THE THERMOELECTRICALLY COOLED HELMET

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ABSTRACT

The thermoelectric (TE) cooled helmet consists of a TE cooled liquid filled cushion lining the top interior of a safety helmet, such as used by motorcyclists and race-car drivers.

A single, 12 volt TE module is used to remove heat from the liquid cushion, through a flexible braided wire "heat collector" located within the cushion. Heat is exhausted to ambient through an "outboard" heat sink finned aluminum radiator. Movement of the helmet produces a forced convection heat dissipation effect in the radiator and effectively removes the waste heat.

The technical details of design and test performance data are presented from both laboratory and field-test evaluations.

INTRODUCTION

The Primary feature of a safety helmet is safety. As such, hard-shell helmets used by motorcyclists and race-car drivers embody a helmet liner consisting of about one-inch thickness of poly-foam. This liner serves the purpose of being easily crushable upon receiving a heavy blow and absorbs the shock instead of transmitting it to the head of the wearer. However, this foam liner is very similar to that used in refrigerators as thermal insulation. As a result, the normal heat transfer from the head to the outside air is blocked, creating an uncomfortable and dangerous hot environment to the head.

Carpenter[1] observed that motorcycle riders feel that their helmet interior reaches 130 °F during hot days. He dispelled this myth by actually measuring temperatures which indicated that the interior quickly rises to body temperature (98.6 °F) and "can edge to 100 °F". He further observed that "once the temperature in your helmet reaches 98.6 °F, your head can no longer give off heat". When this occurs, the physiological and psychological effects are very real and potentially dangerous due to a deadening of the senses and a decrease in ability to concentrate.

Kissen[2] and Konz[3] concluded that head cooling is the most efficient of any other part of the body because it "has the highest skin temperature (and thus largest delta-T) as well as a large constant-volume blood flow". This contention has been substantiated by other studies[4,5,6]. In fact, some authors believe that "head cooling is so efficient and is such a significant factor in the perception of overall thermal comfort, that it is not a luxury but a necessity for pilots flying in demanding aircraft[7]".

Getting back down to earth, the point is that the one-inch thickness of insulation lining the interior of a motorcycle helmet restricts and can virtually eliminate the heat exchange with the outside world of the most efficient part of the body.

It was not until the early 1980's until a practical solution to this problem was invented. This system did not sacrifice any element of safety and simultaneously met the constraints imposed on the interior and exterior design by safety organizations such as DOT, SNELL, and various foreign and domestic industrial standards. This concept was subsequently patented by McCall[8] in 1984. Using this concept, Burke[9] assembled and tested the first working engineering unit and established the technical viability of the product. More recently, Buist & Streitwieser [ibid.] re-developed the entire unit utilizing the latest technology in small economical, 12 volt TE module, a specially designed heat sink radiator, a one-piece liquid filled vinyl cooling cushion embodying a flexible "heat collector" and a unique temperature controller[10].

SYSTEM DESCRIPTION

The basic components of the TE cooled helmet are illustrated in Figure 1:

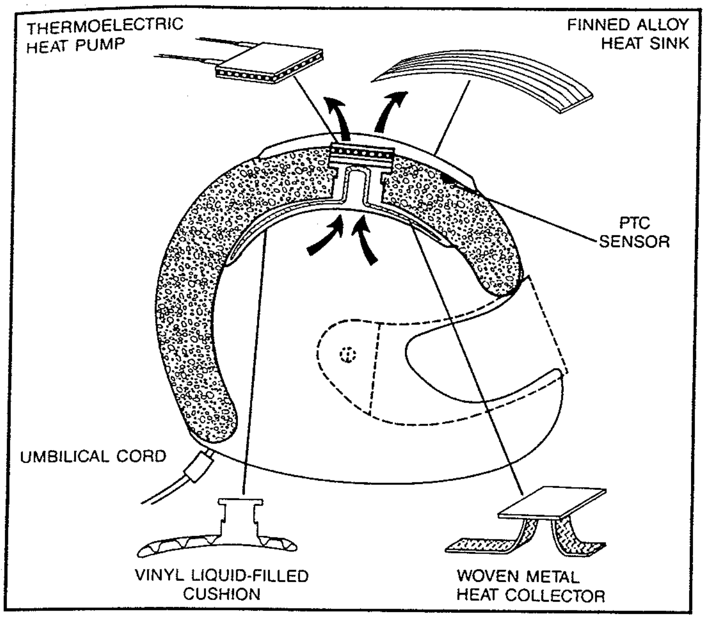

Figure 1. The Helmet Cooling System.

The key to the cooling system, of course, is the TE module. Voltage applied to this module will cause heat to be pumped from the inner cushion to the outboard heat sink. A flexible "heat collector" is used inside the liquid filled vinyl cushion to facilitate heat transfer from the cushion to the cold side of the TE module.

The temperature limiter is a PTC (Positive Temperature Coefficient) resistor which is used to sense the heat sink temperature and feed a signal to the thermal controller box. This signal overrides the manually setable voltage level to the TE modules depending on the heat sink temperature. This, in turn, provides maximum net cooling to the cushion under all operating conditions. This unique control system was invented by Streitwieser[10] specifically for systems with variable heat sink resistance and/or temperature.

HEAT SINK DESIGN

The design of the heat sink was complicated by several mechanical constraints. First of all, it was necessary to match the curvature of the helmet. This was necessary not only from end to end but also side to side. Secondly, no part of the heat sink could project beyond the normal curvature of the helmet by more than 3/16 of an inch. These factors resulted in taller fins in the middle but gradually decreasing fin heights to each side. Furthermore, an extra wide fin was required in the center of the heat sink to accommodate tapped holes for assembly clamping screws. Thirdly, the overall weight of the heat sink was to be minimized to the extent that the end product could not exceed 2000 grams. It was also necessary to machine a flat surface into the underside curved heat sink to accommodate the attachment of the TE module. This thinned the heat sink plate at a very critical area which impacted lateral heat flow. Finally, it was necessary to achieve overall smoothness in shape in order to avoid sharp edges and meet the needs for an aesthetically pleasing appearance.

As a consequence of the complexity of these design features and constraints, no mathematical thermal model of this heat sink was generated. The optimization procedure consisted of fabrication of several heat sink configurations and derivation of the optimum design experimentally. The performance test results of the final heat sink design are illustrated in Figure 2. This data was generated by applying heat and measuring heat sink temperature only at the module attachment area to simulate actual operation. It is observed that the heat sink resistance decreases rapidly from the 7.29 C/W value in still air and nearly levels off at value of 0.935 C/W at 20.5 MPH air velocity.

The measured temperature gradient in the heat sink at 20.5 MPH air flow is illustrated in Figure 3. As expected, the front of the heat sink ran significantly cooler than the back due to the air striking this area first and the relatively less effective air flow at the back. A simple experiment was performed to test whether or not the heat sink could be shortened without seriously degrading performance. It was discovered that 0.5 inch and 1.0 inch removed from the heat sink resulted in a 12.1°F and 24.1°F increase, respectively at the TE module attachment area. Therefore, no changes were made to this heat sink design.

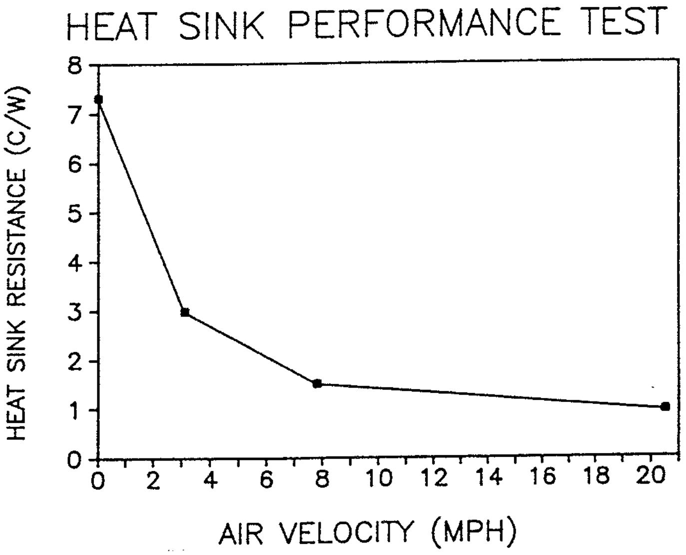

Figure 2. Heat Sink Resistance vs Air Speed. Tested at room temperature.

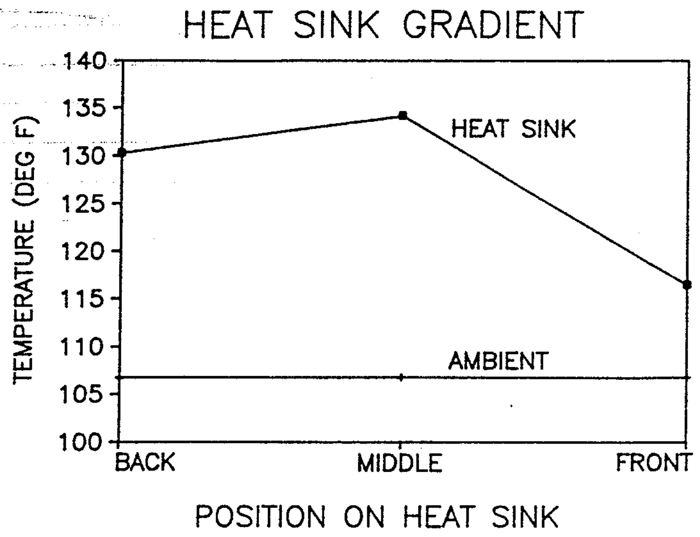

Figure 3. The temperature variance across the Heat Sink as measured empty at 20 MPH air flow and 12VDC applied power.

TE MODULE DESIGN

The philosophy of design for the TE module was to select an existing economical TE module that would produce maximum heat pumping under the following conditions: (1) An air velocity of 20.5 MPH yielding a heat sink resistance of 0.935 C/W; (2) An ambient of 98 °F; and (3) A cushion temperature of 85 °F. Although the choice for ambient was totally subjective, the optimum 85 °F cushion temperature had been determined through early tests[9]. This design parameter was later verified through our own tests as well as independent evaluations[12].

Since the cooling unit was to operate at 12 volts nominal, the standard TE module configuration composed of 127 couples was selected. Furthermore, based on rough estimates of heat pumping capacity requirements, the "family" of 127 couple TE modules were chosen which had a TE pellet cross-section of 0.040 x 0.040 inch. The remaining "free" variable to optimize was TE pellet length. The results of this optimization procedure are illustrated in Figure 4.

The existence of an optimum sized TE cooler was anticipated from the rapid fall-off of maximum heat pumping capacity as a function of heat sink "softness"[11]. That is, as the size of a TE module increases its "infinite-heat-sink" heat pumping initially increases. However the "soft-heat-sink-multiplier" decreases rapidly resulting in an optimum TE module size.

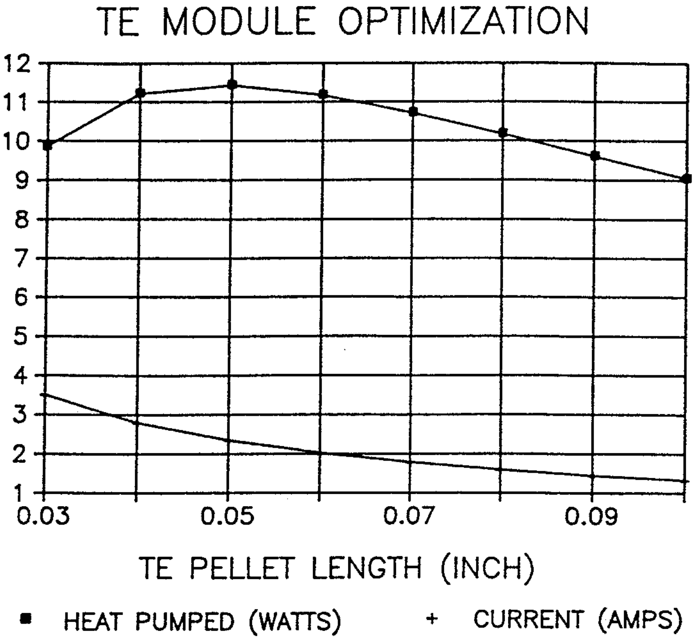

Figure 4. TE Module optimization for maximum heat pumping under the conditions: 12VDC, 254 TE Pellets with width = 0.040".

Notice that the TE pellet length that produced the highest heat pumping (11.4 watts) was 0.050 inch. However, 0.060 inch was chosen for the final TE module design. This TE pellet geometry yielded only a 2% decrease in heat pumping to 11.2 watts, with a 14% reduction in power. That reduced the optimum current from 2.34 amps to 2.02 amps. This not only conserved power, but allowed the heat sink to run a little cooler without any significant change in the internal cushion cooling capacity.

QUALITY-CONTROL PERFORMANCE TEST

An interesting quality control specification emerged from these tests which has general application for forced-air heat sink systems or sub-assemblies. If "full" power is applied to the TE module in a condition where the air velocity across the heat sink is zero, the cold side of the TE module will very quickly cool down but the heat sink will tend to warm slowly and essentially "run-away" if left on indefinitely. The resultant is that the cold side of the TE modules will reach a minimum temperature in about 30 to 40 seconds. This minimum not only depends on the quality of the TE module but also the quality of the thermal bond between the TE modules and the heat sink.

Several tests were performed in this configuration with the same TE module but with varying percentage of coverage of bonding interface between the TE module and the heat sink. The results are shown in Figure 5. It is observed that these test results were very dependent on the integrity of the thermal bond.

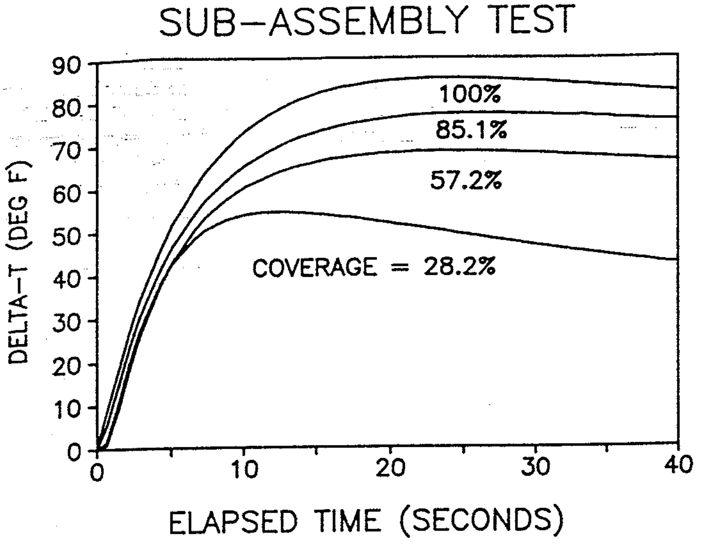

Figure 5. Transient performance tests of a TE module + heatsink sub-assembly.

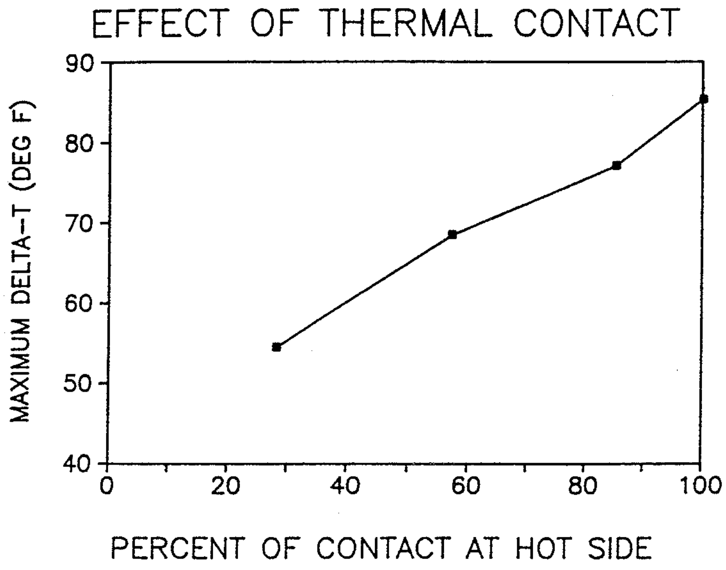

Figure 6. Summary of maximum transient delta-T of TE module + heatsink sub-assembly vs percent of contact coverage on hot side.

The maxima versus percent of thermal contact area are summarized in Figure 6. Notice that the degradation in maximum delta-T is roughly linear with percent of contact area with a slope of about 0.4°F degradation in minimum cold side temperature with every 1% reduction in coverage of the thermal bond. This is quite sensitive and has worked very well in practice, too. This technique is highly recommended as a quality-control performance test for similar configurations. It should be especially effective for testing single or multiple stage TE coolers mounted onto small headers used for cooling small components such as detectors, laser diodes, computer chips, etc.

CUSHION DESIGN

An interior cooling cushion was used to provide the heat transfer from the wearer's head to the cold side of the thermoelectric module. It consisted of a vinyl cushion filled with a water based solution. Some chemical additives served the multi-purposes of antifreeze, anti-contamination, algaecide and an eye soothant. The liquid not only provided a comfortable interior for the helmet but also served as the heat transfer medium. A "heat collector" assembly was developed which greatly improved the heat transfer characteristics of the cushion. This consisted of a copper plate with flexible braided copper wire extending down into the cushion. The performance of a cushion with and without a heat collector is shown in Figure 7. It is observed that not only did the cushion run about 9°F cooler, but also ran more nearly isothermally.

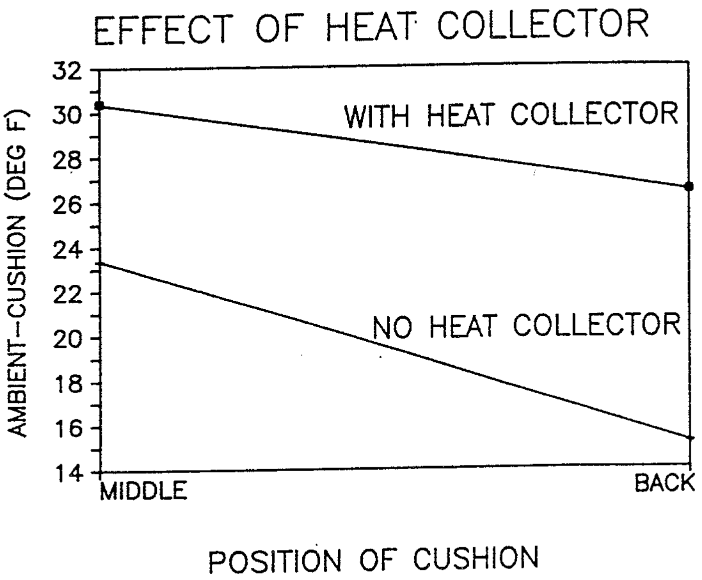

Figure 7. Comparison of Cooling cushion performance with and without the use of a heat collector. Ambient temperature = 80°F.

REGULAR HELMET TESTS

To establish a baseline, a "regular" full-face helmet with no cooling unit was installed with temperature sensors and placed on the head of a human subject. The results of this test shown in Figure 8 verified Carpenter's[1] findings discussed earlier even in a mild room temperature environment. However, subsequent tests under actual motorcycle racing conditions[13] indicated even higher temperatures than that recorded by Carpenter. At the completion of a race, the helmet interior rose to 102.4°F while the ambient temperature was 98.3°F. These tests very definitely established the need for cooling in helmets in order to meet the demanding needs for rider comfort and safety.

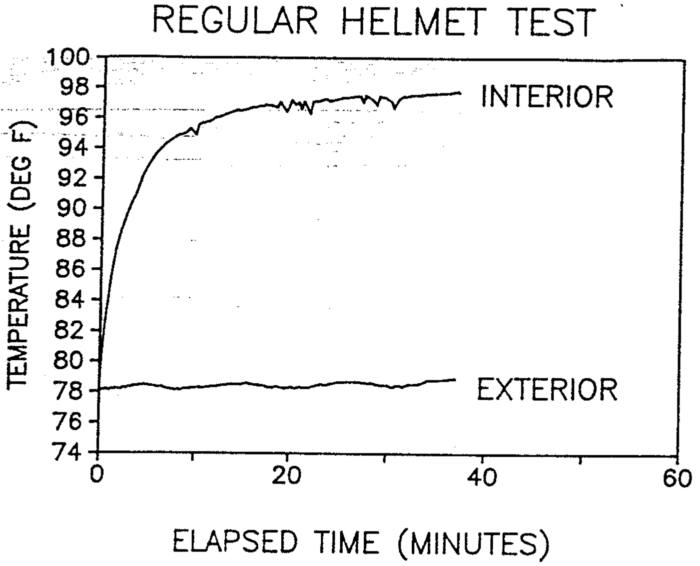

Figure 8. Room temperature test of a regular non-cooled motorcycle helmet.

LABORATORY TESTS

Several performance tests were made on the completely assembled thermoelectrically cooled helmet in the laboratory simulating environmental conditions expected in actual use. The results of an empty helmet tested at a mild 80°F ambient and hot 106°F ambient are shown in Figures 9 and 10. The air velocity for each case was 25 mph. It is observed that the heat sink temperature rises very rapidly to its steady-state value 30-40°F above ambient. Also, the temperature gradient in the heat sink was very significant and agreed very well with previous tests made on the individual heat sink.

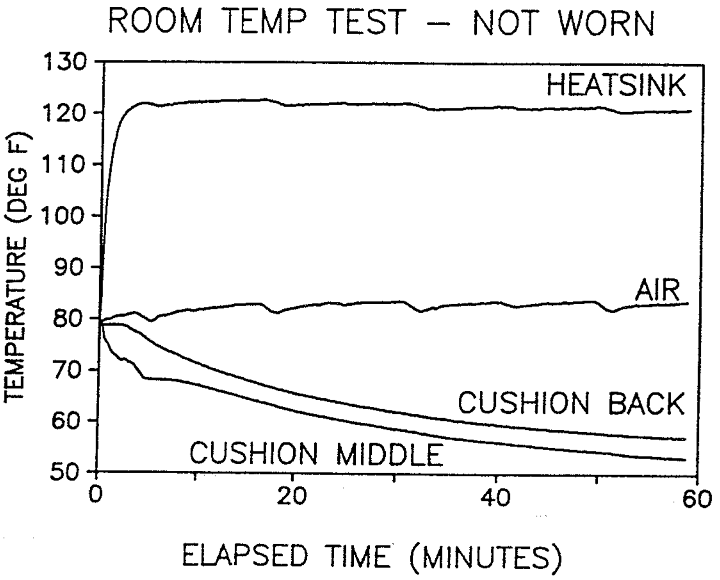

Figure 9. Room temperature test of empty, not worn TE cooled helmet at 12VDC applied and 25 MPH air flow.

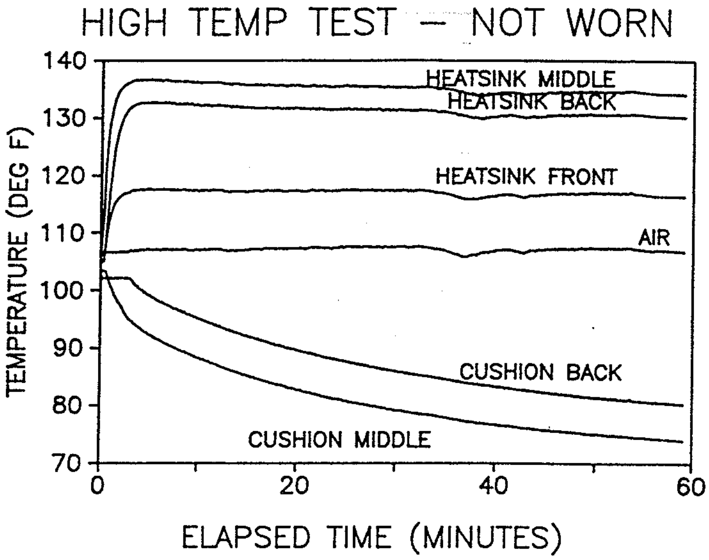

Figure 10. High temperature test of empty, not worn TE cooled helmet at 12VDC applied and 25 MPH air flow.

It is important to note that the front of the heat sink rose only about 10°F above ambient at an air speed of 25 MPH. The temperature at this point in the system is most sensitive to air speed. It actually runs warmer at even considerably lower TE power levels when the air speed was reduced. This phenomenon was the key to automatically controlling power to the TE cooling unit to a desired level at all air speeds and led to the creation of a unique temperature control system[10].

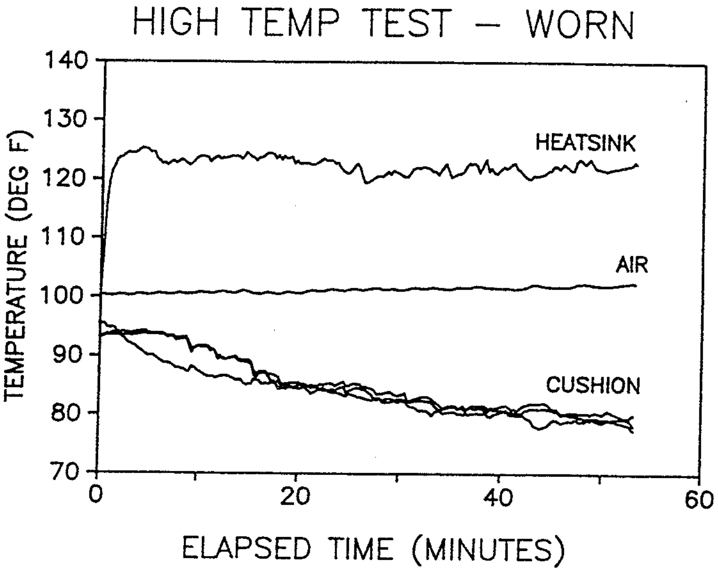

Figure 11. High temperature test of worn TE cooled helmet at 12VDC applied and 25 MPH air flow.

The most important observation, of course, was the decrease in temperature of the cooling cushion. The ultimate temperature of the cushion was reduced 25-30°F below ambient. The observed temperature gradient in the cushion was quite large. However, these tests were performed in a very motionless condition and it was believed that real-world conditions would enhance temperature uniformity. It was expected that the agitation and vibrations of normal riding would "mix" the cushion liquid and thereby establish a flatter profile.

Indeed, that was the case as observed in Figure 11. This test was made using a human subject wearing the helmet in a 100°F ambient condition simulating riding conditions. Larger fluctuations in the system were very evident but overall "thermal mixing" occurred as well. This unit was left on to continue cooling for the purpose of collecting data. Actually, however, the subject experienced the most comfortable temperature within 10-15 minutes of operation.

FIELD TESTS

Field tests were performed by test riding in the deserts of California. These findings were identical with an independent product evaluation report made by "Road Rider"[12]. They concluded that the "helmet performed completely as advertised" and that it was "very, very good". They further concluded that "the thermoelectric cooled helmet earned straight A's for concept and basic technological design." Our tests also agreed with "Road Rider" concerning the effect of helmet color. That is, we discovered that, although there was some difference in external surface temperature for various colors, there was essentially no difference in internal temperatures. Two helmets, both full-face, one white and one black, were tested in an ambient temperature of 101°F. The white helmet achieved a cushion temperature of 79°F and the black reached 78°F. This temperature was too cold to both riders. It was discovered through experimentation that the most comfortable temperature for the cushion was 85-88°F. It was necessary to reduce the power to 75% of maximum in order to operate within this comfort range.

RACING TESTS

Tests were also performed under actual motorcycle race conditions by professional motorcycle racer, Mike Cook of Richardson, Texas[13]. Initial Tests were performed at the Hallett Racing Circuit in Hallett, Oklahoma on April 18, 1987. Additional testing was performed during April 25-26, 1987 at the Oak Hill Raceway in Henderson, Texas. The weather conditions on both occasions were sunny and hot with temperatures reaching 98°F. Comparison tests were made between a "regular" helmet and the TE cooled helmet. Mr. Cook's comments were that: "...The TE cooled helmet worked great...The difference (between the cooled helmet and a non-cooled helmet) was unreal...There was a 22°F difference between the two helmets and a noticeable difference in the body heat build-up...". He further observed that: "...My hair was actually cool and dry on top with very little sweat on my forehead". He labeled the TE cooled helmet as "A racer's dream".

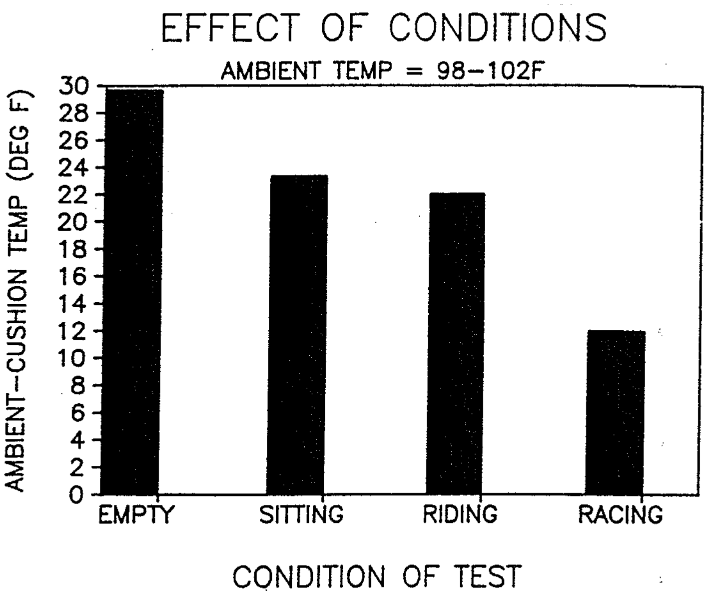

Figure 12. Summary of High temperature tests of TE cooled helmet at 12VDC applied and 25 MPH air flow.

CONCLUSIONS

Cooling of the head is well established as the most efficient method of cooling the body. A TE cooling system has been designed and developed to effectively provide active cooling to the head without sacrificing any element of safety. A comparison of the relative net cooling capability of the TE helmet under various conditions is summarized in Figure 12. A single, 12 volt TE module was used which provided adequate cooling but drew less than 2 amps of current from the power system. In fact, current draw is usually less than 1 amp under typical operation. The entire TE cooling unit added less than 9 ounces to the helmet weight making it the lightest weight self-contained system ever developed for cooling a helmet.

Simulation tests in the laboratory have validated the theoretical design parameters and established the feasibility of providing a personal cooling from a single 12 volt TE module. Field tests in the scorching desert and on a sweltering motorcycle race track have proven that this cooling system works very well under stringent conditions and established user acceptance of this unique and effective TE cooling system.

REFERENCES

[1] B. Carpenter, "Heads, Helmets and Heat": Road Rider Magazine, September, 1987.

[2] A.T. Kissen, J.F. Hall, F.K. Klemm: "Physiological Responses to Cooling the Head and Neck Versus the Trunk and Leg Areas in Severe Hypothermic Exposure", Aerospace Magazine, August, 1971.

[3] S. Konz & J. Duncan: "Cooling with a Water Cooled Hood", Proceedings of the Symposium on Individual Cooling, Kansas State University, pp 138-169, 1969.

[4] A.T. Kissen, W.C. Summers, W.J. Buehring, M. Alexander & D.C. Smedley: "Head and Neck Cooling by Air, Water or Air Plus Water in Hyperthermia", Aviation, Space, and Environmental Medicine, March, 1976.

[5] E. Scvartz: "Effect of a cooling hood on physiological responses to work in a hot environment", Journal of Applied Physiology, 29:36-39, 1970.

[6] B.A. Williams & A. Shitzer: "Modular liquid cooled helmet liner for thermal comfort", Aerospace Med. 45:1030-1036, 1974.

[7] S.A. Nunneley, S.J. Troutman & P. Webb: "Head cooling in work and heat stress", Aerospace Med. 42:64-68, 1971.

[8] J. C. McCall: "Thermoelectric Cooled Head Gear", U.S. Patent #4,483,021, , November, 1984.

[9] E. Burke & D. Lash: Development of a thermoelectrically cooled prototype helmet, Private communications of work performed at Marlow Industries, Inc. and Abaddon Products Company, 1983-1984.

[10] G.D. Streitwieser & R.J. Buist: "An Electronic Temperature Controller for Thermoelectrics with Variable Heat Sink Resistance", Proceedings of the 7th International Conference of Thermoelectric Energy Conversion", March, 1988.

[11] R.J. Buist & P.L. Townsend: "Thermoelectric Cooler Performance Corrections for Soft Heat Sinks", Proceedings of the "6th International Thermoelectric Energy Conversion Conference", March, 1986.

[12] B. Carpenter: "Cool-Power Helmet", Road Rider Magazine, September, 1987.

[13] M. Cook: "Motorcycle Race Test of TE Cooled Helmet", Report to Cool-Power, Inc., April, 1987.