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SURVEY OF ENVIRONMENTAL PARAMETER SENSORS FOR A PERSONAL HEAT STRESS MONITOR

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ABSTRACT

This report summarizes the results of a directed survey and review of environmental parameter sensors for use in a personal heat stress monitor unit. A discussion of sensing techniques is given with descriptive details on the sensor's physical characteristics, theoretical basis of sensor operation, and suitability for use in a personal monitor unit. The parameters of interest in this survey are air velocity, dry bulb temperature, wet bulb temperature, natural wet bulb temperature and 6-inch globe temperature or mean radiant temperature.

The sensors and measurement techniques found to be useable or adaptable through modification for use in a heat stress monitor are identified and a preliminary design is given which will permit the construction and testing of a complete system. With reference to the 6-inch globe temperature, two options are given with each requiring additional development effort for implementation.

The objective of this survey did not include data recording methods or data processing. However, a short discussion is included discussing current techniques which are applicable to the system requirements.

I. INTRODUCTION

An important jobhealth aspect of certain hot working environments is the heat stress exposure imposed upon the worker. Extensive investigations have been conducted to establish the influencing parameters governing heat stress conditions in hot environments and to correlate these factors with the various physiological response effects, i. e. the heat strain, observed in human subjects. These studies have yielded quantitative measures of environmental heat stress and relevant exposure limits for work in hot working environments. However, the generally controlled environments in which most of these studies have been conducted are not fully representative of the wide spectrum of actual jobs and working conditions in which heat stress problems may be of concern. That is, there are many hot environment jobs that entail a diversity of work tasks under various heat stress exposure conditions for varying time durations which need to be assessed firsthand in order to specify their particular heat stress exposure risks. This need for practical measurements of on-the-job heat stress profiles has been recognized by the National Institute for Occupational Safety and Health and is the motivation in developing a personal heat stress exposure monitor unit to be worn by the worker.

The physical size and performance guidelines specified for some of the monitor parameter measurements (Sec. II. B) are not optimally satisfied by existing sensor configurations. For these parameters a significant design and development is needed to approach and meet the system goals. The approach taken in this study was to first document the various sensors and environmental measurement methods that have been used in previous heat stress studies and experiments as may be found in the scientific literature and in commercial data. Information sources which were utilized to locate the desired literature were computer searches by: (1) the Smithsonian Science Information Exchange (SSIE), (2) the Defense Documentation Center (DDC), (3) the NASA data bank, (4) the EPA air pollution information center (APTIC), and (5) a compilation of the engineering index (COMPENDEX). In response to these requests a considerable number of abstracts dealing with relevant papers was received. From the information sources uncovered in this search of sensor technology, copies of all reference items judged to be applicable to the requirements of environmental heat stress monitoring were acquired for review and further utilization.

To find potential commercial suppliers for the desired sensors, a list of the names and addresses of industrial sources was compiled. Using various industrial indexes, 404 companies were identified whose product lines include one or more items which were of possible value to the survey. Letters were sent to each of these suppliers requesting product information. The response to this request was approximately 50% of the letters sent.

This baseline of sensor technology information then served as the point of departure for evaluating the suitability and adaptability of available basic sensors and associated physical implementations for use in a personal heat stress monitor. This information also identified the sensor requirements specified which have not previously been achieved because of prior state-of-the-art technology limits or other reasons and thereby helped delineate the specific problems connected with development of a suitable personal heat stress monitor. Conceptual, theoretical and experimental approaches were formulated as possible new approaches for satisfying the desired heat stress sensor specifications. Finally, on the basis of unified and comprehensive concepts of a practical personal heat stress exposure monitor, technical recommendations and detailed supportive design information for an optimized personal instrument system have been compiled and reported.

II. TECHNICAL DISCUSSION

A. Background Information Relevant to Human Heat Stress

The instrumentation for measuring the environmental parameters associated with human heat stress are relatively well established. The technical aspects of this base of information prescribe the bounds within which any new or modified environmental measurement technique must operate to yield useful data consistent with established methods of analysis and interpretation. The paragraphs below present a synopsis of the current basis for environmental measurements and will serve as a general guide for any new advances in heat stress instrumentation technology.

1. Heat Stress Environmental Parameters

The physical parameters which define the heat stress conditions of a hot working environment are:

(a) Dry bulb temperature: Temperature of air as measured by a temperature sensor vented to air circulation but shielded from any sources of radiant heat;

(b) Wet bulb temperature: Temperature of a wetted water-absorbent wick shielded from any sources of radiant heat and aspirated to maximum evaporative cooling by the forced motion of ambient air (more precisely defined as the psychrometric wet bulb temperature);

(c) Natural wet bulb temperature: Temperature of a wetted water-absorbent wick exposed to natural air circulation motions and unshielded from surrounding sources of radiant heat;

(d) Globe temperature: The equilibrium temperature attained by a flat-black-colored, thin-wall copper sphere six inches in diameter as measured by a temperature sensor located at the center of the sphere; and

(e) Air velocity: The effective speed of air circulation motion at the worker's location within a hot working environment.

The dry bulb temperature and the wet bulb (psychrometric) temperature as defined above are conventional environment parameters normally measured in a variety of experimental tests and processes. Several temperature sensor devices including both manual and electrical output types are available for use in monitoring these parameters. Natural wet bulb temperature is a somewhat more specialized environmental parameter more directly associated with environmental heat stress measurements. However, this parameter can be measured as readily as the psychrometric wet bulb temperature by modifying the psychrometric sensor assembly so that the wetted wick is exposed to surrounding radiant heat sources and only receives aspiration by the natural ambient air circulation.

The globe temperature and air velocity parameters as defined above are also specialized environmental factors more directly associated with environmental heat stress measurements. The globe temperature is a composite thermal parameter dependent upon the transfer of radiant heat energy between the copper sphere and the surrounding surface and the convective heat exchange between the sphere and the surrounding air. Thermal radiation is in the form of electromagnetic energy and is transferred between any two surfaces at a rate dependent upon the temperatures and emissivities of the surfaces and independent of the temperature of the intervening air medium. The blackened outer surface of the spherical copper globe exhibits an emissivity approximately equal to unity which allows it to efficiently exchange radiant heat energy between it and its surroundings. If the surfaces which surround the globe are warmer than the air, the steady state temperature inside the globe will be above air temperature, and, conversely, with walls and other surroundings cooler than the air, the globe temperature will be below air temperature. Convective heat exchange between the sphere and the ambient air is dependent upon the air speed and air temperature at the sphere surface. The net effect, once thermal equilibrium is reached between the copper globe and its surroundings (and internal air), produces an internal temperature designated as the globe temperature which is a measure of the portion of the environmental thermal radiation energy contributing to human heat stress. The spherical shape of the globe gives essentially a 4π steradian field of view of the surroundings allowing it to integrate the effects of a wide variation in temperature of these surroundings.

The response time of globe sensors in the 2 to 6 inch (5 to 15 cm) diameter range is 5 to 20 minutes, making them suitable only for long-term average measurements. Therefore, the conventional globe temperature sensor will not provide useful indications of short-term variations and peaks in heat radiation conditions. For faster response, the globe diameter and wall thickness may be reduced. A change in diameter will, however, alter the steady state temperature of the globe as compared to a 6-inch globe under similar environmental conditions. The possibility also exists of replacing the globe sensor with one which senses electromagnetic heat radiation energy directly and is not affected by convective and reradiation cooling as is the globe. Materials exhibiting either direct quantum-electric response or other thermally induced electrical response to long-wave thermal radiation are the most potentially applicable sensors for this requirement.

The measurement of air velocity in the context of human heat stress monitoring in hot working environments is more properly characterized as the measurement of air speed about the worker which contributes to evaporative and convective heat exchange between the worker and the air. The direction of air motion is unimportant in this measurement; however, the air flow sensor should be responsive to air movements in essentially any direction and must be placed in a position representative of the worker location. Thus, it is noted that conventional meteorological anemometers (e. g. of the cup or propeller type) which have relatively high starting air flow thresholds and responds primarily to relatively steady air speeds in one plane are not applicable to biological heat stress measurements. Heated thermistor or hot-film anemometers provide a much more useful and effective air flow response for heat stress monitoring purposes since they can be made essentially omnidirectional and have rapid response times capable of detecting the turbulent fluctuations in air speed common to force-ventilated hot working environments.

2. Quantitative Monitoring and Interpretation of Environmental Heat Stress

An environmental heat stress index based upon the natural wet bulb temperature, the globe temperature, and the dry bulb temperature has been developed. The assessment of hot working environment heat stress conditions has been tentatively standardized to provide uniform evaluation procedures and methodology for all jobs involving such environmental conditions. This environmental heat stress index is defined separately for indoor and outdoor working conditions where the difference in these two conditions is the heat load imposed by solar radiation. The basic index, designated as WBGT, is a composite effective natural wet bulb/globe temperature expressed for the two environments as:

Indoor Environments

$$(WBGT)_{in} = 0.7\, T_{NWB} + 0.3\, T_{GT} \quad (1)$$

Outdoor Environments

$$(WBGT)_{out} = 0.7\, T_{NWB} + 0.2\, T_{GT} + 0.1\, T_{DB} \quad (2)$$

where:

T_{NWB} = Natural wet bulb temperature;

T_{GT} = Globe temperature; and

T_{DB} = Dry bulb temperature.

Threshold values of WBGT have been established from physiological studies of hot working environments which govern the acceptable thermal exposure limits that can be safely endured by health workers. The Standards Advisory Committee on Heat Stress has published the details concerning the proposed standard guidelines for determining a worker's thermal exposure[1]. Their report recommends the WBGT index as the parameter to be used for evaluating the environmental conditions affecting human heat stress.

B. Personal Heat Stress Monitor Requirements

The environmental parameters to be measured by the personal heat stress monitor device are: (1) dry bulb temperature; (2) psychrometric wet bulb temperature; (3) natural wet bulb temperature; (4) ambient air velocity and (5) thermal radiation. The design goals for these parameters are listed in Table I .

The design goals for the physical configuration of the heat stress and general requirements were:

(1) The five environmental sensor devices are to be mounted on the worker;

(2) The total weight of the five sensors and associated components mounted on the worker should not exceed 0. 75 pound (est.);

(3) The sensors must be located on the worker such that shielding effects of the worker's body on the measured parameters will be minimized ;

(4) The air velocity sensor will have as nearly as omnidirectional (4π steradians) field of view about the worker as possible;

(5) The thermal radiation sensor will have as nearly as omnidirectional (4π steradians) field of view about the worker as possible;

(6) None of the sensors shall be affected by heat or moisture from the worker's body;

TABLE 1. HEAT STRESS MONITOR PARAMETERS TO BE MEASURED AND DESIGN GOALS

Parameter	Range	Accuracy	Response Time*
Globe Temperature	70° F to 250° F	±1° F	0.5 min
Mean Radiant Temp. **	70° F to 250° F	±1° F	0.5 min
Dry Bulb Temperature	70° F to 150° F	±0.5° F	0.5 min
Wet Bulb Temperature	50° F to 100° F	±0.5° F	0.5 min
Natural Wet Bulb Temp.	50° F to 100° F	±0.5° F	0.5 min
Air Velocity	10 to 2000 ft/min	±2.5%	2.0 sec

*Time to achieve 95% of any total change within specified range.

**An alternate to the globe temperature is the mean radiant temperature (MRT). The MRT is defined as the uniform wall temperature of an enclosure (walls, ceiling, and floor) with a surface emissivity of 1.0 which will provide the same thermal effect on an object within the enclosure as the actual wall temperature.

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(7) The sensor configuration mounted on the worker must not interfere with the worker's normal work tasks; and

(8) All of the sensor output signals shall be suitable for signal conditioning and storage by a single miniaturized unit.

These general requirements for the personal heat stress monitor unit established the physical configuration and implementation guidelines for the survey and evaluation of appropriate sensor technology. As such, they represent the desirable design goals used for the monitor unit.

C. Instrumentation for Monitoring Human Heat Stress

There are numerous techniques, sensors, and systems for measuring the environmental parameters which cause heat stress on humans. Some heat stress parameters can be measured by any of several alternative sensors conventionally used in many environmental tests and monitoring applications. The sensor (thermistor) used for the dry bulb, wet bulb, and natural wet bulb measurements falls into this category.

Other environmental heat stress parameters such as the 6-inch globe temperature, requires a more sophisticated measurement method to be compatible with the time response requirements and physical considerations needed in the personal heat stress monitor. For all of the parameters of interest, specific sensor types must have the designated performance characteristics in order to obtain results consistent with previous methods of heat stress observations and interpretations.

The current proposed standard for heat stress in hot working environments defines the environmental parameters of concern and gives general guidance on sensors and instrumentation suitable for their measurement. The following paragraphs discuss these recommended sensors, which are based upon performing the measurement from stationary installations and locations in the working environment under test. Also, discussions are presented regarding alternate sensors and measurement methods which show merit as being applicable to the portable requirements of a personal heat stress monitor unit to be worn by the worker. Although some of the sensors discussed do not meet the requirements as defined or are unusable in the portable heat stress system, they are nevertheless included for completeness. Basic theoretical considerations are included in the discussion where such factors enhance the understanding of the sensor with reference to performance characteristics and design considerations.

1. General Considerations for Temperature Sensors

a. Desired Characteristics

The selection of the best suitable temperature sensors for the personal heat stress monitor should be based upon the consideration of several parameters or characteristics. Although some methods may be eliminated from consideration because of their lack of suitability or for their inability to meet certain basic requirements, in most cases a trade-off exists between several characteristics. The desired characteristics and some considerations for temperature sensors are discussed in the following paragraphs:

(1) Accuracy - The first consideration for the measurement of temperature is the accuracy of the measuring sensor and its associated circuitry. The desired accuracy (Ref. Sec. II. B) for the globe temperature is $\pm 1°$ F. The accuracy required for the dry bulb temperature, the wet bulb temperature and the natural wet bulb temperature is $\pm 0.5°$ F. The sensor used and its associated circuitry must be capable of being calibrated to within this tolerance over the entire temperature range. The resolution and conformity of the temperature measuring device must be such that the required accuracy is obtainable.

Accuracy of the temperature measurement for the wet bulb thermometers is also dependent upon the proper wetting and aspiration of the wick which covers the sensing element. A water reservoir and a forced air aspirator is required so that maximum evaporative cooling is obtained. The wick must be kept clean so that impurities do not retard evaporation, and oil or grease do not retard wicking.

The accuracy of the dry and wet bulb thermometers is dependent upon the proper shielding of the sensors from thermal radiation. The shielding must be applied in such a way that the free circulation of air over the sensor is not restricted. Also, the shielding must be designed so that absorption of incident radiation does not cause the internal temperature of the shield to rise and indirectly irradiate the sensor. Again the forced air aspirator would help assure accuracy. The shielding could be a thermal insulator, and the temperature of the forced air could be measured accurately.

(2) Repeatability - The sensor chosen must be stable under conditions of mechanical vibration and shock conditions, extraneous electrical or magnetic fields and component aging. No hysteresis effects should be noticeable. The reading obtained should be the same when the temperature is reached from higher or lower values.

It is also desirable that long term aging effects of the sensor and associated circuitry do not affect the accuracy or calibration of the measuring system. The associated signal conditioning electronic circuitry should be inherently stable and free from drift.

(3) Power Consumption - Since the personal heat stress monitor is intended to be carried or fastened to a human subject, a portable power supply is necessary. For a given operating time, the smaller the power consumption can be made, the smaller the portable battery pack can be made. Since other components in the system are expected to consume at least three watts, the temperature sensing circuitry may consume up to 0.3 watts without significantly affecting the overall power consumption.

(4) Ruggedness - The heat stress monitor will probably be subjected to a wide range of environmental stresses including mechanical shock, vibration, and manipulation, as well as exposure to heat, humidity, and chemical environments. The sensors chosen must withstand these stresses for many cycles of eight hours or more.

(5) Commonality - Since all of the temperature measuring elements must operate over similar ranges and accuracies, commonality between the sensing elements would be a distinct advantage in terms of spare parts, maintainability, and circuit design requirements.

(6) Range - The heat stress monitor is expected to be used over a specific range of ambient temperatures under a wide range of humidity and radiation conditions. These conditions require that the wet bulb and natural wet bulb temperatures' range be 50° F to 100° F, the dry bulb temperature range be 70° F to 150° F, and the globe or radiant temperature range be 70° F to 250° F.

(7) Response Time - It is desired that the time required to achieve 95% of any total change be 30 seconds or less. This requires a thermal time constant (63%) of 10 seconds or less. The sensor's mass, thermal conductivity, and surface exposed should be such that thermal equilibrium is reached in a short period of time. Since the thermal time constant is shorter for an aspirated system, the forced air aspirator would shorten the response time of the wet and dry bulb thermometers. The natural wet bulb is restricted to natural air circulation, so proper design would necessitate the selection of the smallest wick which would remain saturated under very dry or extremely hot conditions.

(8) Physical Size and Weight - Since the personal heat stress monitor is to be attached to a worker, it is desirable that its size and weight be kept at a minimum. Since the actual temperature sensing element is usually small, this requirement in general applies to the associated electronic circuitry, and more specifically to its power supply.

(9) Signal Conditioning Requirements - For power consumption, accuracy, size, and simplicity considerations it is desirable that the sensor signal require very little signal conditioning and amplification. The output of many temperature sensing elements do not vary linearly with temperature, so electronic compensating networks, special correction factors or digital processing must be used to determine the actual temperature. Some temperature sensors have a very small output, and require a reference element, so circuit complexity is increased and much amplification is needed to produce a useable signal. The ideal sensor in this respect would have a linear output with a large variation in output per degree of temperature change.

(10) Cost - For most of the commercially available sensors applicable to the system requirements, the parts cost will be small in relation to other design and fabrication costs. To attempt a savings by selection on the basis of cost alone would probably result in larger overall expense because of the need for more complex signal conditioning electronics.

b. Temperature Measurement Techniques and Methods

Various temperature measurement techniques will be discussed and evaluated for use with the personal heat stress monitor . Some advantages and disadvantages of each method will be discussed.

(1) Liquid in Glass

For occasional manual temperature observations at fixed locations in the environment where some time delay can be tolerated, a liquid in glass thermometer is adequate. Accuracy and repeatability for a high quality mercury in glass thermometer is usually within $\pm 0.5°$ F over the entire temperature range of the heat stress monitor. Due to the necessary glass construction, this thermometer is easily broken, and suitable protection must be afforded for rugged portable operation. Of course, there is no power consumption with these self-contained units. The time constant for liquid in glass thermometers is relatively long. Mercury units are usually slower than dyed alcohol units, and time constants in the range of 30 to 120 seconds are typical. These time constants would give 95% response times in excess of one minute. The sizes range typically from 0.1 inch to 0.3 inch in diameter, and 6.0 to over 12.0 inches long. The cost of these units is low.

For continuous monitoring and recording, a sensor with electrical readout is required. Therefore the common mercury or dyed alcohol glass thermometers are unsuitable for use in the personal heat stress monitor.

(2) Thermoelectric Devices[2]

A small dc voltage is produced when two junctions formed by dissimilar conductors are maintained at different temperatures. These junctions, called thermocouples, are manufactured with several combinations of metals for different applications and are often used for temperature measurement.

In practical thermometry, one junction is placed at the desired measurement point while the other is maintained at a fixed known temperature. This type of a reference junction would be difficult to implement for the personal heat stress monitor.

Accuracy of temperature measurements by thermocouples is dependent upon the accuracy of the electronic instrumentation, the manufacture of thermocouple wire, the stability of the reference junction temperature (or voltage equivalent), and upon the application of the sensor. All thermocouple junctions exhibit a small degree of nonlinearity which becomes more evident as the temperature range is extended.[3] A thermocouple made of copper and constantan exhibits a nonlinearity of $\pm 1°$ F from the best straight line approximation over the temperature range of 50° F to 150° F. This amount of nonlinearity would have to be partially offset by a compensation network. Accuracy in the range of 0.2 to 0.5° F can be obtained with care in installation and instrumentation.

A thermocouple may be made of very fine wire, so that the measuring junction has a short thermal time constant. The time response requirement for the personal heat stress monitor could be met with the proper selection of thermocouple wire. The range of most thermocouples is compatible with the requirements for the personal heat stress monitor.

The output voltage of most thermocouple pairs is in the range of only 20 microvolts/° F. A very sensitive and stable amplifier with a large amount of voltage amplification would be necessary. Although the cost of the thermocouples would be minimal, the cost of the associated electronics might be considerable for portable application such as the personal heat stress monitor.

(3) Thermoresistive Sensors

Several sensors are available whose resistance is a function of temperature. These devices may have either a positive or negative temperature coefficient which may be essentially linear or highly nonlinear. Some of these devices are discussed below.

(a) Resistance Temperature Detectors

Resistance thermometers use the change in electrical resistance of a conductor to determine the temperature. Nickel, copper, and platinum have fairly high positive temperature coefficients. Suitable sensors are made of these and other metals. Copper and nickel sensors are considerably cheaper than platinum; however, the temperature coefficient of nickel is appreciably nonlinear. The coefficient for copper is linear but copper has such a low resistance that very accurate resistance measurements are required to obtain good temperature resolution.

The platinum sensors are extremely stable and exhibit a well-behaved positive temperature coefficient to over 1000° F. As is also true in the case of other thermoresistive sensors, accuracy of measurement is greatly dependent upon the precision of the resistance measurement. With precision resistance bridge measurements, accuracies to better than 0.05° F can be obtained using platinum resistance elements. Platinum wire sensors have excellent long term stability and repeatability and are often used as temperature standards against which other types of temperature sensors are calibrated.

For a small platinum wire with the required time response in a properly designed bridge circuit, the output is about 250 microvolts/° F. Although this is much higher than thermoelectric types, a considerable amount of stable amplification is required. The power requirement for the sensor bridge and the amplifier may approach 50 milliwatts per assembly, an amount which can almost be ignored compared to the other power requirements of the personal heat stress monitor.

The physical construction of the platinum sensor could be made to be fairly rugged, and one type of sensor could be used for measuring all of the required temperatures. The temperature range of platinum wire sensors is much in excess of the requirement for a heat stress monitor.

With proper thermal design, a platinum resistance temperature detector might exhibit a response time only slightly in excess of the 30-second requirement. However, since there is a practical limit to the minimum size that platinum wire can be made, and since a high resistance is desirable, many turns of wire are necessary. This requires a sensor size which usually does not have a fast thermal response time. Of the types surveyed for which data was available, only one had a time constant which met the requirements.

The cost for the platinum temperature detectors is comparable to the cost of the required electronics, and should not be of much consideration when compared to the overall system cost.

(b) Thermistors

Thermistors are semiconductors of ceramic material made by sintering various mixtures of metallic oxides.[3] They exhibit a high, non-linear negative temperature coefficient of resistance. The resistance-temperature characteristic follows an inverse exponential curve. By proper design of bridge circuits and by using more than one thermistor, the resistance temperature curve can be made almost linear. These composites are discussed in the following section.

By careful manufacture, thermistors can be made that have an accurate temperature tolerance and that are interchangeable from unit to unit. In the temperature range of 50° F to 150° F, thermistors with a temperature tolerance of $\pm$0.36° F are available at a moderate cost. Contrary to popular belief, thermistors are quite stable when they are properly aged before use (less than 0.1% drift in resistance during periods of months). Routine temperature measurements to 0.1° F are not unusual for temperature at ranges much greater than the heat stress monitor temperature ranges.

The power consumption of a thermistor thermometer can be made quite small. Due to self-heating effects, the amount of power applied to the thermistor must be limited when the thermistor is used for accurate temperature sensing. The output of a typical bridge is in the neighborhood of 3 millivolts/° F, so very little signal amplification is needed. Therefore the power requirement for the amplifier and signal conditioning circuitry is minimal.

The thermistor can be made waterproof by applying suitable coatings or by enclosing them in a protective enclosure. Care in handling would be necessary for an unprotected thermistor because of its small size and fragile construction.

Thermistors are made with a fast response time by keeping the physical size small and by using very thin lead wires. For an uncoated thermistor, time constants of less than 10 seconds are possible. This would give a 95% response time of less than the 0.5 minutes specified for the personal heat stress monitor.

The cost of thermistors is small compared to other temperature sensors, and since only minimum signal conditioning is required, the cost for associated electronics is also comparatively small.

(c) Linearized Thermistors

The non-linearities of ordinary thermistors can be eliminated in several ways. The first order approach is to place resistors in series and parallel with the thermistor so that the non-linearities are not as pronounced. Although this decreases the sensitivity of the sensing network, some trade-off between sensitivity and linearity is desirable.

One manufacturer of linear thermistors offers units which are available in values of 36 ohms/°F to 720 ohms/°F for a temperature range of 32°F to 212°F. These assemblies used with a constant current source would supply an output voltage which is inversely proportional to the temperature. These assemblies would be suitable for the personal heat stress monitor except for the time constant requirement. The smallest package available for these units is a 0.625" x 0.495" x 0.245" package. The thermal time constant associated with this size would be much too long to meet the requirements. Although a specially packaged linear thermistor may meet the requirements, this is available only at additional engineering costs.

Another manufacturer of thermistors offers a similar linear thermistor composite. It is made of a thermistor composite and a resistor composite. In these composites, two or three thermistors are used in a network with two or three separate precision metal film resistors to produce a linear output. Depending on how the resistors are connected to the thermistors, either a linear resistance, or a linear voltage versus temperature is obtainable. Depending upon where the output is taken, either a positive slope or negative slope output voltage versus temperature is obtainable. Various temperature ranges are available with slightly varying output slopes. One composite which is suitable for the personal heat stress monitor is approximately 0.080 inch diameter by 0.150 inch long, and has a time constant of 10 seconds in free, still air. It has a range of 32°F to 212°F (0°C to 100°C) with a thermistor accuracy and interchangeability of $\pm$0.27°F ($\pm$0.15°C) and a maximum linearity deviation of $\pm$0.39°F ($\pm$0.216°C). Due to self heating effects, the input voltage must be kept to less than 2.0 volts, so the power dissipation is insignificant. The thermistor composite is available in a vinyl sheathed probe which makes it more rugged and waterproof with a longer time constant. The same composite type could be used for dry bulb, wet bulb, and natural wet bulb temperature. If a unit is needed to measure the globe or mean radiant temperature above 212°F (100°C), some other provisions would have to be made. Signal conditioning components would be minimal since the linear output is available. The output is about 3 mV/°F. To amplify the output signal a low gain dc amplifier with a dc offset would be required. The cost of the composite would be $10.50 or $38.50 for the vinyl-sheathed probe and the parts cost for a suitable amplifier would be in the same price range.

(d) Semiconductor Resistors

There are several types of positive temperature-coefficient silicon thermistors that are commercially available. The most promising type is a silicon sensing element in a hermetically sealed glass package, 0.35 inches long by 0.10 inch in diameter. A typical unit with a constant current source would have an output of 5 millivolts/°F. This magnitude of signal would require only minimal signal conditioning and amplification. These units are only supplied in units which have industrial tolerances. Therefore some provision for calibration would have to be made. From the manufacturer's published nominal curves it can be determined that their linearity is good over the temperature range under consideration, but empirical tests would have to be made to determine if the desired accuracy and linearity from unit to unit is obtainable.

A single type semiconductor resistor could be used to measure all of the heat stress temperatures since its range is well in excess of the required specification but the response time would be somewhat in excess of the desired 30 seconds. A time of approximately two minutes would be required to obtain 95% of the end resistance change after exposure to still air at a different temperature. The cost of these units is very minimal, but time expended in engineering evaluation and calibration would be the more significant factor.

(e) Semiconductor Transducers

A recent advance in thermometry is the monolithic temperature transducer/sensor.[4] These integrated circuit devices include a semiconductor temperature sensor, operational amplifier, output stage, and a voltage regulator, all in one hermetically sealed integrated circuit package. One type has a calibrated accuracy of ±.9°F over the temperature range of -13°F to 185°F (-25°C to 85°C), with excellent stability, good linearity and a power consumption less than 10 milliwatts. The operational amplifier can be connected to give a wide range of voltage gains, so that temperature scale factors can be tailored for the given temperature range. The thermal time constant of the devices is approximately one minute, so the time required to reach 95% of a given change would require a time period of about two and a half minutes. The cost of the units is very minimal since most of the required electronic circuitry is self contained.

(f) Aspirators

The wet bulb temperature must be taken with a rapid flow of ambient air over the wet temperature sensor. The temperature sensor must also be shielded from radiation. Both of these requirements are met by a properly designed aspirator. The rate of air flow must be such that no additional evaporative cooling is gained by an increase in air velocity over the sensing element. Although this velocity varies with sensor size, barometric pressure, temperature and relative humidity, and it reaches the end value asymptotically, design values can be assigned which will give adequate results. Generally speaking, a shielded wet bulb will require an air velocity of at least 300 feet/minute for adequate accuracy.[5] Since the response time and the effects of radiation are decreased with faster air velocities, increased air speeds are desirable.

A sling psychrometer is often used to determine the wet bulb temperature. It consists of a dry thermometer and a wet bulb thermometer, mounted on a suitable fixture with the two sensing bulbs separated so that there is very little radiant heat exchange. A suitable handle is attached and the psychrometer is whirled by hand in the air to produce the required velocity. This method would not be suitable for a personal heat stress monitor.

In the presence of thermal radiation, a method must be used which provides radiation shielding for the temperature sensing element. Several portable and stationary units are available which utilize an electric fan to draw air over stationary sensing elements. At least three hand held units are available which use liquid in glass thermometers and a battery powered fan. These units have an air velocity of at least 900 feet/minute and a response time of about 2 minutes. In general these units incorporate a small dc motor which is used to turn an axial flow fan blade. The power consumption is about 3.0 watts. This is much in excess of the power requirement for any of the temperature sensors and would primarily determine the size of the power supply. The aspiration units which are commercially available are typically 1.5 inches in diameter by 2.5 inches long, and are built to withstand ordinary lab and field handling. The aspiration assemblies cost in the range of $15.00 to $25.00. In lab use, it has been the experience that the motors wear out and have to be replaced periodically.

Other design options are available for the aspirator for the personal heat stress monitor. Better utilization of space and more efficient use of the available power supply can be realized if a unit is designed specifically for the heat stress monitor. There are many manufacturers of small dc motors which may be utilized. More reliable precision motors with higher efficiency are available at a reasonable increase in cost. At least one manufacturer makes a series of miniature axial flow fan blades in sizes of 1.375 inches in diameter and larger. A wide range of design options are available for both the fan and the motor.

A properly designed aspirator would pull the air over the temperature sensors and then the air would be exhausted through openings around the motor. In this way the heat generated by the motor would not affect the temperature reading. A good radiation shield can be designed such that the temperature sensing elements are not directly exposed to radiation. This may be accomplished with a simple baffle, or by causing the air to flow around a corner. The inside and outside of the shield should be made of a low emissivity material such as polished stainless steel to minimize radiation errors. A simple partition would separate the wet bulb from the dry bulb.

Since dc motors can generate electrical interference which may affect sensitive electronic circuitry, adequate isolation would be required. Conductive interference could be greatly reduced by decoupling the motor from the power supply with a suitably designed filter. Radiated electromagnetic interference may be greatly reduced with adequate metal shielding.

2. Dry Bulb Air Temperature

The dry bulb air temperature is defined as that temperature measured by a dry sensor shielded from all radiation heat sources. The shielding must be applied in such a way that free circulation of air over the sensor is not restricted. Also the shielding must be designed so that absorption of incident radiation does not cause the internal temperature of the shield to rise and indirectly irradiate the sensor. A forced air aspirator would be one method to insure that these conditions are met. The aspirator also would decrease the response time because the heat transfer rate of forced air is greater than that of still air.

Any of the previously mentioned temperature measuring methods may be used to measure dry bulb air temperature. For portable operation with the personal heat stress monitor, the platinum resistance temperature detectors and linearized thermistor networks could both meet all of the desired requirements.

3. Wet Bulb Temperature

Wet bulb temperature is defined as that temperature measured by a sensor whose active surface is immersed in an absorbent woven cloth wick which brings water up from a reservoir by capillary action to the sensor. The wick and sensor must be exposed to a rapid flow of ambient air, the velocity of which is such that a further increase in air velocity will not result in additional evaporative cooling of the wick. The sensor and wick must be shielded from heat radiation sources. The temperature sensor must be waterproofed to prevent contamination and anomalous electrical conduction effects of the wet wick. For unattended continuous wet bulb temperature monitoring, certain operational factors must be considered. In extreme heat or in very dry conditions, supplemental means for maintaining a saturated wick may be required if the drying rate of the wick is greater than the wicking rate. Also it is necessary to keep the wick clean, which under dusty conditions may require frequent changes of the wick and water supply. Although both the wet bulb and dry bulb thermometers can be aspirated, it is necessary to separate the two sensing elements so that the radiant heat exchange between them is negligible.

The function of the wick is to provide, through capillary action, a supply of water to the ambient air in the region of the temperature sensor. The cooling process which occurs due to the evaporation of water at the wick/air interface, cools the wet-bulb by conduction through the saturated wick. A satisfactory material for the wick is soft mesh cotton or linen cloth. Any dirt, oil, or other contaminant which prevents a fully saturated wick or limits the evaporative cooling at its surface may cause an erroneous reading. Thus, the wick should be clean, should fit snugly, and should be wetted with distilled water only. To effect a wet-bulb measuring method which gives the same results as a mercury-in-glass system, the length of the wick from the water source to the sensing element should be at least 0.75 inches and the diameter of the element should be near that of the mercury-in-glass thermometer. Reducing the size of the sensor and the diameter of the wick will decrease the thermal response time of the system but will yield readings which are low as compared with a standard mercury-in-glass wet-bulb thermometer.

Again all of the temperature measuring sensors mentioned before are suitable for measuring wet bulb temperature. In some cases, special packaging is necessary to waterproof the sensing element. The thermistors and semiconductor resistors would have to be given a waterproof coating or a waterproof jacket. A commercially available waterproof sensor would offer substantial cost savings. The sensor construction must be rugged so that the wick may be replaced many times without damage. The more suitable methods for portable operation would again be the resistance temperature detector and the linearized thermistor approach. The ability of any of the methods to meet the response time requirements is problematical. The rate of evaporative cooling is typically slow, so for even a minimum size temperature sensor and a small wick, the time to obtain thermal equilibrium may be in excess of the requirement.

4. Natural Wet Bulb Temperature

Natural wet bulb temperature is measured by a thermometer immersed in a water saturated wick in much the same manner as the standard wet bulb thermometer with two important differences. First, the device is not shielded from radiation and second, the air circulation over the device is as close to the natural air circulation as possible (i. e., no forced air motion is produced within the sensing device). For a personal heat stress monitor, the best place for sensing this temperature is on the top of a helmet, since the body would block natural air circulation and radiant heat at other places near the body.

Since problems of shielding and aspiration do not exist, the measurement of this temperature is straightforward. The applicable portions of the discussion for the wet bulb temperature also apply. Since there will be no aspiration the response time will necessarily be large.

Varied results could be obtained if the color of the wick was changed. Darker colors would absorb more radiant energy. It is assumed that a commercially available white wick material would be used.

5. Humidity Sensors

Surveys of the technical literature and of available commercial instrumentation were made in an attempt to find a relative humidity sensor that would be suitable for incorporation in a man-portable heat stress monitor. The option exists for substituting a relative humidity measurement for the natural wet bulb and aspirated wet bulb measurements. Information from a relative humidity sensor, combined with data on the air velocity, air temperature and mean radiant temperature would allow the calculation of natural wet bulb and aspirated wet bulb temperatures. The use of a relative humidity sensor would eliminate the need for the motor-driven blower and water reservoirs required for wet bulb measurements.

The humidity sensors that the literature survey showed to have the best chance of being suitable for a quick response, man-portable system were the electric hygrometers based on equilibrium sorption.[6,7] The commercial survey located several companies that manufactured humidity instruments that used various electric hygrometer sensors. One company employs a moisture sensor in which a lithium chloride impregnated wick is sandwiched between two electrodes which electrically heat the wick. Lithium chloride is a hygroscopic salt that absorbs moisture. When the wick is heated, moisture evaporates from the wick until a heat-moisture equilibrium is reached. The equilibrium temperature is related to the relative humidity. A second company has a cellulose crystallite element mounted on a cantilevered stainless steel spring. As the element expands or contracts in response to the relative humidity, the change is measured by two strain gages. Because of the hygromechanical nature of the response of the crystallite element, no power is required for the element. Power is only needed for the interrogation of the strain gages. This interrogation does not have to be continuous and it needs only to be done intermittently.

The disadvantage of using the electric hygrometer varies from sensor to sensor. Often the sensors are not accurate at low relative humidities or they reach a saturation point at high humidities. Some sensors are large and heavy and have high power requirements. Most sensors were developed for fixed position instrumentation and could be adapted to a man-portable system but to do so would require a major redesign and development effort. Other sensors are either inaccurate, slow responding or sensitive to vibration.

The relative humidity sensor that most closely approaches the target performance requirements is the cellulose crystallite structure mounted on a cantilevered stainless steel spring. The element is approximately 0.5 inch long, 0.07 inch wide and 0.05 inch thick. The combined weight of the sensor and the 3 x 3 inch printed circuit electronics card is approximately 1 ounce. The sensor is position and vibration insensitive. The disadvantages that must be considered are the slow response time and the accuracy of the calculation of the natural and aspirated wet bulb temperatures. The sensor requires from 6 to 9 minutes to achieve 95% of a final value after a step response input change. The calculation of wet bulb temperatures from the relative humidity, velocity and temperature measurements would combine the inaccuracies of all three measurements while the accuracy of the wet bulb temperatures would be much better with direct measurements.

6. Thermal Radiation

The measurement provided by the globe thermometer described earlier provides a composite temperature reading which combines thermal radiation and convection cooling effects. Instruments are available which measure each of these effects separately; however, there is no other simple sensor device available that will provide precisely the same integrated output reading as the 6-inch globe thermometer. The following sections will describe the recommended sensors used in stationary installations for measuring heat stress, an instrument which uses a 1.65 inch globe to give a direct reading WBGT index, theory for the use of small spheres as a radiation detector, and discussions concerning the applicability of various photon and thermal infrared detectors towards meeting the objectives of the heat stress monitor.

a. 6-inch Globe

The Standards Advisory Committee on Heat Stress recommended standard for work in hot environments[1] describes the globe thermometer as follows:

> "Globe thermometer: A thin-walled, blackened (flat black) copper sphere six inches in diameter, with a temperature sensing device at its center.
>
> ...When using the above-described globe thermometer, approximately 20 minutes must be allowed to approach a steady state before reading the temperature."

In the report referenced above, a sketch which is repeated in Figure 1 is presented giving a suggested instrument arrangement for the globe, natural wet bulb thermometer and dry bulb thermometer. The measurement provided by the globe thermometer as described earlier provides a composite temperature reading which combines thermal radiation and convection cooling effect. While this test apparatus is suitable for determining long term weighted average data at a single work place, clearly it would not easily be adapted to a personal heat stress monitor.

b. Direct-Reading WBGT Index Meter

In an attempt to decrease the response time of the globe thermometer, an instrument[8] has been designed which uses 1.65 inch black globe as the radiation sensor. The authors report that stable readings for this instrument may be obtained in 5 minutes or less.

The rationale for this instrument is based on equations (1) and (2) for indoor and outdoor applications. Equation (2) can be rewritten as

$$(WBGT)_{out} = 0.7T_{NWB} + 0.3\,(2/3T_{GT} + 1/3T_{DB}) \qquad (3)$$

Now, if a sensor could be found which gives a combined effect of T_{GT} and T_{DB}, according to the following relationship:

$$T'_{GT} = 2/3T_{GT} + 1/3T_{DB} \qquad (4)$$

then we may write

$$(WBGT)_{out} = 0.7T_{NWB} + 0.3T'_{GT} \qquad (5)$$

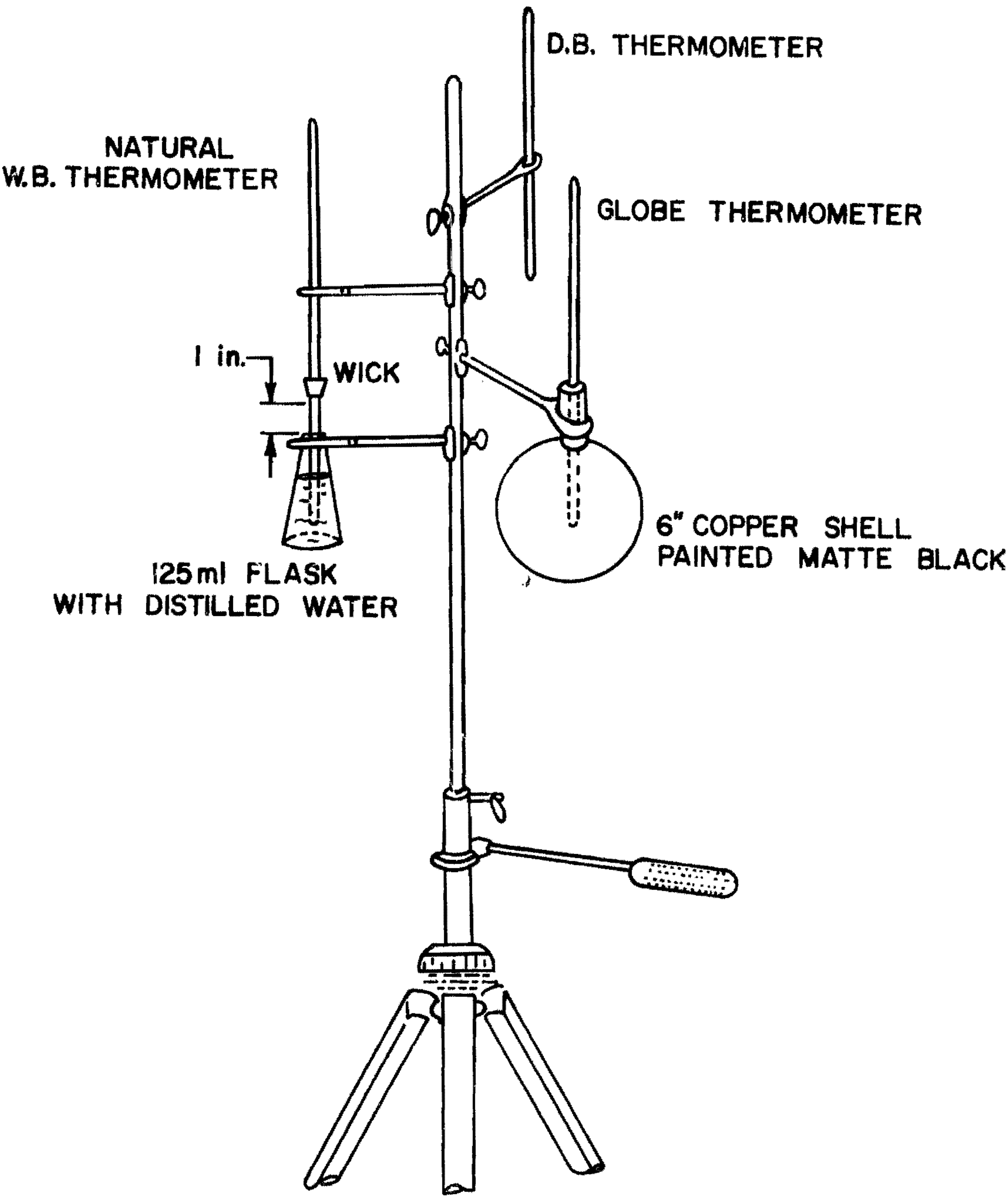


FIGURE 1 SUGGESTED[1] INSTRUMENT ARRANGEMENT FOR ENVIRONMENTAL MEASUREMENTS

In an effort to find a sensor with the combined effect of equation (5), the authors developed a hollow copper globe 1.65 inches in diameter (painted flat black) which satisfies the relationship for the wind speed range of 100 to 1000 ft./min. Within this windspeed range, the error is specified as ±0.4° F. Below 100 ft./min. this error increases rapidly.

To evaluate $(WBGT)_{IN}$, equation (2) may be solved for T_{GT}. This result along with the measured value of T_{DB} is used in the determination of $(WBGT)_{IN}$ as specified by equation (1).

Although the use of this small globe has reduced the time required to measure a globe temperature, its response is too slow, and the wind velocity range is too narrow to meet the performance requirements as specified for the heat stress monitor.

c. Mini-sphere Sensor

As pointed out above, the conventional 6-inch globe is inconveniently bulky and slow responding. The 1.65 inch globe incorporated into the direct reading WBGT index meter is an improvement but still suffers from some of the same limitations. If the assumption is made that the 1.65 inch globe will reach 99% of its final value in 5 minutes, then a first order response passing through this point will reach 95% of the final value in approximately 3 1/3 minutes. The target response for the heat stress system is 95% of final value in 30 seconds. To develop a faster responding sphere, a globe (mini-sphere) needs to be designed which is smaller than any presently in use. The discussion which follows is directed towards this objective.

Simply decreasing the diameter and wall thickness of the globe in order to reduce its thermal mass will shorten the thermal response of the sphere-sensor system. However, as the diameter of the sphere is decreased, the ratio of the net radiant heat interchange to conductive heat interchange is altered, resulting in a temperature for a smaller globe which differs from that measured with a 6-inch globe under similar environmental conditions. The effect of a diameter reduction could be compensated for if the emissivity of the globe is increased. However, since by definition the 6-inch globe has an emissivity as near as 1.0 as is practicable, this approach cannot be considered.

A practical approach to a workable sensor is to use a smaller globe of a desired size and convert its readings back to what a 6-inch globe would have read under similar conditions. This can be done in real time using analog circuits or a digital processor. The relationships which follow are developed to provide the necessary analog or digital corrections for the needed conversions.

The design and calibration of a small globe sensor requires a knowledge of the effect of size on both radiant and convective heat exchange.

The net radiant interchange H_R between a globe with surroundings several feet from the globe is given by the relation

$$H_R = \sigma \epsilon_g (T_{gt}^4 - T_r^4) \text{ cal/cm}^2 \times \text{sec} \quad (6)$$

where:

σ = 1.355×10^{-12} cal/cm^2 x °K^4 x sec

T_{gt} = globe temperature (any diameter) °K

T_r = mean radiant* temperature °K

ϵ_g = globe emissivity.

Note that the net radiant interchange is not affected by the dimensions of the sphere. The three factors which affect the temperature of the sphere are heat exchange by radiation, convection, and conduction. The conduction heat loss is small (usually 1 or 2% of the convective or radiant losses) and is usually neglected in physiological applications. For this reason, it will be ignored in the development which follows. Thus for a sphere in thermal equilibrium with its surroundings, the heat absorbed by radiation must equal the heat lost by convection. This relationship may be expressed as

---
* See definition p. 7

$$H_R + H_c = 0 \qquad (7)$$

where:

H_c is the convective heat exchange factor (cal/cm^2 x sec).

To discuss the effects of wind speed on the exchange of convective heat, dimensionless mean Nusselt numbers

$$\overline{Nu} = H_c d/k(T_{gt} - T_a) \qquad (8)$$

and Reynolds numbers

$$Re = \frac{vd\rho}{\mu} \qquad (9)$$

must be used where d is the diameter of the sphere (cm) and v is the air velocity (cm/sec). The air is described by its physical characteristics:

ρ = air density gm/cm^3

μ = air viscosity gm/cm x sec

k = thermal conductivity of air cal/cm x sec x °K

T_a = air temperature °K.

To relate the Nusselt numbers to Reynolds numbers, Hey[9] proposes the relationship

$$\overline{Nu} = 0.32\,(Re)^{0.60}. \qquad (10)$$

This equation was derived as a best fit for data taken on spheres between 0.1 inch (.24 cm) and 6.0 inches (15.2 cm). It is to be noted that equation (10) can only be used with confidence when $10^2 \leqslant (Re) \leqslant 10^5$. Also since air density, viscosity and thermal conductivity are affected by the temperature of the air, specific solutions for the convection coefficient should be based on this parameter.

To calculate the convection coefficient, substitute equations (8) and (9) into (10) and solve for H_c. This procedure will result in the following relationship:

$$H_c = (.32)\left(\frac{v\rho d}{\mu}\right)^{0.6} \frac{k}{d} (T_{gt} - T_a) \quad cal/cm^2 \times sec \tag{11}$$

Although a good approximation may be made for H_c by using constants for ρ, μ and k, a more precise calculation can be made by using analytical expressions which are a function of the air temperature.

For the density of air[10] we may write

$$\rho = \rho_o \left(\frac{P}{760}\right) \left(\frac{273.16}{T_a}\right) \tag{12}$$

where:

P = pressure mmHg

and

ρ_o = 1.293×10^{-3} gm/cm^3

Very little error is introduced by assuming a constant pressure of 760 mmHg and using this approximation, equation (12) may be written as

$$\rho = \rho_o \left(\frac{273.16}{T_a}\right) \tag{13}$$

An expression for the viscosity of air[10] in terms of absolute temperature is:

$$\mu = \frac{(1.488 \times 10^{-5})\,(T_a)^{1/2}}{1 + \dfrac{(122.1)(10^{-5}/T_a)}{T_a}} \quad gm/cm \times sec \tag{14}$$

This equation is valid for $79°K \leqslant T_a \leqslant 1845°K$ and thus applies for the temperature range of interest here.

The Smithonian tables[11] give values of thermal conductivity at discrete temperatures as shown in Table II . An equation of the form $y = Ax^B$ was fitted to these data to generate an analytical expression relating the two parameters. The resulting equation is

$$k = (6.97)(10^{-7})\, T_a^{0.7882} \quad cal/cm \times sec \times °C \tag{15}$$

TABLE II. VALUES OF THERMAL CONDUCTIVITY (k) FOR AIR AS A FUNCTION OF TEMPERATURE

T_a (°C)	k cal/cm x sec x °C
0	5.80×10^{-5}
10	5.97×10^{-5}
20	6.14×10^{-5}
30	6.30×10^{-5}
40	6.46×10^{-5}

where:

T_a is the absolute temperature in °K.

By knowing the dry bulb temperature, T_a, and the air velocity, v, as measured in the heat stress monitor and given the above relationships for calculating air density, viscosity and thermal conductivity, all the data are available to calculate the convective heat exchange, H_c.

For a globe in equilibrium with its surroundings, the sum of the convective heat exchange and radiant interchange is zero. Using the calculated value of H_c and equation (6) the mean radiant temperature (T_r) may be determined by the following relationship:

$$T_r = (T_{gt}^4 + H_c/\sigma \epsilon_g)^{1/4} \qquad (16)$$

where:

ϵ_g is assumed to be 0.95.

Having determined the mean radiant temperature, it remains to calculate the 6-inch globe temperature as required for the WBGT index. A calculation involving an approximation will give the result within 1 or 2% of the true value. An exact solution can be obtained only by using iterative numerical procedure, but the iteration converges rapidly and is no problem to implement on a digital processor.

The approximation formulas as given by Hey[9] are

$$T_{GT} = T_a + (T_r - T_a)/(1 + \alpha) \qquad (17)$$

where

$$a \approx (0.336)\,(T_r - T_{gt})d^{0.4}/(T_{gt} - T_a)$$

and

T_{GT}	=	6-inch globe temperature °C
T_{gt}	=	mini-sphere temperature °C
d	=	diameter of mini-sphere cm

The derivation of this approximation is given in Appendix A.

An exact determination for T_{GT} is described by Graves[12]. For this solution, the mean radiant temperature, T_r is first found by equation (18) using the measured value of T_{gt} for the small globe thermometer.

From equations (8), (9), and (13) we can write

$$\sigma \epsilon_g \left(T_{GT}^4 - T_r^4\right) = -.32\left(\frac{v\rho d}{\mu}\right)^{0.6} \frac{k}{d}\left(T_{GT} - T_a\right) \tag{18}$$

This equation is re-written as

$$T_{GT}^4 = T_r^4 - \frac{0.32}{\sigma \epsilon_g}\left(\frac{v\rho d}{\mu}\right)^{0.6} \frac{k}{d}\left(T_{GT} - T_a\right) \tag{19}$$

but cannot be solved explicitly for T_{GT}. To start the solution, use T_{gt} as a first guess for T_{GT} in the right side of equation (19). This will result in a value for T_{GT} that is slightly high. Using this new value, substitute it in the right hand side of equation (19) and again solve for a new value of T_{GT}. This procedure is repeated until the calculated value quits changing. It will be found that the iteration converges rapidly and that 2 or 3 loops through the procedure will give adequate accuracy.

Data presented by Bond and Kelly[13] were useful in demonstrating the use of equations (17) and (19). These data comprised independent measurements of the air temperature, the mean radiant temperature and the globe temperatures of a number of different globes all in the same environment. To demonstrate the validity of equation (17), 2-inch globe temperatures were used to calculate 6-inch globe temperatures. These calculated values are compared with the measured 6-inch globe temperature values given by Bond and Kelly. Table III shows the results of this calculation. Since the mean radiant temperature is determined as an intermediate step in obtaining the 6-inch globe temperature, its calculated values are listed along with the measured values. The mean radiant temperature of the environment was ascertained by two methods : the first using a directional radiometer and the second employing a total spherical radiometer. The calculated values of mean radiant temperature were found using equation (16) and the calculated value of H_c from equation (6). The observed and calculated values for the 6-inch globe temperature are also presented in Table III. The percent error which is given in the right hand column of the table was calculated by taking the absolute difference between the "6-inch calculated" and "6-inch observed" globe temperature readings, dividing by the "6-inch observed" reading, and expressing the ratio as a percent. The largest error for these data is 2.7% for data reading no. 5.

TABLE III
EXPERIMENTAL TEST OF GLOBE THERMOMETER
EQUATION 17

Reading No.	Air Temp. °C	Air Vel. cm/sec	Mean Radiation Temp °C		Globe Temperature °C			6-inch Error %
			Obs	Calc	2-inch diam Obs	6-inch diam Calc	6-inch diam Obs	
1	42.6	51	82.1	82.6	58.3	62.8	61.8	1.6
2	43.1	61	78.2	78.2	55.7	59.4	58.9	0.8
3	42.3	64	79.0	83.9	57.3	59.4	58.3	1.0
4	41.9	51	75.2	76.9	55.3	58.2	57.5	1.2
5	40.8	51	75.0	72.8	52.8	57.3	55.8	2.7
6	34.4	203	33.2	31.3	33.9	33.7	33.9	0.6

An application of the iterative method, equation (16), to the no. 5 measurement resulted in a calculated 6-inch globe temperature of 56.3°C for an error of 0.9%. Thus, the application of this equation generates a calculated value for the 6-inch globe which is closer to the observed value, demonstrating its utility.

Since it is desirable to decrease the diameter of the globe to make it as small as possible and improve its response time, the question may be asked, what is the smallest limit on its diameter. To answer this question, equation (9) is solved for the diameter.

$$d = \frac{\mu\ (Re)}{v\rho} \qquad (20)$$

This relationship, as stated earlier, is valid over a range of $10^2 \leq Re \leq 10^5$. Therefore a minimum diameter sphere would be obtainable with $\overline{Re} = \overline{10}^2$. Using the values of μ and ρ for air at a temperature of 40°C (104°F), equation (20) may be written as

$$d = \frac{13.37}{v} \text{ inches} \qquad (21)$$

where v is the air velocity in ft/min. Calculating the diameter for the worst case velocity of 10 ft/min , results in a minimum diameter of 1.34 inches (3.4 cm) for the globe. If a lower air velocity limit of 20 ft/min is used, a globe diameter of 0.67 inches (1.7 cm) is feasible.

By using the relationships given here, it appears that a globe thermometer can be designed which is small, will have a fast time response and will give a temperature reading that can be converted to an equivalent 6-inch globe temperature. Quantitative prediction of time response with size is not available and not easily derived. Kuehn[14] presents an electrical analogue to the globe thermometer which is composed of two series RC networks. The first network is composed of the thermal resistance of the shell (Rs) and associated layer of "still" air and the thermal capacity (Cs) of the shell. The other network is composed of the thermal resistance of the enclosed gas (R_G) and the thermal capacity of the temperature sensing element (C_T). Considering the effects of shell alone, it follows that for constant R_s, the time constant is directly proportional to the thermal capacity of the shell, C_s. Data presented by Graves[12] gives support to this model. In comparing responses of constant diameter (4-inch) spheres of varying wall thicknesses, Graves reported that for similar environmental conditions, the time to equilibrium was 12.5 minutes for a 0.016 inch thick copper globe compared to 18 minutes for one with a 0.022 inch wall. Thus, a wall thickness reduction of 27% resulted in a time response decrease of 30%, giving credence to the electrical analog proposed by Kuehn.

Most of the published work concerning the time response of globes is concerned with increasing the time response of the 6-inch globe. One attempt to reduce the size and response time was discussed earlier for the 1.65 inch globe used in the direct reading WBGT index meter. An estimation was made that this globe would reach 95% of the final temperature in approximately 3.5 minutes. The wall thickness was not published for the 1.65 inch copper globe but is probably in the neighborhood of 0.015 inches. Using the model discussed above for the globe, the wall thickness would have to be reduced by a factor of 7 to approximately 0.002 inches to achieve the desired 0.5 minute response time. For a 1.65 inch diameter globe, a 0.002 inch wall thickness would result in a fairly fragile sensor. However, if the diameter of the globe is reduced to the 0.5-1.0 inch range, a wall thickness of 0.002 inches would be compatible with the rigors of the heat stress system.

Simply decreasing the R_sC_s time constant alone will not achieve the desired results since the R_GC_T time constant must also be considered. Nevertheless, as the diameter of the sphere is reduced R_G becomes smaller and thermistors may be selected to make C_T almost negligible. Additionally, Graves reported that the response was better for aluminum shells than for copper shells. This fact follows from the lower thermal capacity by volume for aluminum. In light of the factors presented above, there is good reason to believe that a globe sensor could be constructed having a time response approaching the desired 0.5 minute.

The measurement of temperature in the minisphere can be accomplished using the same temperature sensors used for the other heat stress parameters. Although the required temperature range is wider, the accuracy has been relaxed to $\pm 1^{\circ}F$. Suitable sensors include thermistor and platinum resistance probes. The upper end of the temperature range specified for the 6-inch globe is $250^{\circ}F$. Under similar environmental conditions, the maximum temperature for the minisphere will be lower. For this reason, the specification can be relaxed for this temperature probe.

d. Infrared Detectors General

The equations developed for the globe thermometer showed that for a given air temperature, air velocity, and mean radiant temperature (MRT), an equivalent 6-inch globe temperature may be calculated. MRT can be defined as the temperature that a black body must have to produce the same radiation density at a point as that produced by its surroundings. In considering a sensor for the MRT then we must consider the black body response curve for the temperatures of interest. As will be shown, the wavelengths of interest for the portable heat stress monitor all fall within the infrared band. Thus, detectors which are suitable for this application will be found classified as infrared detectors. The following sections examine some of the instruments and techniques which are available to implement the measurement of MRT.

The methods by which heat is transmitted can be classified into three distinct types known as convection, conduction and radiation. For any example of heat transmission, any combination of these methods may be operating simultaneously. Since conduction is responsible for only 1 or 2% of the heat transfer in the globe, this mechanism was ignored in the development in the preceding section where thermal behavior is predicated only on equations involving convection and radiation. Given these relationships and by knowing the air temperature and air velocity as measured in the personal heat stress monitor, it is possible to calculate the convective cooling which would occur in a 6-inch black globe. To calculate or predict a 6-inch globe temperature, without using a globe, a quantitative measurement of the MRT is needed. An instrument designed to measure the parameter is the radiometer.

A radiometer is a radiation measuring instrument having a substantially flat response to a wide band of wavelengths in the infrared region. In general, radiometers measure the difference between the source radiation incident on the radiometer detector and a radiant energy reference. All radiometers and radiometric measuring instruments contain at least the following three essential components: (a) a detector element, which converts changes in incident electromagnetic radiation into variations of an easily measured property, usually an electrical signal, (b) an optical system which determines the detectors field of view, and (c) an amplifier and output indicator, usually electronic, to transform the output of the detector element into the desired form of presentation.

In considering radiometers for this application, it is important to first identify the spectral distribution of black-body radiation over the temperature range of interest. The source temperature that the radiation sensor sees will range from less than 70°F (294°K) to approximately 3000°F (1922°K). Figure 2 shows a log-log plot of Plank's equation giving radiant emittance as a function wavelength for black-body temperatures of 80.6°F (300°K) and 3141°F (2000°K). The peak emittance for this range of temperatures varies from 1.4 μm for the higher temperature to 10μm for the lower temperatures. The shape of the curve is identical for all temperatures and for different temperatures need only be shifted along the line representing the Wien displacement law. For example, at a temperature of 250°F (394°K) the peak emittance occurs at a wavelength of 7.35 μm. From the plots shown in Figure 2, it is evident that most of the energy to be detected by the heat stress monitor will occur between the wavelengths of 0.4 μm and 10μm in the spectrum. These limits will be useful in selecting a detector for thermal radiation.

The infrared detectors which may be considered fall into two general classes[15]: (1) thermal detectors and (2) photon or quantum detectors. A thermal detector responds to absorption of infrared energy by the bulk material and is usually coated with a black surface. The absorbed radiation increases the temperature of the detector which in turn changes a temperature-dependent physical property of the material. In contrast, photon detectors utilize the interaction of impinging photons within the radiation sensitive material.

e. Photon Infrared Detectors

In the photon detector, the interaction of photons with the electrons within the material is a very fast process and

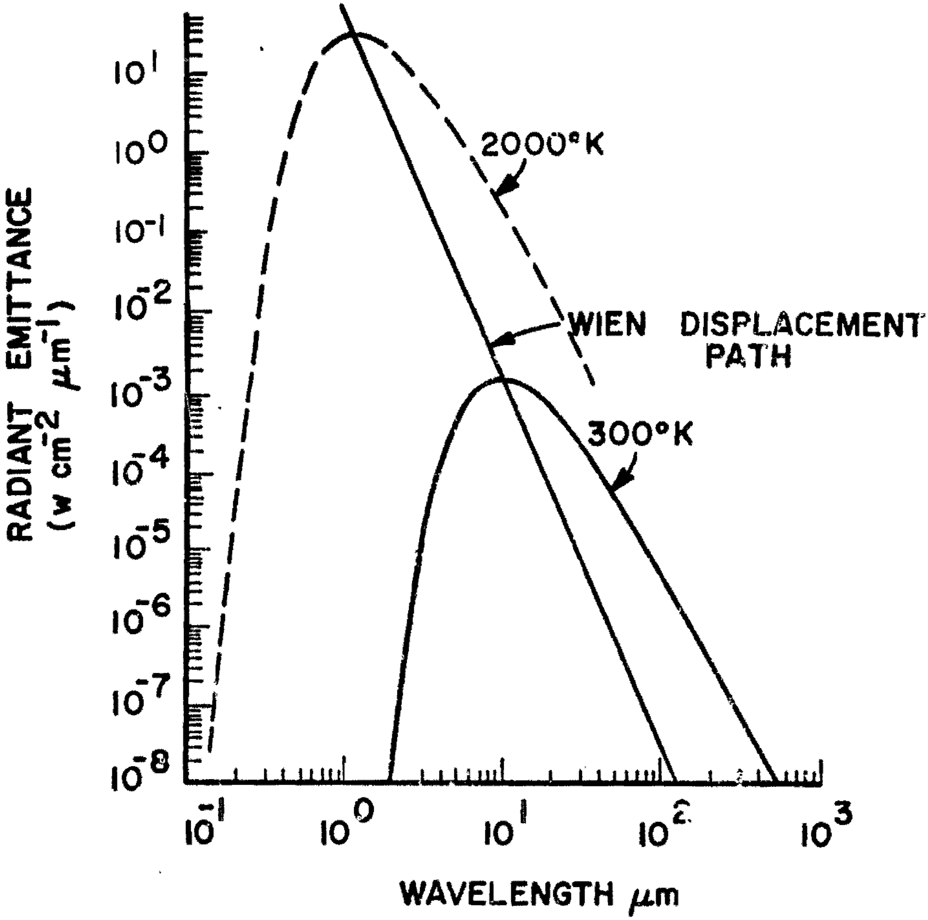


FIGURE 2
RADIANT EMITTANCE AS A FUNCTION OF WAVELENGTH FOR BLACKBODY TEMPERATURES OF 300°K (81°F) and 2000°K (3141°F)

consequently the time constant of these detectors in most cases is very small. The majority of these materials, however, must be cooled to a low operating temperature in order to avoid saturation by thermal energy and to limit the thermal dependent Johnson noise. Techniques which are used for cooling detectors of this type include dry ice cooling or thermoelectric cooling (Peltier effect). In other cases, lower temperatures are necessary which may be obtained by cooling with liquid nitrogen, hydrogen, or helium. Neither of these methods would be suitable for a lightweight portable system since the liquid cooling would involve an unmanageable Dewar flask and the thermoelectric effect would use too much power for a practical battery operated system. For instance, one manufacturer has a series of thermoelectric infrared detectors which require typically 2 watts power dissipation to cool each sensor for recommended operation. Table IV lists the three family types of photon detectors.

TABLE IV
TYPES OF PHOTON IR DETECTORS

Type	Material
Photoconductive Detectors	Silicon (Si) Lead Sulfide (PbS) Lead Selenide (PbSe) Germanium - Gold Doped (GeAu)
Photovoltaic Detectors	Silicon (Si) Gallium Arsenide (GaAs) Germanium (Ge) Indium Arsenide (InAs)
Photoelectromagnetic Detectors	Indium Antimonide (InSb)

Not all photoconductive devices require cooling. For example, one supplier has a lead sulfide IR detector designed to operate at normal ambient temperatures. This device, however, has an upper response of 3 μm which puts it outside the spectrum of interest. Another ambient temperature operation lead selenide detector also manufactured by this company is sensitive up to approximately 4.5 μm. Typical time constants for these detectors are 10^{-5} sec. for lead selenide and 10^{-3} sec. for lead sulfide but vary with the operating temperature of the detector. Unfortunately, the detectivity, responsivity, resistance, time constant, and long-wavelength cutoff also change with fluctuating operating temperatures and for a calibrated sensor, a constant detector temperature would need to be maintained. It would be difficult to incorporate these detectors into a portable system because of the heavy demands on the power supply to provide an isothermal condition for the detector.

An alternative to maintaining the temperature would be to let the temperature of the detectors fluctuate with ambient variations and measure the substrate temperature with a separate detector. Knowing the temperature of the detector and its characteristics as a function of temperature would allow any output to be corrected to some fixed reference. This would require a complex calibration of the detectors and a complex correction applied to the resulting data.

A large number of silicon and germanium quantum devices are available which fall into the categories of photo-transistors, photo-diodes, photo FET, PIN diode, etc. This subset of photoconductive detectors is for the most part, sensitive to the visible part of the electromagnetic spectrum. The devices have a fast response time, high sensitivity, good linearity, low noise and require relatively simple supporting circuits. Nevertheless, the spectral range of these silicon detectors is limited to wavelengths below 1 μm, completely out of range for the band of interest, making them unusable for this system.

Another type of photon IR detector is the photovoltaic sensor. These detectors actually generate a temperature dependent voltage when the incident radiation illuminates a junction of dissimilar metals. These devices also have fast time constants but are only sensitive to a narrow range of wavelengths at the low end of the IR spectrum.

The third member of the photon IR family is the photoelectromagnetic detector. In this device photons absorbed at the surface generate charge carriers which diffuse into the bulk and are separated en route by a magnetic field. This separation of charge produces an output voltage which varies with the intensity of the incident radiation. The photoelectromagnetic detector also has the advantage of a fast response time but has the disadvantage that its resistance is often very low ($< 1\,\Omega$) so that it is difficult to use.

f. Thermal Infrared Detectors

Thermal detectors can be divided into four general types as listed in Table V. In general, the thermal detector absorbs infrared energy, and the resulting temperature rise changes an electrical property, such as resistance or capacitance.

Many thermal detectors have a time response in the millisecond range. Sensitivities for thermal detectors are typically lower than photon types with specific detectivities (D*) in the range of 10^7 to 10^8 cm(Hz)$^{1/2}$/watt; however, they can respond to the full infrared spectrum. In the sections which follow a short discussion of each type is given along with its advantages and disadvantages as a possible thermal detector for the heat stress monitor.

TABLE V
TYPES OF THERMAL IR DETECTORS

Type	Materials
Thermocouple and Thermopile Detectors	Various Metallic Alloys Nickel (Ni) Bismuth (Bi) Antimony (Sb) Various Semiconductors
Thermistor Detectors	Mixture of Metal Oxides
Pyroelectric (Ferroelectric) Detectors	Triglycene Sulfate Tryglycene Fluoroberyllate
Golay Cell Detectors	Xenon Gas

1.) Thermistor Detectors

Since the resistance of most conductors varies with temperature a radiation detector can be made by taking a resistor with a very small thermal capacity and blackening its surface so that it can absorb infrared radiation efficiently. Devices of the type, also referred to as bolometers, were first made in 1880 by Langley, who used these platinum foils for solar observations. Platinum sensors are still in use, but the thermistor bolometer having a higher detectivity is more frequently employed. To increase the detectivity these detectors are sometimes cooled with liquid helium.

D* is useful for comparing the performance of different detectors since it is the signal-to-noise ratio when one watt is incident on a detector having a sensitive area of 1 cm^2 and the noise is measured with an electrical bandwidth of 1 Hz.

The elements on a common substrate in the detector are usually mounted in pairs with one element open to and the other screened from the radiation. By placing the elements in the opposite arms of a bridge circuit the effects of changes in ambient conditions are compensated. An improvement in detectivity is obtained in some cases by the use of immersion optics. The element is mounted in contact with a hemispherical germanium lens. Germanium is used because it transmits satisfactorily for wavelengths above 2 μm. This optical arrangement reduces the area of the image by a factor of 16. Hence a smaller detector element may be used and should lead to an improvement in D*.

A conventional bridge circuit for biasing a thermistor bolometer detector is shown in Figure 3. In the network shown,

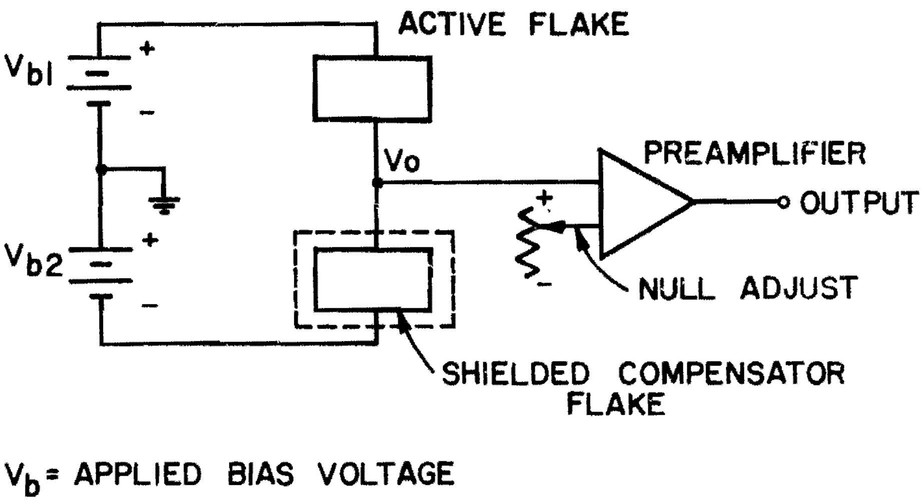


FIGURE 3. CONVENTIONAL BRIDGE CIRCUIT
FOR BIASING THERMISTOR BOLOMETER DETECTORS

the bias voltages V_{b1} and V_{b2} are chosen so that their sum produces the required bias temperature in the active flake. Their ratio is chosen so that the signal voltage V_o, is approximately zero with no radiation incident upon the active flake.

The network shown has the disadvantage that (a) uncorrelated bias voltage fluctuations are transmitted to the bridge output with only 50% attenuation; (b) correlated supply voltage fluctuations produce noise at the bridge output terminal in proportion to the null offset if $V_{b1} = V_{b2}$; (c) direct coupled amplification is exceedingly difficult since the signal level may be a few millivolts, while the null offset, if not removed, may be a few volts.

Smith[16, 17] discusses an alternative type of bias network which eliminated some of the problems listed above and moderates others. Nevertheless, the range of bias voltages required for optimum performance range from 30 volts/flake to more than 100 volts/flake. These voltages could be supplied in a portable system but would require separate batteries to supply the required voltages or a DC/DC converter and regulator making an inefficient use of system power.

In many applications of these sensors as radiant energy measuring devices, the increasing radiation is chopped resulting in an AC signal which is much easier to amplify. The problems associated with DC circuits such as null offsets and DC drift are eliminated in the AC circuits; however, the requirement for a mechanical chopper is a serious limitation in considering this type of detector for the personal heat stress monitor.

2.) The Pyroelectric Detector

In most thermal detectors, the signal amplitude increases as the intensity of the incident radiation increases. This signal increase will continue until the condition is reached where saturation temperature is achieved during the heating period. With the pyroelectric detector[18], however, it is the rate of temperature change rather than the actual temperature which is significant. Thermal radiation which is incident upon a pyroelectric element is either absorbed by the element or by electrodes attached to the face of the element. Either way, the radiation heats the pyroelectric layer and generates a small charge on the element's electrodes. The charge generated is proportional to the temperature change (dT) and hence the current out of the element into an external resistance is proportional to the rate of change in temperature, dT/dt. The parameter expressing the quality of the element is the pyroelectric coefficient (P), the proportionality factor relating the charge generated to the temperature change. Presently, triglycine sulfate and triglycine fluoroberyllate are being used in commercial IR detectors. At room temperature, these crystals develop surface charges of typically 3×10^{-8} coulomb/cm^2 for a temperature change of 1°C. Because of this property the crystals produce a voltage that is proportional to the amount of absorbed infrared radiant power. These detectors have many attractive features including a typical spectral response from 1 to 45 µm.

The pyroelectric detector is useful where there are changes occurring in radiation flux and, if this does not naturally occur in the signal itself, then the incoming radiation must in some way be optically chopped or scanned to measure a steady state radiation source as required in the heat stress instrumentation. As with the thermistor detector already mentioned, this requirement for chopping is a major limitation since a number of detectors would be needed with each one requiring a motor or solenoid driven radiation interruption element. This electromechanical system would be bulky, mechanically fragile and consume additional power from the system power supply.

3) The Golay Cell

Although the Golay cell is not a solid state device, it will be mentioned because it does operate at room temperature. The device consists of a small cavity containing gas (such as xenon, helium, etc.) at low pressure. Radiation entering the cavity is absorbed by a membrane which in turn heats the gas. Part of the chambers wall is made of a flexible membrane silvered on the outside, which is distorted when the gas is heated and deflects a beam of light shining on to a photoemissive cell. From the design of the cell, a small amount of incident radiation will cause a large change in the output of the photo cell. The spectral response of the cell is mainly determined by the window fitted to the aperature of the cavity.

Although the response time is fast enough to meet the requirements for the heat stress monitor, the device is rather sensitive to convective cooling, vibration, microphony and other hazards of a non-ideal environment and would not be functional in a portable system.

4) Thermocouple Detectors

Thermocouples were first used to detect infrared radiation a few years after the discovery of the Seebeck effect in 1826. While the radiation detector thermocouple uses the same principal as the ordinary thermocouples which have already been discussed, the construction of the two devices are quite different. For the radiation detector, the thermal mass must be kept as small as possible and its surface must be black to ensure efficient absorption of radiation. It is also desirable to have the detector made of materials which give it a large voltage output per degree temperature change.

The first thermocouple detectors were made of metals formed as thin wires or foils. Semiconductor studies have shown that better figures of merit can be obtained by using various combinations of materials. Available detectors are made by mounting single elements or groups of elements in the same capsule so that one may be exposed to the radiation while the other is shielded from it. Groups of thermocouple detectors so constructed are more commonly referred to as thermopiles.

Detectors may be mounted in vacuo or in a gas, the choice of which affects the sensitivity, the response time and spectral response. The following equation and example will demonstrate how, using typical specifications from a commercially available thermopile, the MRT may be derived from the thermopile voltage output.

The radiant emittance, W, for any target may be determined by the following expression.

$$W = \epsilon \sigma T_T^4 \qquad \text{watts/cm}^2 \tag{22}$$

where:

ϵ = emissivity
σ = Steffan-Boltzman constant
= 5.67×10^{-12} watts/cm^2 °K^4, and
T_T = target temperature (°K)

If we want to use a thermopile detector to measure the temperature of the surroundings, we will start with the assumption that the FOV (field-of-view) of the thermopile is filled with a homogeneous temperature at some distance. For this condition the voltage generated by the thermopile V_{det}, can be expressed as follows:

$$V_{det} = A_D \epsilon_T \sigma R (T_T^4 - T_D^4) \tag{23}$$

where:

ϵ_T = target emissivity
T_D = detector case temperature (°K),
A_D = area of the detector (cm^2); and
R = detector responsivity (volts/watt)

Now if the temperature of the target filling the FOV has a temperature of 50°C (323°K) and the detector case temperature is 30°C (303°K) then, using parameters from a current manufacturer's data sheet, assume the responsivity is 15 volts/watt, and the active area 0.01 cm^2. If a value of 0.95 is used for ϵ_T, then V_{det} = 1.98 mV. This is a voltage level which could be amplified using low-noise, low drift operational amplifiers to produce an output compatible with recording devices or multiplexed telemetry units.

Equation 23 may be solved for T_T in terms of the independent variable T_D as follows:

$$T_T = \left[T_D^4 + V_{det}/(R \cdot A_D \cdot \epsilon_T \cdot \sigma) \right]^{1/4} \qquad (24)$$

Figure 4 shows a plot of this equation for values of V_{det} equal to 1, 5 and 10 mV where A_D = 0.01 cm and R = 15 volts/watt. It will be observed from this plot and the related equations that given any voltage out of the thermopile, the target temperature is indeterminate unless the detector case temperature (T_D) is known. Because of this requirement, an accurate use of these sensors would require a separate thermistor probe on each detector to measure its case temperature. As a first approximation, for the heat stress system, it could be assumed that the detector case temperature will follow the measured air temperature. Because of the large thermal mass of the thermopile detector housing, this assumption would only hold for nearly constant or slowly changing air temperature. For small differences between the case temperature and target temperature (i.e. V_{det} = 2 mV), the error in wall temperature is approximately proportional to the error in air temperature. At higher wall temperatures the slope of the curve relating the two parameters is less resulting in a lower absolute error for the approximation.

One class of thermocouple type detectors fall into the general category of pyranometers[19]. The pyranometer is designed to measure the intensity of solar radiation falling on a horizontal surface. The instrument is designed by dividing the sensing surface into a number of segments of which half are white and half are black. The reference junctions are beneath and attached to the white sections and the measuring junctions are in contact with the black sections. The black sections absorb more radiation and their temperature (T_b) is higher than the temperatures of the white sections (T_w). The difference in temperature generates a net potential which causes a current to flow in the thermopile circuit. This current is a function of the difference between the temperature between the "hot" and "cold" junction and is also a function of the average temperature, T of the thermopile. This relationship may be expressed as:

$$T = \frac{T_w + T_b}{2} \qquad (25)$$

If the pyranometer is calibrated at some predetermined temperature, its output will be in error whenever the temperature of operation is greater or less than the temperature of calibration. Thus, unless some other

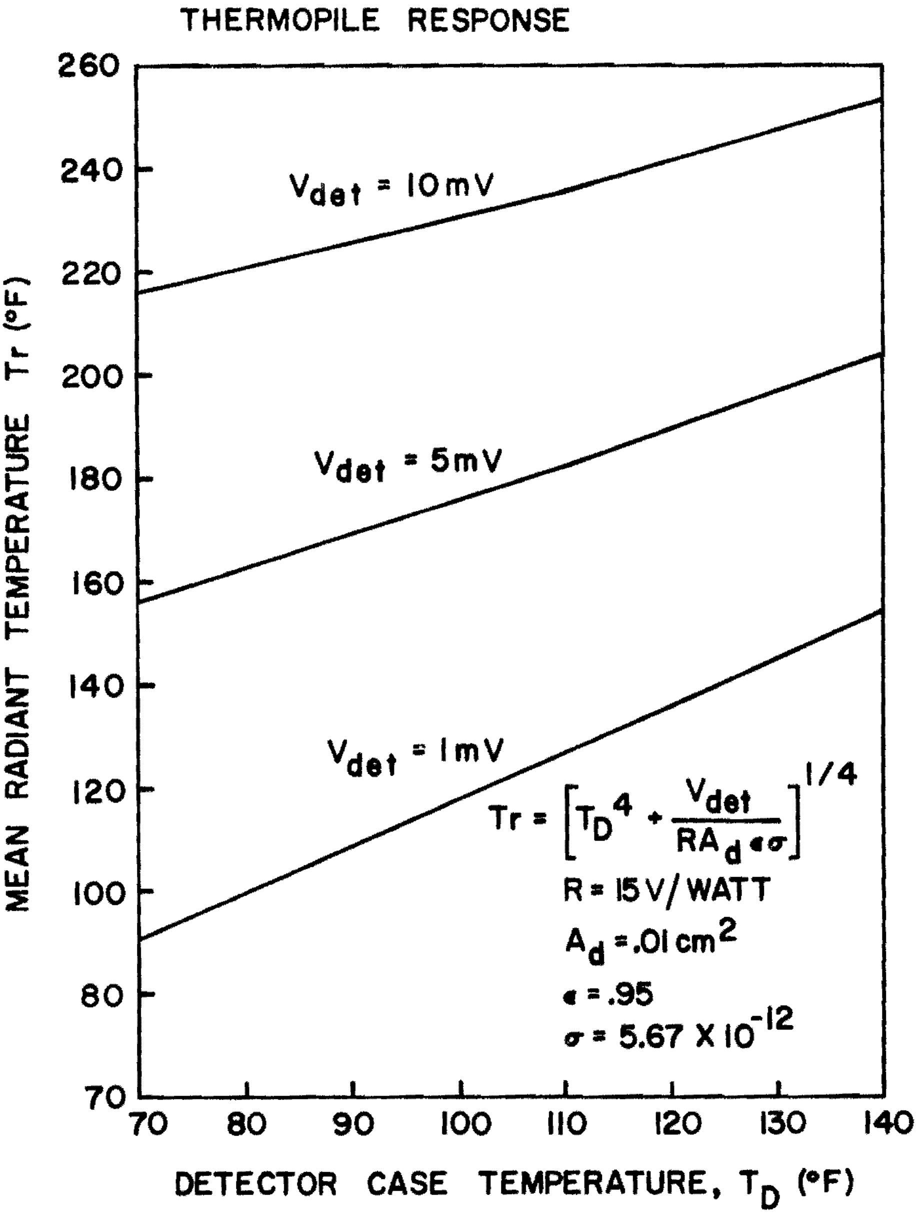


FIGURE 4. CURVES SHOWING THERMOPILE OUTPUT AS A FUNCTION OF MEAN RADIANT TEMPERATURE AND DETECTOR CASE TEMPERATURE.
DATA IS BASED ON PARAMETERS FROM A COMMERCIALLY AVAILABLE DETECTOR.

means is used to compensate for ambient variations, circuitry and hardware would need to be added to a portable system to maintain a constant reference temperature.

Another radiometer using thermocouples which has been developed by the Jet Propulsion Laboratory[20] has a uniform response over the entire UV, visible and on part of the infrared spectrum. This radiometer labeled the MK-IV consists of an internally blackened cavity, a thermal resistor, and the main body. The thermal resistor conducts the heat produced in the cavity to the main body, whose temperature must be held constant by controlled electrical heating or cooling of the main body. The temperature drop across the thermal resistor (measured by a thermopile), serves as a measure of heat flux through the thermal resistor which is a function of the incoming irradiance. The requirement for the controlled temperature of the main body would require heavy demands on a portable power pack and for this reason, this detector along with similar commercially available devices were judged not suitable for the heat stress monitor.

5.) Panradiometer

An instrument known as a Panradiometer was developed at Cornell University Medical College[21] in 1951. The device, intended primarily for outdoor use to measure bioclimatological heat exchange, employs four 6-1/2 mm diameter spheres: two highly polished, one painted white, and one flat black. The black sphere, which absorbs energy in the visible and infrared range becomes the hottest; the white sphere, which reflects much of the visible radiation and emits strongly in the low temperature range becomes slightly cooler than the air temperature due to heat losses by reradiation to a cool sky. The polished spheres, being almost totally reflecting in the visible range and only slightly less reflective in the infrared range become only slightly warmer than the ambient air. Each sphere is fitted with a thermocouple to measure its temperature and a heating element for adjusting its temperature. By measuring the power required to bring all of the spheres to the temperature of the hottest it is possible to calculate the total radiation and the average temperature of the surroundings. One of the polished spheres is used as a hot sphere anemometer to provide wind speed information during experiments. Although precise numbers for the time constants of the sphere sensors are not given in the description of the device, complete measurements for defining the radiant environment were obtained in 5 to 15 minutes.

The Panradiometer in its previously developed form is too large, too slow, and consumes too much power to be used in a personal heat stress monitor; however, the sensor technology utilized in its design indicates one approach which could possibly be applied after a considerable development effort.

7. Air Circulation Velocity Sensors

The review of methods and techniques for measuring air velocity provided information on several different methods. The method that is chosen for air velocity measurements as part of a personal heat stress monitor must be small enough and light enough to be easily carried continuously by the worker. It must not significantly infringe upon his ability to perform his job while carrying the sensor.

a. Laser Doppler Anemometer

One anemometer system that is suitable for measuring both very low and very high velocities is a laser Doppler anemometer[22]. This system makes use of the Doppler effect in which the frequency of light scattered from a particle changes in relation to the velocity of the particle. By comparing the frequencies of the scattered light with the original light, the velocity of the particles in the air flow can be determined. This method requires that a sufficient quantity of particles for light scatter exist in the flow stream. These particles may be added or natural. This anemometer requires a laser system, an optical system and sophisticated data reduction equipment.

b. Sonic Anemometer

Sonic anemometers[23] measure the velocity of the air by simultaneously sending two acoustic signals along the same path in opposite directions. The additive and subtractive effects of air velocity on the signal transmission cause a difference in reception times. This time difference in reception is a measure of the air velocity along the signal path. This system is linear for velocities appreciably less than the speed of sound. However, the transmission time differences become too small for short measuring paths at low air velocities, requiring longer transmission paths. The system is also directional and an omnidirectional system would require three mutually perpendicular signal paths and six transmitters and six receivers.

c. Ion Tracer Anemometer

Ion tracer anemometers[24] generate a small volume of ionized air which is carried by the air flow out to sensors positioned in a circle around the point of ionization. By knowing the travel time between the generator and the sensor and also which sensor was activated, both direction and speed can be determined. The system is very good for low velocity flows, but it requires a high voltage power supply and precision instrumentation and the system may not work well in an atmosphere high in contaminants.

d. Revolving Vane Anemometer

Many typical anemometers employ a vertical fan or revolving vane[25]. These usually consist of a light-weight revolving wheel, whose rate of revolution is related to air velocity. Each instrument requires an individual calibration and, at low velocities, the friction drag of the wind driven wheel is considerable. The instrument is highly directional, easily damaged, and needs periodic re-calibration.

e. Pitot Tube Anemometer

A standard method of measuring air velocities in a duct is with a pitot tube[25]. It is a simple method but highly directional. The pitot tube is used with a manometer. Because the accuracy decreases with a decrease in velocity, a precision manometer is required at low air flow speeds.

f. Transported Thermal Signal Anemometer

The transported thermal signal anemometers[26] operate in the same manner as the ion tracer anemometer. One thin, heated wire acts as a transmitter, generating the thermal signal. A second wire with a very slight thermal inertia is placed downwind and acts as a receiver by measuring the temperature of the air. The time required for the heated air to pass from the transmitter to the receiver is a measure of air velocity. The sensor can be made omnidirectional by using a series of receivers in a circle around the transmitter. The measuring range is typically 16 to 300 ft/min. The problem of thermal bouyancy of the heated air is a complicating factor, as is the problem of turbulence at faster flow frequencies. The instrumentation necessary is more complicated due to the timing requirements and the omnidirectional sensing head requires some precise manufacturing.

g. Cup Anemometer

For meteorological measurements of wind speed, the instrument that is almost universally used is the cup-anemometer[25]. It consists of a shaft from which three of four hemispherical cups are radially mounted. The air flow causes the cups and shaft to spin and the rate of spin is related to the air velocity.

h. Heated Thermal Sensor Anemometer

A convenient and practical method for measuring air velocities involves the use of a heated thermal sensor[27,28]. The technique involves heating the thermal sensor and exposing it to the air stream. The amount of convective cooling of the heated sensor by the air stream is a measure of the velocity of the air passing around the sensor. Several sensing elements can be used in this manner such as the heated bulb thermometer, heated thermocouple, heated thermopile, heated thermistor, hot wires or hot films. The instrumentation required is rather simple and power requirements are small. Usually the sensor is sensitive to flow direction but this can be alleviated through the use of three mutually perpendicular sensors or a change in sensor geometry.

1.) Heated Thermal Sensor Theory

The heated thermal sensor anemometer operates on the principle of convective heat loss from an artificially heated temperature sensor[29]. The thermal sensor is warmed by the electrical power into the sensor which is converted to heat, Q_j, by the Joule effect. The sensor quickly reaches an equilibrium condition in which the rate of heat generation is equalled by the rate of heat loss. This Joule heat being generated is matched by the heat the sensor loses through convection, Q_c; radiation, Q_R; and conduction, Q_D. This equilibrium relationship can be expressed as

$$Q_j = Q_c + Q_R + Q_D \qquad (26)$$

Conductive heat loss and radiant heat loss are both small compared to convective heat loss and can usually be neglected. Neglecting these components, Equation (28) can be rewritten

$$Q_j = Q_c \qquad (27)$$

Joule effect heat generation is governed by the electrical power input, P_E, while convective heat loss is a function of the air temperature, T_a; the sensor temperature, T_p; and the air velocity, v. These functional relationships can be written:

$$Q_j = f\ (P_E) \qquad (28)$$

$$Q_c = f\ (T_a,\ T_p,\ v) \qquad (29)$$

For an anemometer using a hot wire sensor, the equilibrium equation was found by Hinze[30] to reduce to

$$I^2 R_p = (T_p - T_a)\ (A + Bv^{1/n}) \qquad (30)$$

where

I is the current in the wire

R_p is the probe resistance
T_p is the probe temperature
T_a is the air temperature
A, B and n are constants for a particular fluid and sensor

For sensors with a linear relationship between resistance and temperature[31], the probe resistance is given by

$$R_x = R_o [1 + \gamma (T_x - T_o)] \tag{31}$$

where:

R_o = resistance at T_o
γ = sensor constant
R_x = resistance at T_x

Substituting this relationship into Hinze's equation yields

$$I^2R_p = [(\frac{R_p}{\gamma R_o} - 1/\gamma + T_o) - (\frac{R_a}{\gamma R_o} - 1/\gamma + T_o)] (A + Bv^{1/n}) \tag{32}$$

or

$$I^2 R_p = \frac{R_p - R_a}{\gamma R_o} (A + Bv^{1/n}) \tag{33}$$

Solving for velocity yields

$$v = \left[\frac{I^2 R_p}{R_p - R_a} (\frac{\gamma R_o}{B}) - \frac{A}{B} \right]^n \tag{34}$$

The same type of study can also be done for other sensors such as films, thermocouples, and thermistors but the basic result remains the same.

$$v = f (R_p, R_a, I) \tag{35}$$

2) Excitation Methods

There are many ways of exciting the sensor but two of the most common methods are constant current and constant resistance. In the first method, a constant current is supplied to the sensor, heating it. As it is cooled by the air flow, its temperature is reduced and, consequently, the resistance is changed. By measuring the voltage drop across the sensor, the resistance can be determined. A simplified constant current anemometer circuit is shown in Figure 5.

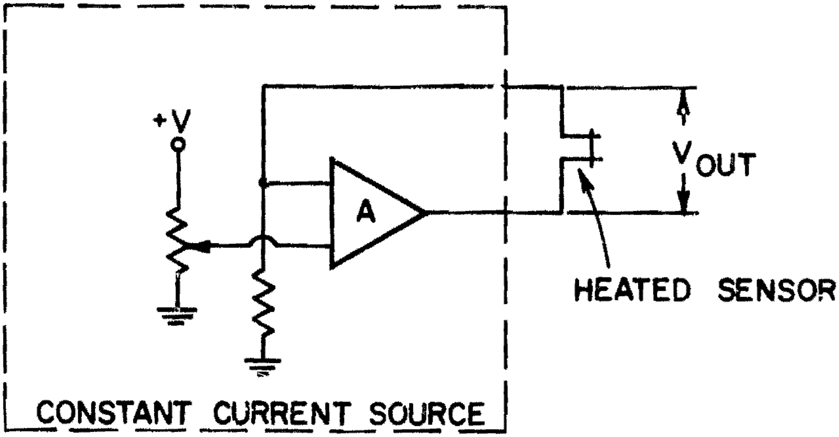


FIGURE 5. GENERALIZED CONSTANT CURRENT ANEMOMETER CIRCUIT

At high velocities, the difference in the output from the heated sensor for a given change in velocity is quite small, so reproducibility is more difficult to obtain. Also at high velocities, the wire temperature is reduced and the thermal loss through the supports may become significant. Because significant variations in probe temperature take place during flow variations, the thermal capacity of the probe limits the response time.

The method that has become more widely used is the constant resistance technique. Because of the temperature-resistance nature of the thermal sensor, a constant resistance implies a constant temperature. A feedback system is used to control the voltage to the thermal sensor. When the air flow cools the sensor and thus changes its resistance, the voltage e changes. This change in voltage causes the amplifier to increase the power to the thermal sensor, raising its temperature and thus restoring the resistance to its previous value. The power required to maintain the constant temperature and resistance, indicated by the output voltage, V_{out}, is a measure of the air velocity, (v). Figure 6 shows a simplified schematic of a constant temperature anemometer.

In a constant resistance feedback operation, the magnitude of the probe temperature variations is substantially reduced. This reduction in temperature excursion allows an improvement in the response time of the system. While the constant temperature technique lacks the simple circuitry that can be achieved with the constant current method,

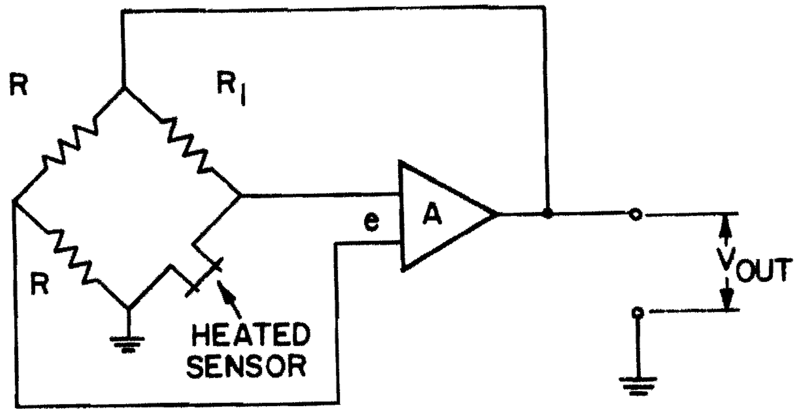


FIGURE 6. GENERALIZED CONSTANT TEMPERATURE ANEMOMETER CIRCUIT

it has become more popular due to the availability of linearization techniq'.es, higher frequency response, and greater accuracy for large velocity fluctuations.

For both of these techniques, the ambient air temperature must be monitored. One variation of the constant temperature method incorporates the ambient air temperature sensor in the feedback loop along with the heated thermal sensor. The heated sensor is then maintained at a constant temperature increment above ambient temperature.

3) Anemometer Calibration and Linearization

The constant temperature heated sensor anemometer is well suited for the measurement of fluctuating air velocities because of its short response time and good spatial resolution as well as its low velocity sensitivity. Accurate interpretation of the instrument response requires concise information concerning the heat transfer mechanism and the sensor geometry. Lack of this information forces a reliance on an empirical calibration for each sensor.

The typical heated sensor anemometer output is generally a nonlinear function. In some applications it is more convenient to have a linear voltage-velocity relationship. This can be accomplished electronically by generating the inverse function of the voltage-velocity relationship. The output signal of the constant temperature anemometer is applied to this linearizer and its output signal will then be proportional to velocity.

8. Data Acquisition

The function of the data acquisition section of the heat stress monitor device is to condition and record the output of the five sensors in such a manner that the data can be successfully retrieved and analyzed as required. The basic guidelines are that the data acquisition section does not degrade the accuracy, range, and response time of the retrieved data and that sufficient recording capacity is provided to record all variables for the required two hours. The system must also meet the human factors considerations of size, weight and ease of operation. While it is not part of the objective of this report to survey or establish design approaches for such a data recording device for use with the personal heat stress monitor, it is beneficial to develop and maintain an awareness of the data recording requirements as a factor in selecting the most desirable system.

A vast amount of effort and research has been performed in measuring and analyzing heat effects on man in his working and resting environments. In general, the bulk of the measurements have been made using stationary instrumentation setups employing the established temperature, humidity, and air circulation velocity sensors described above. Much of the instrumentation has been standard general purpose meteorological and medical equipment designed for use with companion data recording devices.

Medical instrumentation is advancing rapidly beyond the traditional techniques of clinical mercury thermometers, manually acquired heart rate and hand written records and, consequently, recording instrumentation for these parameters is becoming more available. Most of these systems are power-line operated, and are relatively large single-parameter instruments not readily adapted to the portable use requirements of a personal heat stress monitor.

The requirements for large amounts of active biological data for aerospace applications has resulted in the development of a number of advanced systems for monitoring and telemetry physiological parameters. Mansberg[32] describes a multichannel body temperature measurement system capable of continuous monitoring of 24 separate thermistor sensors attached to a subject while performing specific activities. In this wire-connected system, data was recorded on a stationary digital printer as it was acquired.

There has been no specific development of a heat stress monitoring system which attaches to a subject and yet completely frees him of wires connecting to a recording system. To avoid the wire link to recording instruments in other similar applications, portable telemetry instruments have been developed to transmit the measured data to remote recording systems[33]. A small lightweight telemetry transmitter, transmitting data to a remote recording system, offers an excellent method of acquiring the environmental measurements required in the personal heat stress monitor. Available state-of-the-art telemetry transmitters and receivers are easy to use and provide reliable operation over a wide range of environmental conditions.

Another alternate method for heat stress data acquisition which would prove to be truly portable in any location with essentially no setup time and which may be more economical in comparison to wireless telemetry, particularly in large quantity, would entail the use of a small magnetic tape recorder of the cassette type attached to the subject's body. The measured data could be commutated into a single channel recorder in an easily retrieved format for later linearization, processing and analysis. The five variables will have to be sampled at a rate that is consistent with the response time requirements. The 30-second response time of the temperature sensors infers a minimum sampling rate of approximately 0.15 Hertz for each of these variables. The two-second response time requirement on the air velocity measurement infers a sampling rate of approximately 2.5 Hertz. If all of the variables are sampled at this rate, the sampling clock rate would be 5 x 2.5 or 12 Hertz. This indicates a very minimal bandwidth requirement by modern recording standards since at a tape speed of 1-7/8 ips (normal cassette tape speed), intermediate band FM recording techniques will give a bandwidth from dc to 625 Hertz.

III. DESIGN OF A HEAT STRESS MONITOR

The packaging of the monitor unit must take into account not only the sensor requirements but also the human factors involved. The placement of the sensor units and recording system on the subject must be such that it allows him to perform his work tasks in a normal manner. It must also be comfortable and not produce additional fatigue.

The most logical point of attachment for three of the sensors is on a helmet or hard hat. Since many work areas require protective head wear, the wearing of a hard hat or helmet containing sensors will not be particularly unnatural. Above the head of the subject is also the location which has the clearest omnidirectional field of view of the environmental surroundings and the hat can provide shielding from the subject's body heat and moisture. The disadvantages associated with using the hard hat for sensor mounting is the possibility of compromising the safety aspects of the head gear. Any protrusions near the inner liner have the potential for causing lacerations to the scalp under the duress of a severe blow to the helment. Secondly, apparatus protruding above the normal contours of the outer surface of the hat reduces the clearance between the workers head and low overhanging objects.

Figure 7 shows a picture of a mock-up for the recommended hat mounting of the mini-sphere radiation sensor, the air velocity sensor and the natural wet bulb thermometer. Since these three sensors all require an omnidirectional view of either thermal radiation, air velocity or a combination of the two, this location will provide the "least impaired" position on the worker. The globe sensor as shown here is mounted on a shaft. An alternate mounting scheme is given in the discussion which follows. More details concerning all the recommended sensors are included in the discussion which follows.

The remainder of the sensors, the signal conditioning electronics, batteries and telemetry unit or tape recorder can be conveniently mounted on the subject's belt. All of the necessary signal conditioning electronics could be contained in one small package mounted on the belt; however, to minimize package size and power consumption, there should be a minimum of processing of the data before it is recorded. This, of course, means that any linearization and scaling that is required to make the data useable will have to be performed later at the time of data analysis.

A. Air Circulation Velocity Sensor

A review of the current technical literature and the existing manufacturers' information quickly reduces the number of instrumentation

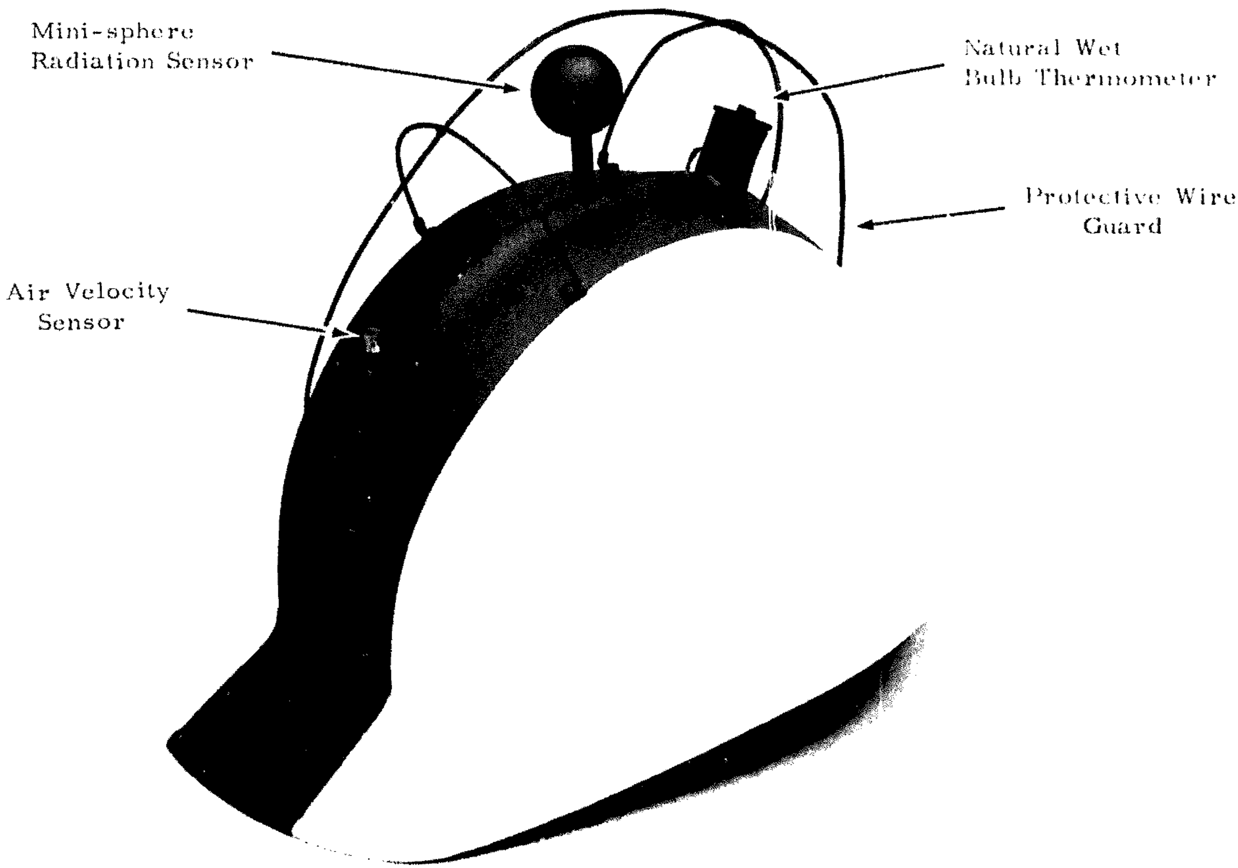


FIGURE 7. MOCK-UP OF HARD HAT SHOWING PLACEMENT OF AIR VELOCITY, THERMAL RADIATION, AND NATURAL WET BULB SENSORS

possibilities for an anemometer for use on a personal heat stress monitor. The instrument must be lightweight, rugged, small and require little power. The revolving vane and the pitot tube are highly directional and not adequate for low velocities. The laser Doppler method is complicated, bulky, and highly specialized. The sonic, ion tracer and transported thermal signal anemometers require complex instrumentation and may not be easily adapted to the environmental conditions. Use of some type of heated thermal anemometer seems to provide the best trade-off between portability and accuracy.

Several manufacturers offer an off-the-shelf air velocity sensor that could be adapted to fit the requirements of the program. One company offers an extensive line of hot-wire and hot-film probes which have a high frequency response because of their small size and mass. They are, however, fragile and are subject to particle contamination. Since the probes will not be used in a laboratory environment, the fragility and sensitivity to contamination are serious handicaps. At least three other companies manufacture portable anemometers that are more suitable for the program objective. One of these employs a hot wire system using a stainless steel wire instead of platinum. A second manufacturer uses a heated thermopile composed of three thermocouple junctions. A third uses a heated platinum wi e wound on a 1/32 inch alumina rod. These instruments are far more rugged and less sensitive to particle contamination. Any of these instruments could easily be adapted to a personal heat stress monitor. For this application all that is required would be the probe and the electronics. The standard analog meter, case, and battery as furnished by the manufacturer are all unnecessary since the anemometer will be powered by the same source as the rest of the sensors and the information will be either recorded or telemetered. The response times for the probes are less than the specified 2 seconds and the total power required for the electronics and the probes is approximately 0.5 watts. The electronics generally fit on a small printed circuit card, so size is not a problem.

One of the drawbacks is that at low velocities, approximately 100 fpm or less, the accuracy drops below the target accuracy of 2.5%. This drop off in accuracy may be due in large measure to the analog meter. Since the proposed system will not employ the analog meter, the inaccuracies may not be as large. A precise calibration of the sensor as it is mounted on the system will increase the accuracy for low velocities. The output of the sensor is nonlinear, generally logarithmic, but linearizing circuits are available if a linear response is desired.

Of the heated thermal anemometers commercially available, the type that most closely approaches the optimum for this application is the element that employs a heated platinum wire wound on a 0.032 inch alumina rod. The principal advantage of this sensor is its insensitivity to particulate contamination due to its size. The size and rugged construction also make the probe much less fragile than other thermal anemometers.

The probe contains a second temperature sensor to monitor the ambient room temperature while the electronic circuitry maintains the heated sensor at a constant temperature above ambient. The electronic circuitry is contained on a 3 x 3 inch printed circuit card and power requirements for the instrument varies between 0.3 and 0.6 watts, depending on air velocity. The output voltage can easily be adjusted to accommodate various ranges. A typical voltage-velocity curve scaled for a 0 to 5 volt range is shown in Figure 8.

The anemometer can easily meet the 2 second response time and the accuracy can be brought to within ± 5 fpm + 3% of reading. The sensor has an omnidirectional field of view for flow perpendicular to the sensor axis and has a cosine response for out of plane flow. Thus for flows impinging on the sensor at an angle of 45° from the normal of the sensor axis, the signal would be decreased 3 dB. This response should be adequate for most situations but, if a more precise response is needed, three mutually perpendicular sensors could be used.

The velocity probe can be mounted on the top of a safety helmet where it would have the best omnidirectional view. The electronics card can be placed in a belt pack with the connecting wires running up to the back of the worker's helmet. The sensor should be protected from impact against solid objects by some type of protective wire guard or a fine wire screen. A wire guard should be several inches from the sensor to reduce the possibilities of a "shadow" effect on the sensor. A fine wire screen placed completely around the sensor will prevent damage but would require a recalibration of the sensor with the screen to correct for flow variations.

Generally a sensor should be one diameter away from any obstacle in the path of the air flow in order to measure an undisturbed air velocity. For a helmet mounted probe, the sensor would have to extend approximately 8 to 10 inches (the approximate diameter of the head) from the helmet. For this application, however, extending the probe out from the helmet would be inadvisable. With an extended probe, any movement of the head would be amplified at the sensor, the probe essentially acting like a whip. This would cause the sensor to provide high artificial velocity measurements. A probe mounted 1 to 2 inches above the helmet appears to be a good compromise position to provide accurate air velocity measurements.

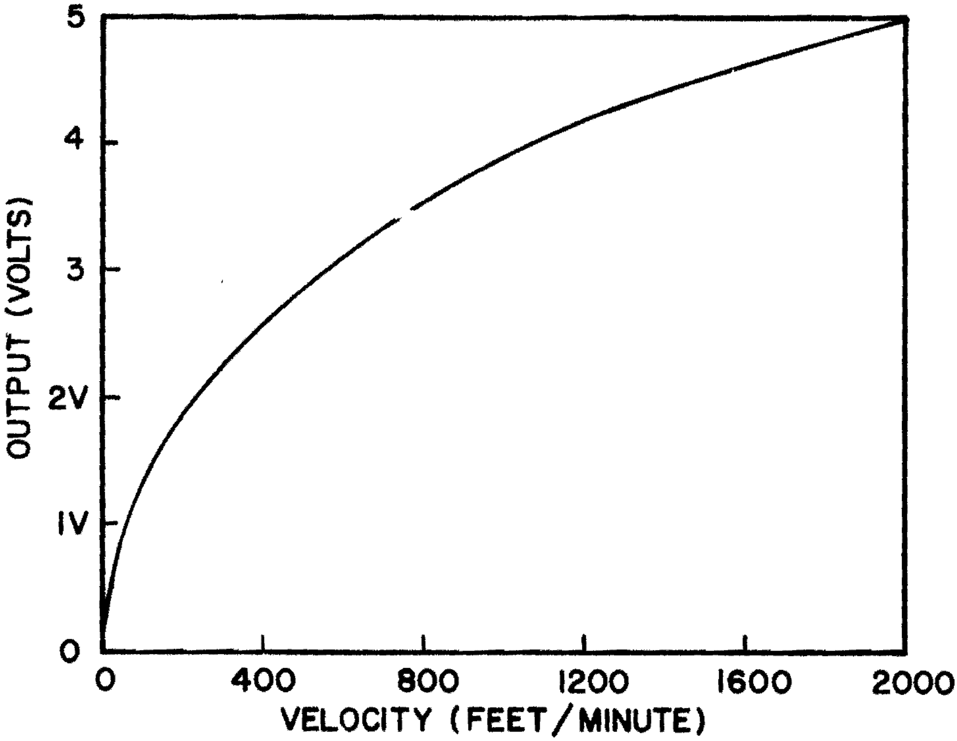


FIGURE 8. TYPICAL TRANSFER FUNCTION FOR A HEATED THERMAL SENSOR ANEMOMETER (DATA COURTESY OF SIERRA INSTRUMENTS)

B. Wet Bulb and Dry Bulb Temperature

1. Aspirator

As previously discussed, the measurement of wet and dry bulb temperatures can be greatly facilitated by the proper use of an aspirator. Figure 9 is an illustration of the recommended package design for a belt-mounted aspirator and electronics assembly. Figure 10 is a drawing of the package with the covers removed for illustration. It can be seen that air is drawn over two sensors, one for the dry bulb, and another wetted sensor for the wet bulb temperature. The air is drawn through a protective screen and then the flow is divided so that part of it is diverted over the wet bulb and the rest flows over the dry bulb. The flow over the sensing elements is roughly perpendicular to that at the air intake. This arrangement allows the sensors to be shielded from direct radiation. The walls of the air channel are made of polished stainless steel to minimize thermal emissivity. After the air passes over the sensors it passes through the axial flow fan blade and over the motor. This aids in cooling the motor so it does not become a heat producing source. The air is then exhausted through two perforated areas on the side and back of the aspirator package.

Water for the wet bulb thermometer is placed in a compartment below the aspirator. The wet bulb sensing element passes through the top of the water container and is surrounded by a tight fitting wick. The wick-covered portion of the sensor extends approximately one inch into the aspirated area to insure proper evaporative cooling of the water supplied to the sensing area. The wires from the wet bulb sensor exit the water reservoir through a separate sealed opening. The water supply is spill resistant due to the constrictive nature of the wet bulb sensor orfice.

The dry bulb sensor is suspended in the other aspirator channel and separated from the wet bulb sensor by a shield. Its leads are routed to the electronics compartment.

The size of the two channels is designed so that the motor/fan combination will draw air over the sensor at a rate greater than 900 ft /minute. The intake and exhaust ports have enough area so that pressure dropped across them is not significant.

The fan motor is connected directly across the unregulated battery voltage. Regulation is not necessary if the motor is selected such that the required air flow is obtained with minimum battery voltage.

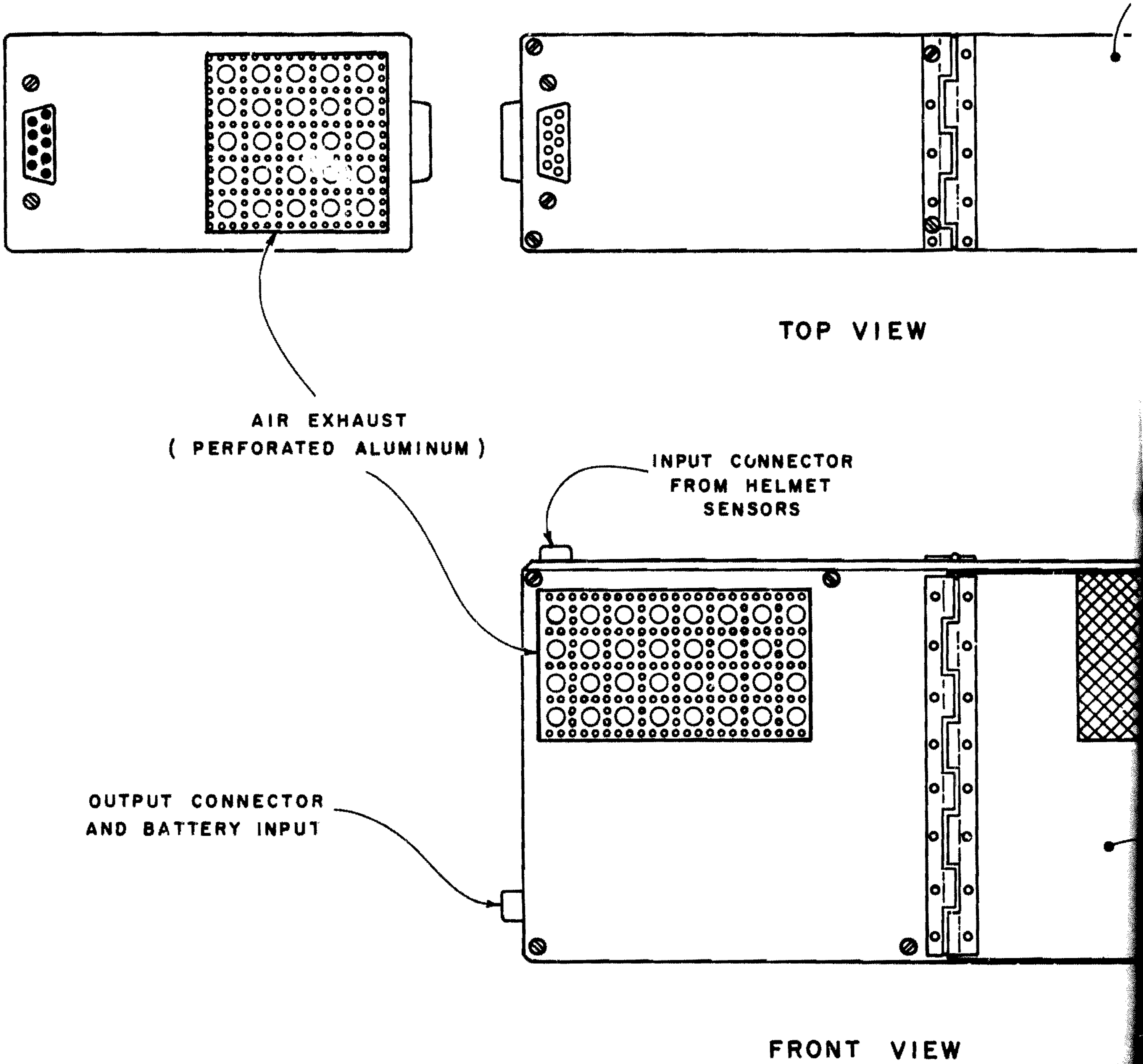
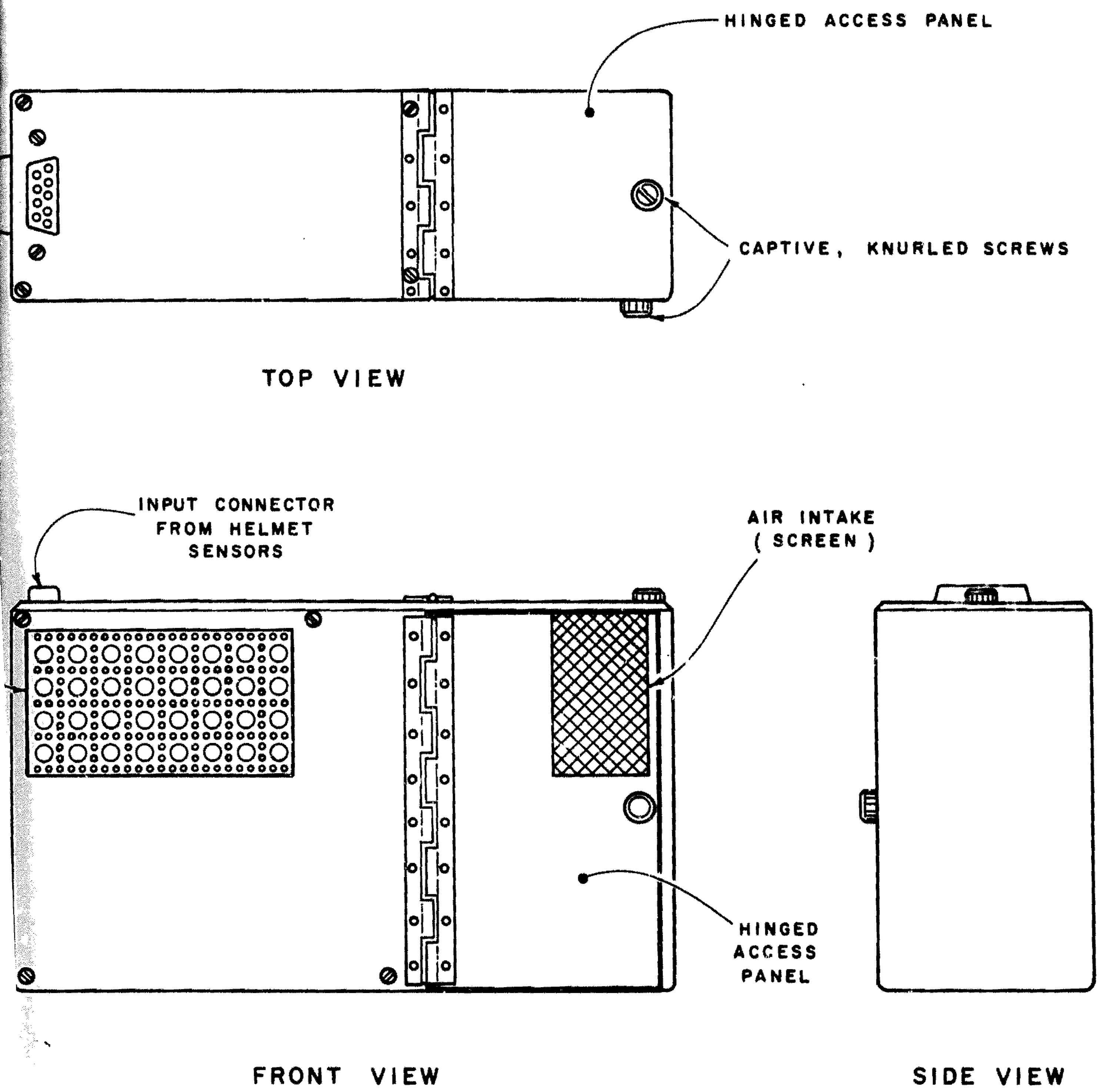


FIGURE 9. ILLUSTRATION OF BELT PACK CONTAINING
ASPIRATED WET BULB, DRY BULB AND SIGNAL CONDITIONING CIR



URE 9. ILLUSTRATION OF BELT PACK CONTAINING
WET BULB, DRY BULB AND SIGNAL CONDITIONING CIRCUITS

The motor selected should be a permanent magnet direct current motor with the following general specifications (based on commercially available motors):

Voltage - 12 volts
Current (no load) - 0.25 amperes maximum
Peak Torque (stall) - 4.0 oz.-in. minimum
No Load Speed - 6,000 $\pm$ 1,000 rpm
Weight - 8.0 ounces max.
Size: 1.3 inches diameter, maximum
2.3 inches long, maximum
0.5 inch shaft extension maximum

The motor should also have a bracket or other suitable method for attachment. The fan selected should be approximately 1.37 inches in diameter and have a suitable mounting hub for attachment to the motor shaft. The pitch and number of blades should be such that approximately 8.0 cubic feet per minute of air is displaced at a fan speed of 6,000 rpm with no back pressure. If the design of the motor is such that rotation is in only one direction, rotation of the fan/motor combination has to be such that air is blown over the motor.

2. Dry Bulb Sensor and Electronics

The design of the electronic circuitry will depend partially upon obtaining signal compatibility with the recording or telemetry system used. If a telemetry system is used, several circuits have been developed that change temperature to a numerically equivalent frequency. Williams[34] and De Kold[35] have presented circuits which are comprised of an oscillator whose frequency varies linearly with temperature. The design discussion which follows will not use this approach.

One of the primary considerations in the design of the temperature sensors has been in reducing the response time. Methods are available which can compensate for thermal time constants. Praul[36] and Freymuth[37] have presented methods which can make temperature sensors react at a speed limited only by the electronic time constant of the circuits involved. These methods are not thought to be necessary since the requirements for the personal heat stress monitor can be met with less complex measurement techniques. All of the specifications and requirements for the measurement of the dry bulb temperature can be easily met with the use of a linearized thermistor composite in an aspirator. This can be accomplished with a minimum of associated electronic and compensation networks. One such thermistor composite which consists of two thermistors in a 0.08 inch diameter by 0.150 inch long bead has a time constant of 10 seconds in free, still, air. The 95% response time in an aspirated system would be well within the 30-second requirement. Of all of the measurement methods reviewed that could meet all of the requirements, this particular thermistor composite required the least amount of signal conditioning and amplification. The thermistor values and the resistor composite values are shown on the schematic diagram for the typical temperature circuitry in Figure 11. A one volt excitation signal is supplied to the composite sensor. The output of the composite is connected to an operational amplifier buffer stage. This stage is needed to supply a high load impedance for the sensing network. The feedback resistor in this stage is made to be approximately equal to the composite's output impedance to provide minimum error due to input bias current. This circuit provides a very high input impedance.

The output of the buffer stage is connected to an amplifier/offset stage. This second operational amplifier offsets and amplifies the temperature signal to a suitable output level. The gain is adjustable by varying the feedback resistance, and a dc offset adjustment is provided by a potentiometer bias adjustment. This circuit may be calibrated during manufacture, and then periodically checked by comparison with a known accurate thermometer, or by calibrating it with a known temperature source.

The operational amplifiers should have exceptional temperature stability, high common mode rejection and high common mode voltage range. These precision operational amplifiers should be latch proof, short circuit protected, and have offset voltage nulling capabilities. The amplifiers must be capable of operating from a low voltage supply with low power requirement.

The frequency response of the amplifiers should be set to the lowest feasible value in order to reject unwanted ac signals and interference. Since the time constant of the sensors will be greater than about five seconds, the maximum bandwidth required is only approximately 1.0 hertz. The operational amplifiers bandwidth may be limited to this value by compensating circuits or by placing the suitable value capacitor across the feedback resistors as shown in Figure 11.

The thermistor sensor assembly itself is suspended in the rear channel of the aspirator. The last 0.5 inch of the three leads are unsupported so that their support does not provide a thermal path to the sensing bead. Small insulating tubing is used to support the very thin leads of the thermistor composite where they enter the bottom portion of the aspirator assembly. These leads are routed to the electronics compartment where the two fixed resistors of the composite are located.

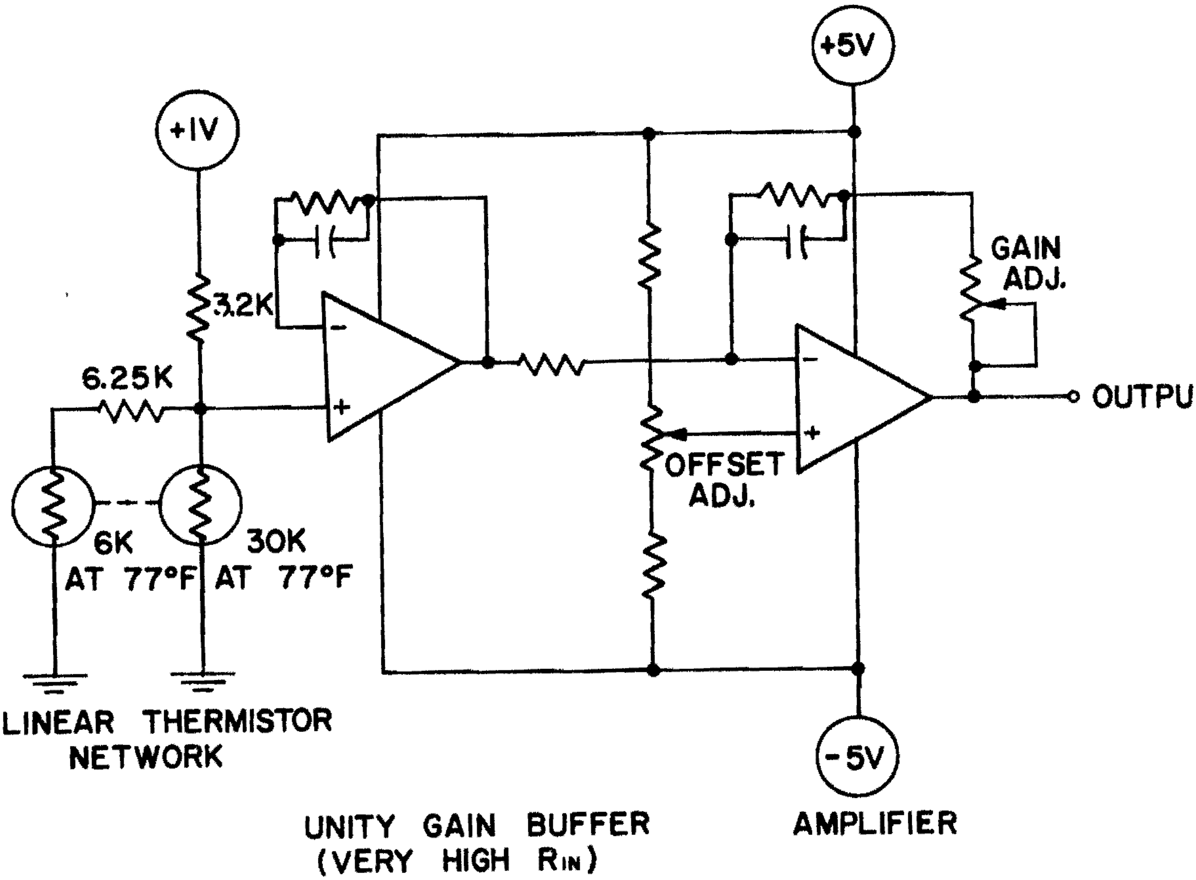


FIGURE 11. TYPICAL TEMPERATURE SENSING CIRCUIT FOR DRY BULB, WET BULB, AND NATURAL WET BULB TEMPERATURES

3. Wet Bulb Sensor and Electronics

The wet bulb sensor can be the same type as the dry bulb thermistor composite with the exception that it be furnished in a small, flexible probe with a vinyl sheath and tip or in a sealed, thin wall stainless steel tube. If the stainless steel tube is used, an alternate arrangement for the wick and water reservoir must be used. This alternate design would be similar to that used in conventional glass thermometer wet bulbs.

The electronic circuitry for the wet bulb temperature is similar to that used for the dry bulb temperature. The only differences would be a change in the gain and offset to accommodate the difference in temperature range.

C. Natural Wet Bulb Temperature

The natural wet bulb sensor is mounted on the helmet as shown in Figure 7. It is composed of the same type thermistor composite as the wet bulb thermometer. The water reservoir assembly is similar in construction to that used for the aspirated wet bulb. Care must be taken to separate the natural wet bulb sensor from the other sensors so that natural air flow and radiation are not blocked. The electronics assembly will be identical to that used for the aspirated wet bulb thermometer.

Figure 12 is a schematic showing the wiring diagram for the hard hat assembly. In this schematic a two-thermistor composite is used for the natural wet bulb thermistor probe and the globe temperature thermistor. In the sections related to the instrumentation for these parameters, other options are suggested which if used would alter sensor design and hence this schematic.

D. Thermal Radiation Sensor

For the dry bulb temperature, wet bulb temperature, natural wet bulb temperature and air velocity parameters, a variety of sensors or sensor systems are commercially available which nearly meet or meet the desired design goals and general requirement of the heat stress monitor. However, this flexibility of choices does not exist for instrumentation to measure the 6-inch globe temperature. There is no simple sensor device available that will provide precisely the same integrated output temperature reading as the 6-inch black globe. In light of this nonavailability of instrumentation, two methods for meeting the requirements of the portable heat stress system are outlined in the sections which follow. Both methods will require a considerable amount of development effort to design and test the feasibility of the method.

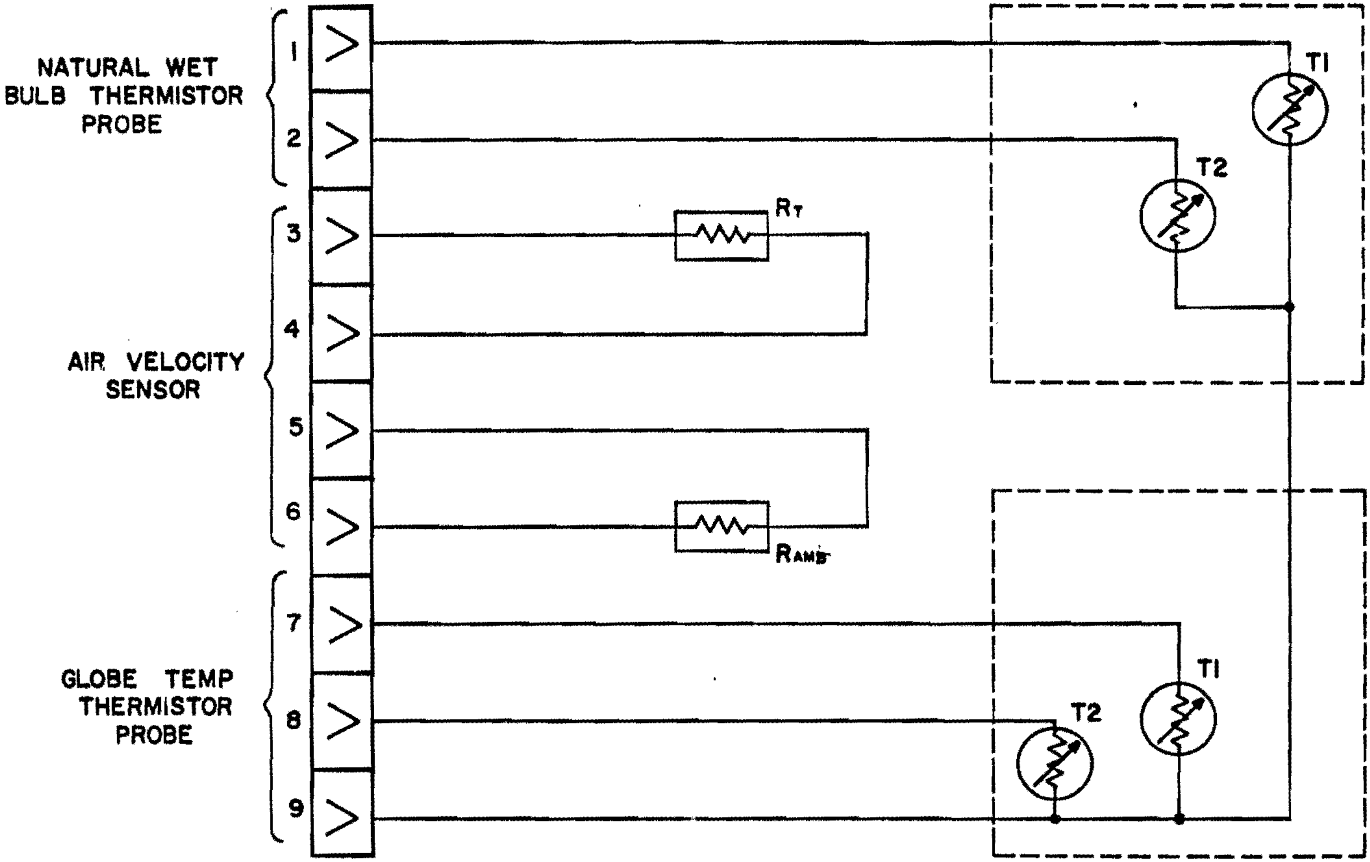


FIGURE 12. SCHEMATIC DIAGRAM OF HARD HAT ASSEMBLY

1. Mini-Sphere Globe Sensor

In light of the theory and experimental evidence presented in the Section II-C-6, it should be possible to design and construct a small globe thermometer with a diameter of 0.5 to 1.0 inch giving an output temperature reading which may be converted to an equivalent 6-inch globe temperature. Larger globes typically are made of copper with a wall thickness of 15 mils or more. Since the rigidity of a spherical shell increases with decreasing diameter for a given material, it is possible to construct a thin-walled, small globe that will still perform satisfactorily. Even though the thin-walled sensor will be more susceptible to damage than the globes presently being used, Graves[12] showed that a shell can sustain severe denting and still perform satisfactorily. Graves also reported that tests on globes of differing design showed that an aluminum shell was found to respond faster than copper of the same thickness. This is a predictable result since the product of density and specific heat for aluminum is about 36% smaller than that for copper.

A suggested design for the globe thermometer is shown in Figure 13. It is felt that this design is a definite improvement over the one shown in Figure 7. The sphere suggested here is a thin-walled aluminum or copper sphere supported by a nylon filament stretched between two supports mounted on the top of the helmet. In addition to the mechanical support, these members of the apparatus serve as part of the protective guard for the three sensors mounted on the helmet. A third piece of nylon thread, chosen for its strength and low thermal conduction, is mounted vertically between the sphere and the support to prevent rotation about the horizontal support. All nylon threads are fastened to the support and sphere using small amounts of epoxy. This type of sphere will be relatively inexpensive to construct and if damaged, the thermistor element can be recovered and reused.

Heat flow along the electrical leads of the thermistor used in the globe can cause serious errors in temperature measurements. The leads external to the sphere will assume some temperature near the ambient air. At the point of penetration through the shell wall, a temperature between that of the external leads and the shell will be reached. If the feed-through temperature is significantly different from the rest of the shell, conduction down the sensor leads may result in an erroneous reading for the globe temperature reading. To minimize this error, the leads coming from the thermistor should be of low thermally conducting wire and may be coiled to give them more length, thus lowering the temperature gradient along the wire. It should be noted that too much coiling would add thermal mass and may increase the response time. Also, thermally insulating the lead wires from the sphere at the point of penetration will reduce the temperature interaction alluded to above. This may be achieved by using low conductance epoxy to secure the thermistor leads near the nylon support filament.

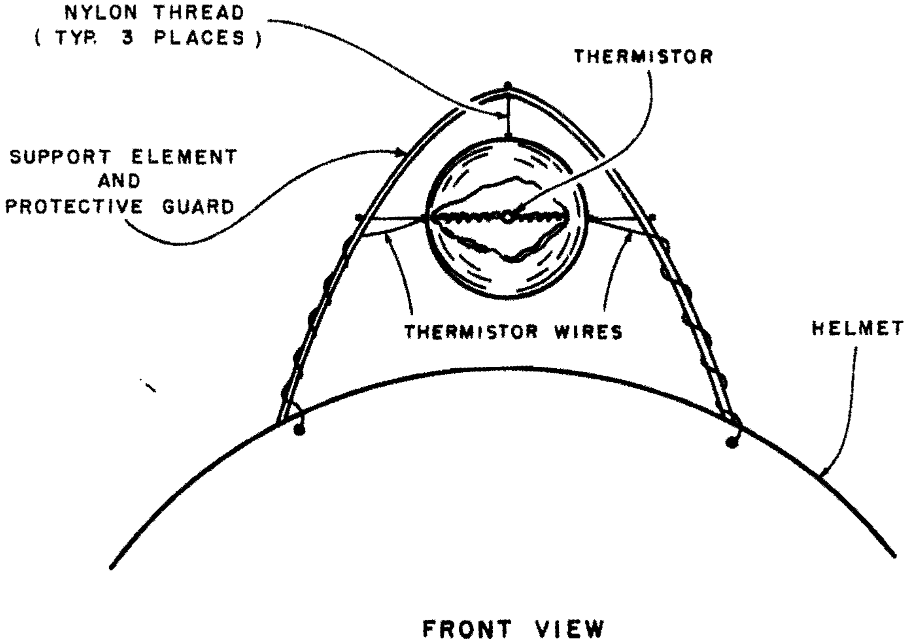


FIGURE 13. SUGGESTED DESIGN FOR A SMALL DIAMETER, LOW THERMAL MASS GLOBE SENSOR (MINI-SPHERE)

The linear composite type of sensor used for the dry bulb temperature has a maximum temperature limit of 212°F. If the full specified temperature range of 70°F to 250°F is desired for the mini-sphere globe sensor, an alternate temperature sensor must be used. Another bridge-type sensor that utilizes a positive coefficient semiconductor to obtain a linear output is commercially available. It has a temperature range of -50°F to 350°F (-46°C to 177°C) with a sensitivity of 2.5 mV/°F with an excitation voltage of 5 volts. The linearity is ± 0.75%. The package size is 0.2 x 0.2 x 0.0625 inches. The response time of the temperature sensor is much faster than that expected of the minisphere. If this sensor is used, a slightly different electronic circuit would be used. Figure 14 is a circuit diagram which consists of a single operational amplifier stage.

Since the minisphere is subject to more convective cooling than the larger 6 inch sphere, it will not reach as high a temperature under similar radiation conditions. Therefore the 250°F maximum temperature requirement may be relaxed somewhat since this temperature is not likely to be reached. In this case, in the interest of conformity, the same linearized thermistor composite type which was used in the dry bulb sensor may be used. The electronics circuitry would be the same as that for the dry bulb temperature except for the value of some components, which would be adjusted to accommodate wider temperature range.

Kuehn[14] has investigated the response of the globe with respect to the gas contained within the globe. Since part of the time response of the globe is determined by the conducting medium within the globe, then a gas with a high thermal diffusivity should decrease the response time. Helium would be a good choice for the gas since its thermal diffusivity is about eight times that of air. Data presented by Kuehn shows that indeed the fastest acting globes were the helium filled ones.

For a thin wall, small diameter globe as proposed here, a hermetically sealed unit filled with helium would be difficult to fabricate. It is likely that to construct such a device would require additional sealant which would offset any thermal improvements made by using the helium interior.

To make static calibrations on the small globe thermometer, place the mini-sphere along with a 6-inch globe in a wind tunnel with uniformly heated walls that present a nearly complete enclosure to the globe. The air flow through the tunnel should be as uniform as possible. A tunnel suitable for this test should have wall heaters to provide preset temperatures anywhere between air temperature and 250°F. Air speed should be adjustable between the limits of 10 and 2000 ft./min. The air temperature needs to be variable over the range of 70°F to 150°F. Although the sensor should be tested as mounted on a hard hat type helmet, the air velocity should be measured by an anemometer removed from the helmet to obtain the highest accuracy for this parameter.

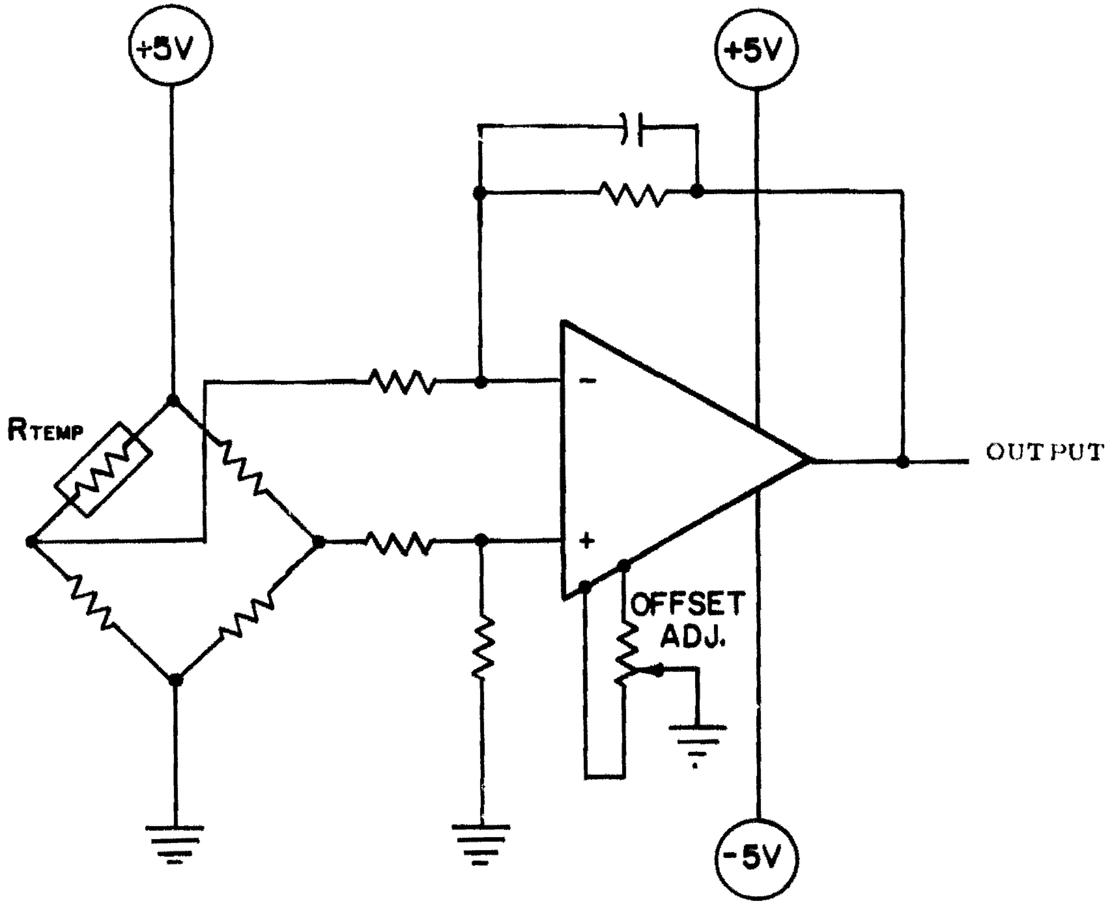


FIGURE 14. TEMPERATURE SENSING CIRCUIT FOR GLOBE TEMPERATURE

To test the time response of the sphere, preheat the device to a temperature well above the air stream (250°F) and then quickly insert into the air flow which has been previously adjusted to the desired conditions. To record the data, a continuous record of the globe temperature should be made on a recording oscillograph or similar analog device. The transient response so recorded will provide the necessary data to determine the time constant for the sphere. The equilibrium temperature will be used to compute a 6-inch globe temperature.

It is recommended that a number of test globes with varied wall thickness and sphere diameter be constructed to test the accuracy of the sensor and to measure the time response as a function of the physical configuration. For all tests, the thermistor needs to be centered within the sphere. It should be noted that although the varying of globe material, diameter, and thickness has a direct bearing on the time response, in general, globes with equal diameter will perform similarly with respect to the equilibrium temperature.

One factor which must be considered in developing an accurate globe sensor for use on the helmet, is the emissivity of surface of the helmet within the field of view of the globe. If the surface is a flat black (ϵ = .95), this surface will appear cool to the globe sensor and will cause an abnormally low temperature reading in the globe because of the radiant thermal losses. On the other hand, a shiny surface such as highly polished aluminum (ϵ = .04), polished brass (ϵ = .03) or chromium (ϵ = .08) will provide a reflective surface which will be a thermal barrier between the sphere and the helmet. A reflective shield such as this would have the disadvantage of mirroring hot spots to the sphere, giving the sensor larger than average field of view for certain orientations. Because of the curvature of the helmet, and the diffuse nature of the reflection, this should not be a serious problem but needs to be considered in testing the mini-sphere. It is possible that the optimum surface will be some intermediate value such as aluminum paint (ϵ = .5). The emissivity of aluminum paint can be varied somewhat by changing the ratio of aluminum to lacquer in the liquid state.

2. Thermocouple Detector

The mini-sphere discussed in the preceding section has the advantage of having a uniform response over a nearly 4π steradian field of view and is simple and inexpensive to construct. The disadvantages of the sphere include its slow response and vulnerability to mechanical damage. An alternate approach to measuring the thermal radiation (Section II-C-6-f) is the thermocouple detector or thermopile.[38] These detectors, having a fast response time measured in milliseconds, are self calibrating and relatively rugged compared to a thin walled sphere. The cost for a sensitive thermopile may be in the area of $300 per detector.

To configure a number of these sensors for an integraded, uniform field of view is very difficult but a good approximation may be made as will be shown.

The thermopile detector may, at the time of manufacture, be varied within limits for any FOV (field of view). This adjustment is made by changing the distance between the active flake and the detector window. Since the detector has a cosine response with maximum sensitivity normal to the plane of the detector element, an angle of 45° with respect to normal is the maximum field of view which can be tolerated. At this angle the voltage response is 0.707 (-3 db) times that at normal incidence. Using these limits then as the FOV, four of the detectors mounted in a horizontal plane, at equally spaced intervals around the perimeter of the helmet will cover a FOV of representing about 59% of the total 4π steradians. A fifth sensor mounted in the top of the helmet looking up towards the sky will provide the additional coverage with no overlapping of the 0.707 response curves. The net effect then for this placement of sensors is a coverage of 88% of the upper hemisphers. This orientation for the detectors leaves a downward looking portion of the total FOV which is not visible by the sensors. While this gap does not provide a parallel to the 6-inch globe as presently used, it does approximate that seen by a mini-sphere as discussed in the preceeding section.

Typical resistances for commercially available thermopile radiation detectors range from 2k to 30k ohms. Thus as a group, they are easily adapted to signal conditioning by commercially available monolithic operational amplifiers. Since, based on the plot shown in Figure 5, the detectors outputs may be 1 mV or less, it is recommended that a quality chopper stabilized operational amplifier be used for amplifing the thermopile output. On the upper end of signal amplitudes, the output may be as high as 10 mV. Therefore, if the signal range for the recording or telemetry instrumentation is 0-5 volts, the amplifier gain should be 500 (54 dB). Because of the 30 second response required for this detector, the operational amplifier may be configured as a low pass filter by putting a capacitor from its output to the inverting input.

Since the desired output from the thermopile detectors is an integrated sum, the operation amplifier is configured as an adder with separate summing resistor for each detector. The individual response on the detectors may vary from unit to unit so these resistors should be individually adjusted for a uniform response.

The discussion in Section II. C. 6. F pointed out the fact that MRT cannot be accurately determined unless the detector case temperature is known. It was also pointed out that as a first approximation, the case temperature may be assumed equal to the air temperature and use this value to calculate MRT. Thermal variation due to body heat and other environmental factors make this a poor approximation.

A better approach would be to mount a thermistor on one of the detectors, record its output along with the other parameter, and use this value for the MRT calculation. An improvement over the single thermistor would be to use 5 thermistors, one on each detector, and take an average as the case temperature. The same thermistors used for the air temperature and wet bulb measurements can be used and because of their low impedance output may be summed together, using a passive resistive network, to find the average temperature.

A system so constructed may be calibrated with the procedure outlined for the mini-sphere detector. Convective cooling is not a factor in the action of the detector element. However, air temperature needs to be controlled to provide a range of temperatures for the detector case.

E. Power Supply

Many options exist for determing which power supply shall be used. The design depends upon the intended period of useage. Figure 15 contains a block diagram of the power supply.

1. Batteries

For long-term economy and high power density, a nickel-cadmium battery system has been chosen. A twelve volt nominal battery would provide sufficient voltage for the electronic instrumentation. Since the nickel-cadmium batteries' nominalvoltage is 1.25 volts, ten cells would be required to give 12.5 volts. Since the design of operational amplifier circuits is greatly simplified if a plus and minus supply exists, a nominal $\pm$ 6 volt configuration is used. This nominal voltage is reduced to $\pm$ 5 volts after passing through the regulator circuits.

The capacity of the batteries is estimated by tabulating the estimated current drains of the various components with a 12 volt supply as shown in Table VII.

TABLE VI
CURRENT DRAIN FOR HEAT STRESS INSTRUMENTATION

Instrumentation	Current Amperes
aspirator	0.30
wind velocity	0.08
temperature electronics	0.02
Total	0.40

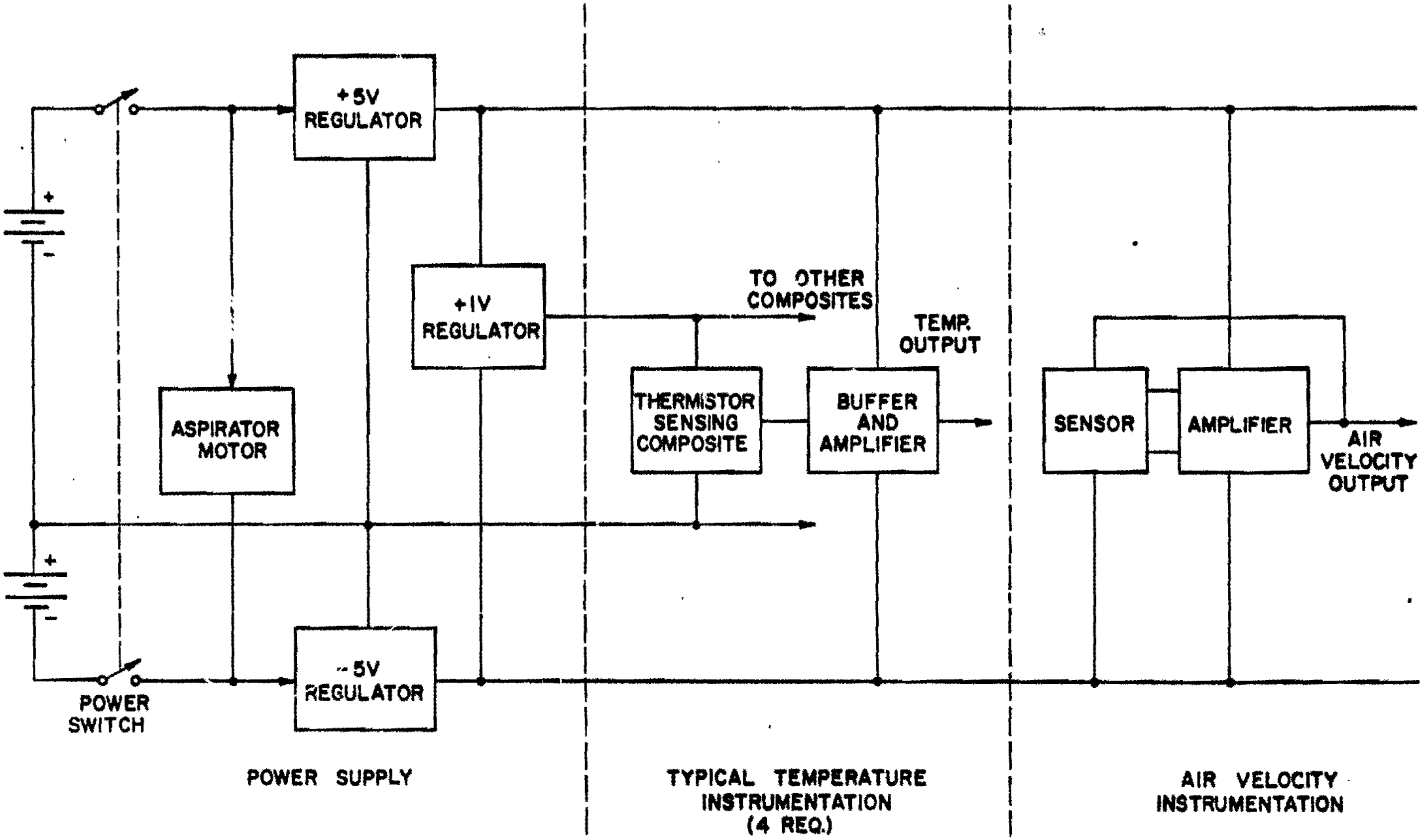


FIGURE 15. BLOCK DIAGRAM FOR POWER SUPPLY SHOWING CONNECTIONS TO SIGNAL CONDITIONING CIRCUITS

This amount of current drain will require a moderate size battery pack. To best facilitate the placement of the batteries on a waist belt, and to furnish a plus and minus supply, the battery pack can be separated into six volt packs. Table VII summarizes some of the options available with commercially available nickel-cadmium battery packs:

Table VII. Nickel Cadmium Battery Packs vs. Operating Time for the Portable Heat Stress System

Operating Time Hours	Voltage	Cell Type	Size L x W x H	Weight oz	Comments
2.7	6	Sub C	5.0x1.0x2.0	10.5	Two packs required
5.0	6	1/2 D	7.0x1.4x1.84	18.4	Two packs required
10.0	6	D	7.0x1.4x2.65	29.0	Two packs required
5.0	12	1/2 D	6.7x1.7x2.8	35.0	One pack required

Any of the above battery packs may be used, the choice depending upon the intended use, operating time requirement and maximum tolerable weight.

Nickel-cadmium batteries will withstand rugged duty and extremes in environmental conditions. The typical discharge temperature range is -40°F to 140°F. These temperature limits represent the maximum continuous operating and storage temperatures with a reasonable life expectancy. The batteries may be operated or stored at higher temperatures for short durations without noticeable degradation in battery life. The only influences the elevated temperatures have on the battery are its charging characteristics and charge retention. The higher cell temperature has a negligible effect on discharge capacity and voltage.

2. Voltage Regulators

To improve circuit stability, two voltage regulators are used to regulate the plus and minus supply. Another regulator furnishes a +1.0 volt supply that is used as the exitation for the temperature sensors. As with all portable equipment it is important to minimize the power loss in the regulation circuits since this loss must be supplied by bulky batteries. It is important then, that the voltage regulators be able to operate with inputs of only tenths of a volt more than their output. This would allow the full capacity of the battery to be utilized. This full utilization of the power supply voltage can be accomplished with a properly designed discrete component regulator. The use of integrated circuit voltage regulators would have to be carefully examined in this respect.

F. Belt Pack Design

As previously mentioned, the belt provided a convenient mounting for the dry bulb thermometer, wet bulb thermometer and battery pack. If the package shown in Figures 9 and 10 is worn on the back of the belt, it probably would not interfere with normal work activities. Miners quickly become accustomed to comparatively heavy battery packs to power headlamps, so few problems are anticipated with this configuration.

The belt could be made with a wide material or combination of materials that would insulate it from the body heat. Many flexible, durable and light-weight insulating materials are available. Some experimentation may be necessary to determine if the body temperature would affect the accuracy.

If the workers should perspire heavily, the perspiration could affect the wet bulb temperature. This would especially be true if the clothing around the aspirator was saturated. This problem can be partially alleviated by a belt design that would be wider in the area of the aspirator and impervious to moisture. The belt would increase the path distance from the clothing or body to the aspirator intake, so that the effect of perspiration would be lessened. A helmet mounting for the aspirated bulb would be more effective in eliminating the effects of body moisture. However, the added bulk on the head gear, the increase of motor noise near the workers' ears and the possibility of exhaust interacting with the air velocity dynamics make this location a less attractive option for the wet bulb. Again some experimentation will be necessary to determine the best configuration.

Compartments for the batteries may be incorporated into the belt design. The wiring harness connecting the batteries to instrumentation package and telemetry or magnetic recorder may also be sewn into the belt to eliminate exposed wires which could be snagged by the worker. Figure 16 is an interconnection diagram for the system showing the cable configuration for the belt, the instrumentation package and the helmet. The connector on the top of the instrumentation package (see Figure 9) is the termination for the cable leading to the helmet. The other connector illustrated is connected to the belt wiring harness which has three other connectors attached. Two of those connectors go to the batteries, and the third one is connected to the data recording or telemetry package.

G. Data Acquisition

The function of the data acquisition section of the heat stress monitor is to record the output of the five sensors in such a manner that the data can be successfully retrieved and analyzed as required. One approach to the recording of the data as previously mentioned, is to use a single

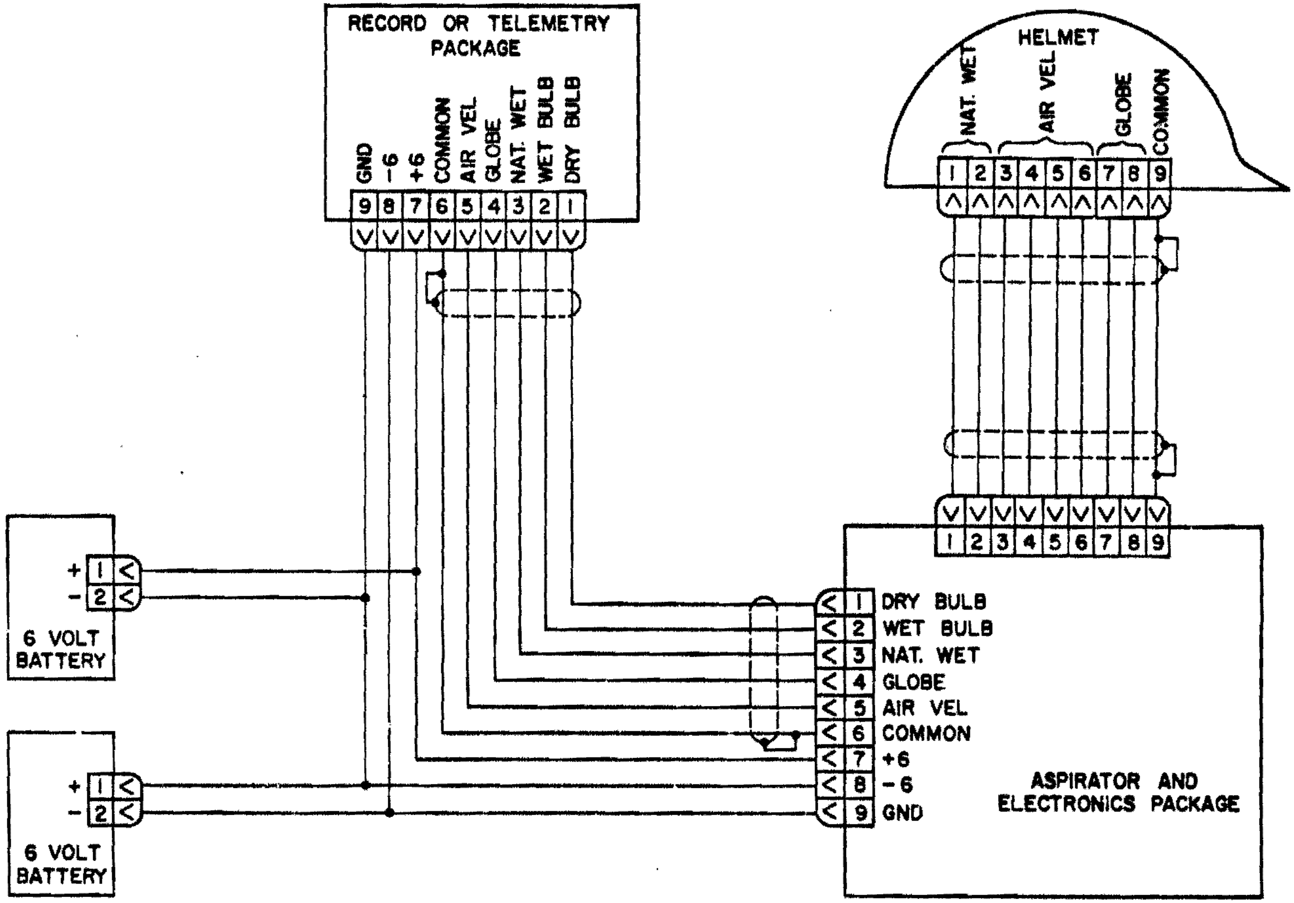


FIGURE 16. INTERCONNECTION DIAGRAM -- PERSONAL HEAT STRESS MONITOR

channel recording instrument as part of the heat stress instrumentation system. Because of the slow response time of the sensors, the bandwidth requirement for such a recorder is very low when compared to modern recording standards.

Magnetic tape recording of information can be accomplished using any of several techniques including direct analog recording, FM carrier recording, and digital recording techniques. The least complex and also the most susceptible to inaccuracies and loss of data is the direct analog method. FM recording is the method most generally used for scientific data acquisition. Digital data recording is best if the data has very wide limits, requires high precision or is to be computer processed later. At the present time, digital data conversion and recording instrumentation would not be easily adapted to a personal, portable instrumentation package.

If a portable recorder is used, a form of FM recording should be employed which will allow the use of relatively simple cassette or cartridge recorders. The analog sensor signals, which have been conditioned to the voltage range of 0 to 5 volts are sampled in sequence by a solid-state commutator and applied to a voltage-to-frequency (VCO)converter. The output of the VCO is then connected directly to the input of the tape recorder. The connected time of each sensor is brief enough to that the time between samples of any given parameter is within the required response time. At the beginning of each scan, a special code or sync signal is added and recorded to flag the start of a scan through the variables.

Retrieval of the data would be accomplished by playing the data back through a frequency-to-voltage converter (phase-lock-loop) connected to a five output demultiplexer. Sequencing of the output is synced with the recorded sync signal and the outputs of the demultiplexer is controlled so that a smoothed output is available for each of the recorded variables.

A second approach to the recording of information is to use a portable telemetry transmitter instead of a magnetic recorder on the subject. Using this approach, the analog data signals would each drive a separate VCO. The five VCO outputs are then summed together to modulate a transmitter. The receiver, located at a fixed station, receives the rf signal and demodulates it to receive the signal generated by summing the VCO outputs. This composite signal is then demodulated by feeding it to a bank of frequency-to-voltage converters. The outputs of these modules will be the original analog variable coming from the sensors.

The analog signals which have been received and demodulated may then be recorded on an FM recorder. Weight, power, and size would not be a overriding factor for the recorder as used here and a 7 track multi-channel FM recorder could be used. A tape speed of 1 7/8 ips for standard intermediate band FM recording gives a signal bandwidth of dc to 625 Hertz; more than adequate for the system time response specifications.

The outputs of the receiver demodulator could also be connected to a bank of digital-panel-meters (DPM) to provide a real time monitor of the data outputs. Many of the commercially available DPM's have a BCD or binary output which may be multiplexed in a serial format and recorded as a digital signal on an entertainment quality cassette recorder. A stereo recorder is well suited for this application where one channel is used for recording a reference clock, the other for the digital signal.

Techniques for recording data in this manner are available and have the advantage that the playback data is in a digital format and is readily interfaced to a digital computer for data processing. If the data is recorded on an analog recorder (either direct or via a telemetry link), an analog-to-digital converter would need to be added to the system to interface with a digital computer.

H. Data Processing

A number of digital processors are available which are adaptable to the needs of portable heat stress system. Of these, the most general is the large scale digital computer. Most computers in this category have a number of peripheral devices which gives the investigator not only the power of much computing capability but offers a variety of methods for inputing and outputing the results for display. This type of processor lacks the flexibility of smaller systems since the data must be taken to it, is generally not arranged for real time analysis and cannot be used on a dedicated basis.

Many minicomputers offer a computing capability which rivals that of the larger general purpose computer. The minicomputer, however, has the additional advantage that a complete system including magnetic recorders, displays, power supplies and related input/output electronics can be mounted in a single equipment rack and can be transported to environments where the heat stress monitor would be used.

A third option available for the digital processing of the data is the use of the micro-processor based instrumentation systems. This solid state device which is sometimes called a "computer-on-a-chip" could be designed into a small portable package to accept data from the output of a telemetry receiver in real time, to apply the needed linearizing and scaling factors and provide digital or analog outputs in engineering units. The micro-processor has the disadvantage of being more difficult to program than the general purpose computer since most commercially available devices must be programmed in machine or assembly languages. The initial expense in developing the hardware and software for a micro-processor system dedicated to this application would be high in comparison to buying time on a larger system. By comparison, follow on units copying the original design would be relatively inexpensive to reproduce since the software is stored in a programmable-read-only-memory (PROM) and may be copied at minimal expense.

To apply the computer to the data coming from the heat stress monitor, the respective channels are coupled, as digital signals, to sample-and-hold buffers which in turn feed data lines in the computer. As the program progresses, the computer will read these inputs into memory and apply the needed corrections to scale all signals to engineering units. If for instance, the mini-sphere is used as a radiation sensor, the equation which is used to convert thermistor voltage to absolute temperature is first implemented. Prior to this calculation, other parts of the program would have determined corresponding values for air velocity and air temperature. These parameters, along with the equations for the properties of air would be used to calculate the equivalent 6-inch globe temperature. All of these calculations can be implemented without input from the investigator. Typical controls might be limited to an on/off switch and reset button. In addition to providing a real time read out of the sensor parameters, the microprocessor could also be used to compute time-weighted averages as specified in the heat stress standards.

IV. CONCLUSION AND RECOMMENDATION

The major conclusion of this report is that a portable heat stress monitor can be built which will meet the performance requirements as specified with respect to the natural wet bulb temperature, the wet bulb temperature, the air velocity and the dry bulb temperature. Mean radiant temperature is one of the fundamental parameters that must be measured for evaluating heat stress but it is also the most difficult. A globe thermometer is a convenient instrument having a nearly 4π steradian field of view. From the evidence given, a small sphere can be developed which will be faster responding than existing globe thermometers and should approach the desired response of 95% of the final value in 30 seconds. The temperature of this mini-sphere will be lower than the 6-inch globe but given air velocity and air temperature numerical techniques are given which can be used to calculate the desired value.

A second approach is suggested to measure values of MRT using commercially available thermopiles. While the sensor does not provide the uniform response that a black globe will, it has the advantage of a faster response time and is more rugged than a thin walled sphere.

A number of thermistors are commercially available which will meet the temperature range, accuracy and time response requirements. The thermistor selected for the portable heat stress system is a composite which has a linear voltage-temperature relationship.

In the design given for the portable heat stress system, the radiation sensor, air velocity transducer and natural wet bulb thermometer are mounted on a hard hat or mechanically similar head apparel to give these sensors rugged mounting fixture and a wide angle of view of thermal radiation and air velocity. Because of the proximity of the helmet to the sensors, errors will be introduced in the related measurements. Therefore, the heat stress sensors need to be re-calibrated after mounting on the helmet.

The wet bulb thermometer and dry bulb thermometer have been designed into a package to be mounted on the waist. A small motor and fan compatible with a battery power supply is incorporated into the unit to provide the proper air flow past the wick of the wet bulb thermometer and to sample ambient air for correct dry bulb readings.

Certainly, one concept which could be considered further for application in the heat stress monitor is the use of the humidity sensor to replace the wet bulb and natural wet bulb thermometer. Commercially available instruments approach the response time and accuracy requirements of the system; nevertheless, for the system as proposed here, it was felt that humidity measurement errors together with air velocity, air temperature errors, and the MRT errors (needed for natural wet bulb calculations) would result in calculated values for the wet bulb temperatures which would not meet the specified accuracies.

One underlying factor in the design of this system is that a digital processor will be used to apply calibration and linearizing factors to the sensor outputs and will also do mathematical operations to convert to the desired outputs. By doing all these corrections "off-line", a smaller, lighter weight, and lower power consuming electronics package is possible for the signal conducting circuitry which accompanies the heat stress sensors. Thus, all detector outputs only need to be amplified to be compatable with the recorder or telemetry transmitter inputs.

The first tests with the portable heat stress system will be controlled experiments to examine the accuracy of the sensors, to measure their response time and to compare them with other established techniques. For these purposes a mini-computer or general purpose large scale computer would be suitable for testing the system concept and evaluating weighted averages from the resulting data. Although this type of processor may entail delays of hours or days in scheduling and processing the data, the necessary software is relatively easy to write and use because of the availability of higher level languages and assemblers.

As the concept is proved and the system becomes operational as a real time heat stress monitor, a processor will be needed which will provide a shorter turn around time for data results. This may be accomplished by using a small, dedicated mini-computer or a micro-processor based instrumentation package. Either processor could be used on-site in an industrial environment to evaluate the heat stress and, in general, compliance with the established codes.

APPENDIX A

The net radiant exchange H_R between a sphere and its surroundings is given by Equation (6), p. 25 as:

$$H_R = \sigma \epsilon_g (T_{gt}^4 - T_r^4) \qquad \text{(A-1)}$$

The term in brackets may be factored as follows:

$$(T_{gt}^4 - T_r^4) = (T_{gt}^2 + T_r^2)(T_{gt} - T_r)(T_{gt} + T_r) \qquad \text{(A-2)}$$

Now let two of the terms in Equation (A-2) equal γ :

$$(T_{gt}^2 + T_r^2)(T_{gt} + T_r) = \gamma \qquad \text{(A-3)}$$

By substituting this factor into Equation (A-2), Equation (A-1) may be written

$$H_R = \sigma \epsilon_g \gamma (T_{gt} - T_r) \qquad \text{(A-4)}$$

Using the equation for convection and assuming constants for all the environmental parameters, the following equation may be written for a small globe:

$$(T_{gt} - T_r) = \frac{K_1 \ (T_{gt} - T_a)}{\gamma \quad (d_{gt})^{0.4}} \qquad \text{(A-5)}$$

where K_1 is a constant combining all assumed constants.
Solving for K_1

$$K_1 = (d_{gt})^{0.4} \ \frac{(T_{gt} - T_r)}{(T_{gt} - T_a)} \ \gamma \qquad \text{(A-6)}$$

For a 6-inch globe, the parallel equation to (A-5) is:

$$(T_{GT} - T_r) = \frac{K_1 \ (T_{GT} - T_a)}{\gamma' \quad (d_{GT})^{0.4}} \qquad \text{(A-7)}$$

A different γ' is used because of T_{GT}.
Solving this equation for T_{GT} gives

$$T_{GT} = \frac{T_r - K_1 \times T_a / (d_{GT})^{0.4} \times \gamma'}{1 - K_1 / (d_{GT})^{0.4} \times \gamma'} \qquad \text{(A-8)}$$

Substituting for K_1 results in

$$T_{GT} = T_a + \frac{(T_r - T_a)}{1 - \left[\frac{d_{gt}}{d_{GT}}\right]^{0.4} \left[\frac{(T_{gt} - T_r)}{(T_{gt} - T_a)}\right] \frac{\gamma}{\gamma'}} \qquad \text{(A-9)}$$

Equation (A-9) has not explicitly solved for T_{GT} since included in γ' is a T_{GT} factor. This may be eliminated from the right hand of Equation (A-9) if it is assumed that the ratio $\gamma/\gamma' = 1$. Hey[9] reports that this assumption will result in an error not exceeding about 1% of the true value. Using this approximation, Equation (A-9) may be written as:

$$T_{GT} = T_a + \frac{(T_r - T_a)}{(1 + \alpha)} \qquad \text{(A-10)}$$

where

$$\alpha = \left[\frac{d_{gt}}{d_{GT}}\right]^{0.4} \frac{(T_{gt} - T_r)}{(T_{gt} - T_a)} \qquad \text{(A-11)}$$

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