe Temperature Index (WBGT)      = 44.54    °C

  Convection heat exchange (C)               = 205.9    kcal/h.
  Radiant heat exchange (R)                  = 863.3    kcal/h.
  Metabolism heat gained (MET)               = 330      kcal/h.
  Evaporation of sweat required (E_REQ)      = 1399.2   kcal/h.
                                              = 2391.9   grams/h.
  Maximum water vapor uptake capacity (E_max.) = 593    kcal/h.
                                              = 1013.7   grams/h.
Heat Stress Index (HSI)                      = 236      %
Rectal Temperature over resting condition    = 1.92     °C
Allowable Exposure Time (AET)                = 5.8      minutes
 >>>>>>>>>>>>>>>>>>>   MAXIMUM ACCEPTABLE CONDITIONS    <<<<<<<<<<<<<<<<<<<
CETS = 28.0  °C                      P4SR                 = 4.5 liters
WBGT = 27.5  °C                      Rectal Temperature = 38 °C
E    = 405 grams/h.                  HSI                  = 100 %

 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>   CONCLUSION   <<<<<<<<<<<<<<<<<<<<<<<<<<<<<

Since radiation heat is very high and metabolic rate is also high,
heat stress index (HSI) is most appropriate index for this evaluation.
Thermal balance can not be maintained.  Therefore, re-design of the worker
characteristics, worker requirements, and environmental conditions are
mandatory.  There are many options that can be used for this purpose:
1. replace old female worker with young male (prefered 20-30 years).
2. replace obese worker with lean worker (to reduce % of body fat).
3. replace unacclimatized worker with acclimatized one.
4. have a trained worker (prefered one with high physical fitness).
5. permit freedom to interrupt work when a worker feels extreme heat stress
6. increase water intake of worker on the job.
7. add extra personnel to shorten duration of heat exposure of the crew.
8. provide air-conditioned space nearby work for rest and recovery.
9. provide the worker with a refrigerated suit.
10. mechanize the physical components of the job.
11. place shielding or barriers around the heat source.
12. reduce air speed to reduce convection heat gained by the worker.
```

Exhibit 2. show print out of the model output