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SURFACE VEHICLE INFORMATION REPORT

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Equivalent Temperature

Foreword—This Document has not changed other than to put it into the new SAE Technical Standards Board Format. Definitions changed to Section 3. All other section numbers have changed accordingly.

1. Scope—The scope of this SAE Information Report is to:

a. Define the Equivalent temperature.
b. Describe how it can be used to evaluate the performance of a heating and/or air-conditioning system in a vehicle.
c. Describe how it can be measured.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein.

2.1.1 ANSI/ASHRAE PUBLICATIONS—Available from ANSI, 11 West 42nd Street, New York, NY 10036-8002.

ANSI/ASHRAE-1992—Thermal environmental conditions for human occupancy
ANSI/ASHRAE55-1992—Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

2.1.2 ISO PUBLICATIONS—Available from ANSI, 11 West 42nd Street, New York, NY 10036-8002.

ISO7726—"Thermal environments—Instruments and methods for measuring physical quantities," International Standards Organization, Geneva 1985
ISO7730—"Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort," International Standards Organization, Geneva, 1984

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this document.

Fanger, P.O., 1982, “Thermal Comfort” Malabar, F1, Robert E. Krieger Publishing Company

Bedford, T., 1936, “The warmth factor in comfort at work,” Rep. Industr. Hlth., Res. bd. No. 76, London

Dufton, A.F., 1932, “The equivalent temperature of a room and its measurement,” Bldg. Res. Technical Paper No. 13, London

Gagge, A.P., et al., 1931, “Thermal interchanges between the human body and its atmospheric environment,” Amer. J. of Hyg., 26:84-102

Gagge, A.P., 1940, “Standard operative temperature generalized temperature scale applicable to direct and partitional calorimetry,” Amer. J. Physiol., 131:93

Hymore, R.R., R.F. Tweadey, and D.F. Wozniak, 1991, “Development of a Test Procedure for Quantifying Performance Benefits of Solar Control Glazings on Occupant Comfort,” SAE International Congress and Exposition, Detroit, MI, Feb. 25-March 1

Madsen, T.L., Olesen, B.W., and Christensen, N.L., “Comparison between operative and equivalent temperature under typical indoor conditions,” ASHRAE Trans., Vol. 90, Part 1, 1984

Madsen, T.L., Olesen, B.W., and Reid, K., 1986, “New methods for evaluation of the thermal environment in automotive vehicles,” ASHRAE Transactions Vol. 92, Pt. 1

McIntyre, D.A., 1976, “Subjective temperature: A simple index of warmth,” ECRC/M 916, The Electricity Council Research Center, Chester, UK

Olesen, Bjarne, 1988, “Evaluation of the thermal environment in vehicles,” Bruel & Kjaer Application Notes

Olesen, B.W. and Jens Rosendahl, 1990, “Thermal Comfort in Trucks,” FISITA '90, Torino, Italy, May 7–11

Wyon, D.P., Tennstedt, C., Lundgren, I., and Larsson, S.A., 1985, “A new method for the detailed assessment of human heat balance in vehicles—Volvo's thermal manikin,” VOLTMAN, SAE, International Congress and Exposition, Detroit, MI

3. Definitions

3.1 CLO—A unit used to express the thermal insulation provided by garments and clothing ensembles, where:

$$1\ c/o = 0.155\ m^2 \cdot °C/W \quad (0.88\ ft^2 \cdot °F/Btu) \qquad \text{(Eq. 1)}$$

3.2 Thermal, Comfort—That condition of mind which expresses satisfaction with the thermal environment.

3.3 Thermal, Comfort—The characteristics of the environment which affect a person’s heat loss.

3.4 Relative Humidity (RH)—The ratio of the mole fraction of water vapor present in the air to the mole fraction of water vapor present in saturated air at the same temperature and barometric pressure; alternatively, it equals the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature.

3.5 MET—A unit used to express the activity level (metabolic rate) of a person. 1 met = 58.2 W/m^2 (18.4 $btu/h{\cdot}ft^2$) which is equal to the energy produced per unit surface area of a seated person at rest.

3.6 **Temperature, Equivalent T_{eq}—**The uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat loss by radiation and convection as in the actual nonuniform environment.

3.7 **Temperature, Air (t_a)—**The dry-bulb temperature of the air surrounding the occupant.

3.8 **Humidity, Absolute—**Ambient water vapor pressure (P_a), or dew point temperature (t_{dp}), the temperature at which moist air becomes saturated (100% relative humidity) with water vapor ($P_{sdp} = P_a$) when cooled at constant pressure.

3.9 **Temperature, Mean Radiant ($\bar{t}_r$)—**The uniform surface temperature of an imaginary enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space.

3.10 **Temperature, Operative (t_0)—**The uniform temperature of an imaginary enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment.

3.11 **Temperature, Optimum Operative—**The operative temperature that satisfies the greatest possible number of people at a given clothing and activity level.

3.12 **Thermal, Sensation—**A conscious feeling commonly graded into the categories, cold −3, cool −2, slightly cool −1, neutral 0, slightly warm +1, warm +2, and hot +3; it requires subjective evaluation.

4. Symbols and Units

h_c, convective heat transfer coefficient, W/m² °C (btu/h · ft² · °F)
h_r, radiant heat transfer coefficient, W/m² °C (btu/h · ft² · °F)
I_d, clothing insulation, clo
P_a, water vapor pressure, kPa
rh, relative humidity, %
t_a, air temperature, °C (°F)
t_{dp}, dew point, °C (°F)
t_{eq}, equivalent temperature, °C (°F)
t_0, operative temperature, °C (°F)
$\bar{t}_r$, mean radiant temperature, °C (°F)
v_a, air velocity, m/s (ft/min)

***5. Background*—**Man's thermal comfort is a result of the combined effect of all six thermal climate parameters—activity level, clothing insulation, air temperature, mean radiant temperature, air velocity, and air humidity. According to ISO 7730, the degree of general thermal comfort can be given by the PMV-index, which can be calculated when the six climate parameters are known. It is recommended that the PMV-index is between −0.5 and +0.5, which means that less than 10% will find that the thermal environment is unacceptable. In addition, the standard includes guidelines for local thermal discomfort like radiant asymmetry, draft, and air temperature gradients. This standard may also be applied for vehicles.

The activity level (met-value) and clothing (clo-value) is dependent on the person. In a vehicle the HVAC system mainly controls air temperature and air velocity, while the mean radiant temperature (surface temperature, sunshine) is significantly influenced by the outside climate and design of the body of the vehicle.

The usual method of evaluating the performance of the heating and air-conditioning system in vehicles is to apply sensors to measure the air temperature at feet and head level. The main purpose being to investigate how quickly the system will raise or lower the temperature in a cold or warm vehicle and to study the differences between temperature at head and feet. This means that only one of the three main climatic parameters that concern thermal comfort sensation (air temperature, mean radiant temperature, air velocity) is measured. This fact is especially unfortunate in vehicles, since the mean radiant temperature usually differs far more from the air temperature than is the case in buildings and the air velocity is also greater and more nonuniform than in buildings. The combined effect of air temperature, mean radiant temperature, and air velocity can be expressed by the equivalent temperature, which is related to the dry heat loss from the body.

In existing standards (ASHRAE, ISO) for the thermal environment the required temperature range is normally given as operative temperature. This is a combination of air and mean radiant temperature. This does not include the influence of air velocity, which on the other hand often is limited to very low values. In a vehicle the air velocity is, however, a major factor and must be taken into account when evaluating the performance of the HVAC system.

6. Calculation of Equivalent Temperature

6.1 Operative Temperature—In all the previously mentioned standards, the operative temperature is defined as the uniform temperature of an imaginary inclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. The exact equation for the operative temperature is:

$$t_o = \frac{h_c \times t_a \times h_r \times \bar{t}_r}{h_c + h_r} \qquad \text{(Eq. 2)}$$

where:

t_a = air temperature, °C
$\bar{t}_r$ = mean radiant temperature, °C
h_c = heat-transfer coefficient by convection, $W/m^2 \cdot °C$
h_r = heat-transfer coefficient by radiation, $W/m^2 \cdot °C$

A simplified equation for calculation of the operative temperature is given in ISO 7730 and ASHRAE 55–92:

$$t_o = A \times t_a + (1 - a) \times \bar{t}_r \qquad \text{(Eq. 3)}$$

where a, depends on the air velocity, v_a:

v_a (m/s) < 0.2	0.2 – 0.6	0.6 – 1.0
a 0.5	0.6	0.7

Both the definition of the operative temperature and Equations 2 and 3 can make people believe that the operative temperature takes into account the cooling effect that an air movement has on a heated body, like a man. The operative temperature does not do that. It only takes into account the relative influence of the parameters—air temperature, t_o, mean radiant temperature, $\bar{t}_r$, and velocity, v_a—on the temperature of an unheated body.

6.2 Equivalent Temperature—When the air velocity is low (v_a < 0.1 m/s) the equivalent temperature is equal to the operative temperature:

$$t_{eq} = t_o = 0.5 \times (t_a + \dot{t}_r) \text{ for } v_a < 0.1 \text{ m/s} \quad \text{(Eq. 4)}$$

For higher air velocities (v_a > 0.1 m/s) the equivalent temperature can be calculated as:

$$t_{eq} = 0.55 \times t_a + 0.45 \times \dot{t}_r + \frac{0.24 - 0.75 \times \sqrt{v_a}}{1 + I_{cl}}(36.5 - t_a)°C \quad \text{(Eq. 5)}$$

where:

I_{cl} = Thermal insulation of the clothing, clo

This equation, developed by Madsen (1984), agrees with the similar equations by Bedford (1936), Gagge (1940), and McIntyre (1976).

The equivalent temperature may also be calculated from the PMV-equation [Fanger (1982), ISO 7730] by setting air temperature equal to mean radiant temperature and air velocity to 0 m/s.

It is seen that the equivalent temperature is influenced by the thermal insulation of the clothing. A given air velocity (v_a), has a higher cooling effect on nude skin (I_{cl} = 0) than on skin covered with clothing (I_{cl} > 0).

7. Measurement of Equivalent Temperature

7.1 Individual Measurements—Air temperature, mean radiant temperature, and air velocity may be measured with individual sensors and the equivalent temperature then calculated from Equation 5. The thermal insulation of the clothing must be evaluated before the calculation. (ASHRAE 55–92, ISO 7730)

The sensors must fulfill the requirements in ISO 7726.

7.2 Integrating Sensor—Measuring each parameter individually requires a lot of instrumentation and it is difficult to measure all parameters in the same position. Instead of measuring each parameter and then calculating the combined influence, it may be easier to use a transducer that integrates the three climate parameters into one temperature, the equivalent temperature.

The sensor requirements for direct measurements of equivalent temperature is that the size, color, and shape simulate the convective and radiant heat loss from a person shape and color of the human clothing/skin. The sensor must be heated to a surface temperature, which simulates the mean clothing surface temperature of a person. From the definition it is seen that the equivalent temperature depends on the clothing insulation, which means that the sensor should be able to simulate different clothing temperatures.

The mean clothing/skin surface temperature of a person for different combination of the thermal parameters may be calculated from the PMV-equation given in ISO 7730 [ISO 7730 (1984), Fanger (1982)].

These requirements are fulfilled with the sensor in Figure 1. The sensor has been carefully designed to simulate the dry heat loss from a person as precisely as possible. The size has been chosen so that the ratio between the heat loss by radiation and by convection is similar to that of a person.

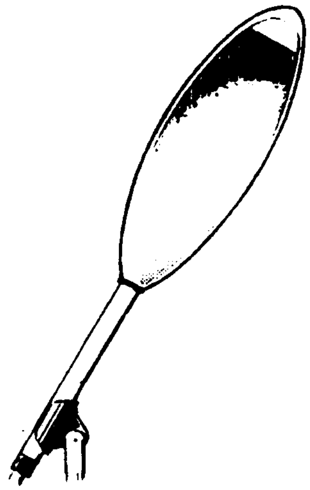

FIGURE 1—AN ELLIPSOID-SHAPED SENSOR

When measuring the equivalent temperature, the sensor is heated. The surface temperature must therefore correspond to the mean clothing surface temperature of the person that the sensor is simulating. The desired surface temperature is maintained by means of a temperature-independent resistance wire wound around the sensor body. The current through this wire is a measure of the heat loss from the sensor. At the same time, there is a wire evenly wound over the heated part of the sensor body. The resistance of this wire is a measure of the mean surface temperature of the body. By means of the measured heat loss and mean surface temperature, the equivalent temperature is estimated.

7.3 Thermal Manikin—In a vehicle the thermal conditions may give a nonuniform exposure on the body of a person. To simulate the human body in the best way, a thermal manikin may be used to measure the equivalent temperature. A thermal manikin [Wyon (1985), Madsen (1986)] is fitted with pliable joints so that it can be placed in different positions. Thermally it is divided into sections, each with its own heating system to ensure that each section will maintain exactly the surface temperature for the clothing it has been set for. After measuring the energy consumption of each of the sections, the equivalent temperature for each part of the body can be found.

Each segment of a thermal manikin operates as an equivalent temperature sensor (see 7.2), but with a shape that much better simulates the human body.

A thermal manikin is also measuring the average equivalent temperature as an area-weighted mean value for all body parts.

When the thermal manikin is not used, it is recommended to take into account the obstruction that the human body will make to the air velocities by mounting the sensors on a skeleton which represents the contour of each body part.

7.4 Average Equivalent Temperature—Due to the very nonuniform conditions in vehicles it is often necessary to measure in more positions representing different body parts. The number of measuring points depends on the applications. If you want to test how fast the vehicle is heated up or cooled down, it may be enough with three points (head, abdomen, feet). When investigating the distribution over a person's body and the effect of different settings of the outlets from the air conditioner, it will be necessary with more positions (head, left arm, right arm, left hand, right hand, abdomen, left leg, right leg, left foot, right foot).

The position and direction of the sensor are set so it as best as possible simulates the shape and projected area of the body parts it represents.

The idea is then to measure the equivalent temperature at each position and estimate an equivalent temperature representing the whole body. As an example, the measured values for each location may be averaged based on an area-weighted average. Using this method, t_{eq}, is related to the average rate of heat loss over the body. Some data indicate that people in their thermal sensation may put a higher weight on the conditions at head level than at other parts of the body. There are, however, at this time, insufficient data to develop weighing coefficients that reflect these differences. As an example, Table 1 shows the area of different body parts, examples of positions of sensors, and the corresponding weighing factors for estimating the equivalent temperature for the body as a whole. In a test with three sensors (head, abdomen, feet) the calculations of the mean value will be:

$$t_{eq}(\text{mean}) = 0.1 \cdot t_{eq}(\text{head}) + 0.7 \cdot t_{eq}(\text{abdomen}) + 0.2 \cdot t_{eq}(\text{feet}) \quad \text{(Eq. 6)}$$

TABLE 1—AREA OF DIFFERENT BODY PARTS, WEIGHTING COEFFICIENTS

Body Segment	Skin Area m^2	Relative Area %	3 Transducers	Area %	6 Transducers	Area %	10 Transducers	Area %
Head	0.180	10.3	1: Head	10.3	1: Head	10.3	1: Head	10.3
Left Upper Arm	0.077	4.0			2: Abdomen	31.1	2: Abdomen	23.1
Right Upper Arm	0.077	4.0			L. Upperarm		3: R. Upperarm	4.0
Left Forearm	0.062	3.5			R. Upperarm		4: L. Upperarm	4.8
Right Forearm	0.062	3.5			3: L. Forearm	6.4	5: R. Forearm	6.4
Left Hand	0.050	2.9			L. Hand		R. Hand	
Right Hand	0.050	2.9	2: Abdomen	66.7	4: R. Forearm	6.4	6: L. Forearm	6.4
Chest	0.185	10.6			R. Hand		L. Hand	
Back	0.204	11.7			5: L. Thigh		7: R. Thigh	11.4
Pelvis	0.080	4.6			R. Thigh		1/2 Trunk	
Left Thigh	0.160	9.1			Abdomen	22.8	8: L. Thigh	11.4
Right Thigh	0.160	9.1			6: L. Foot		1/2 Trunk	
Right Fibula	0.140	8.0			R. Foot		9: R. Fibula	11.5
Left Fibula	0.140	8.0	3: Legs	23.0	L. Fibula		R. Foot	
Left Foot	0.062	3.5			R. Fibula	23.0	10: L. Fibula	11.5
Right Foot	0.062	3.5					L. Foot	

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