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HELMET COLD CONDITIONING: CORRELATION OF STRUCTURAL TEMPERATURES IN ACTUAL AND SIMULATED COLD ENVIRONMENTS

By

John C. Johnson, M.S.
Stanley C. Knapp, M.D.

October 1977

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U.S. ARMY AEROMEDICAL RESEARCH LABORATORY
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An experiment was conducted at the US Army Aeromedical Research Laboratory, USAARL, to correlate the helmet thermal characteristics found in cold temperature conditioning as required by current impact test methodologies (American National Standards Institute (ANSI) Standard Z90.1 and the Department of Transportation (DOT) Motor Vehicle Safety Standard (MVS) No. 218, Motorcycle Helmet 49CSR571.218) and the thermal characteristics which occur during actual use by the wearer in a cold environment.

Four types of helmets were used in this evaluation: sling suspension, form-fit, standard motorcycle, and short motorcycle helmets. Temperatures were taken within the helmet structure using thermocouples at the following locations: on top of the exterior surface of the shell, at the interface between the shell and the crushable liner, at the center of the crushable liner and at the center of the comfort liner.

Data from this experiment was plotted graphically and yielded the following information: 1. Temperatures of helmets preconditioned and tested according to ANSI Standard Z90.1 and DOTMVS 218 do not correlate with temperatures of identical helmets used in the cold environment. 2. The discrepancy between helmet structure temperature following ANSI Z90.1 and DOTMVS 218 cold conditioning and testing, and simulated cold climate use, is dependent upon helmet structure type and the ambient temperature which existed during the simulated cold climate use. 3. The slope of the temperature gradients (temperatures versus depth in the helmet structure for simulated cold climate use, when compared to ANSI Z90.1 and DOTMVS 218 impact test conditions, were opposite in direction. Under simulated cold climate use conditions the helmet is coldest on the outside and warmest on the inside. The reverse of this is true under ANSI Z90.1 and DOTMVS 218 conditions.

Standard helmet impact test methodologies do not simulate potential, real world, cold climate conditions. The standard impact test methodologies are inappropriate for the determination of cold temperature dynamic response of a helmet system.

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SUMMARY

An experiment was conducted at the US Army Aeromedical Research Laboratory, USAARL, to correlate the helmet thermal characteristics found in cold temperature conditioning as required by current impact test methodologies (American National Standards Institute (ANSI) Standard Z90.1 and the Department of Transportation (DOT) Motor Vehicle Safety Standard (MVS) No. 218, Motorcycle Helmet 49CSR571.218) and the thermal characteristics which occur during actual use by the wearer in a cold environment.

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Data from this experiment was plotted graphically and yielded the following information: 1. Temperatures of helmets preconditioned and tested according to ANSI Standard Z90.1 and DOTMVS 218 do not correlate with temperatures of identical helmets used in the cold environment. 2. The discrepancy between helmet structure temperature following ANSI Z90.1 and DOTMVS 218 cold conditioning and testing, and simulated cold climate use, is dependent upon helmet structure type and the ambient temperature which existed during the simulated cold climate use. 3. The slope of the temperature gradients (temperatures versus depth in the helmet structure for simulated cold climate use, when compared to ANSI Z90.1 and DOTMVS 218 impact test conditions, were opposite in direction. Under simulated cold climate use conditions the helmet is coldest on the outside and warmest on the inside. The reverse of this is true under ANSI Z90.1 and DOTMVS 218 conditions.

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Approved:

STANLEY C. KNAPP
Colonel, MC
Commanding

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

It is important to determine the actual temperatures of various helmet structures when the helmet is being worn in an environment of low ambient temperature. The Z90.1 a -73 Vehicular Helmet Standard published by the American National Standard Institute (ANSI) and the new Motor Vehicle Safety Standard No. 218, Motorcycle Helmet 49CSR571.218, published by the Department of Transportation (DOT), require impact testing of helmets conditioned by exposure to -10°C and -20°F respectively. The test program for bump protection evaluation of the Army's Combat Vehicle Crewman's Helmet[1] (tanker's helmet) requires cold conditioning periods of not less than four nor more than 24 hours in duration. All require that the helmets be impacted within five minutes of their removal from the conditioning chamber.

The intended purpose of conditioning helmets in low ambient temperature prior to impact testing is to simulate the low ambient temperatures that could be found in the environments where the helmet has potential use. Snowmobilers, military personnel working in winter conditions, and even motorcyclists wear helmets in these environments. It is also possible that helmets may be stored, transported or otherwise exposed to low ambient temperatures during their service life while not being worn. These cold helmets are often subject to damaging impacts when dropped on the ground or pavement.

There is a wide variety of polymers, composites, fabrics and resins used in the manufacture of helmets. All exhibit different mechanical properties under low temperature conditions and require impact evaluation to assure that their useful energy absorbing mechanical qualities and load spreading properties are not lost at low temperatures. This is especially important since the helmet is expected to protect a human head from impact damage regardless of ambient temperature.

In theory, the pass or fail acceleration criteria of the ANSI or DOT test methods should eliminate those helmets that show significant cold temperature sensitivity such as stiffening and embrittlement.

Current test procedures, though based on the above justifications and rationale, remain a priori and lack a firm experimental foundation. A review of the literature indicates that there has been no data developed on the actual temperatures of helmet structures when worn upon the head. The purpose of this study was to determine the correlation of helmet temperature dynamics under simulated cold climate conditions and the prescribed cold conditioning of standard helmet impact test methods and assess their validity.

METHODS AND MATERIALS

One sample from each of four types of helmets was evaluated in this study. The first, a sling suspension helmet, was represented by the military SPH-3 which, for purposes of this study, was essentially the same as the SPH-4 currently worn by Army aviators. The shell was 10-ply laminated fiber glass under which was a 0.5 inch mean thickness crushable expanded polystyrene foam liner having a density of 5 lbs/cu. ft. The helmet was supported on the head by a cloth strap suspension which provided a nominal 0.6 inch air gap between the head of the wearer and expanded polystyrene liner. The structure of this helmet type, henceforth, referred to as the "sling suspension" helmet, is shown in Fig. 1 through 3.

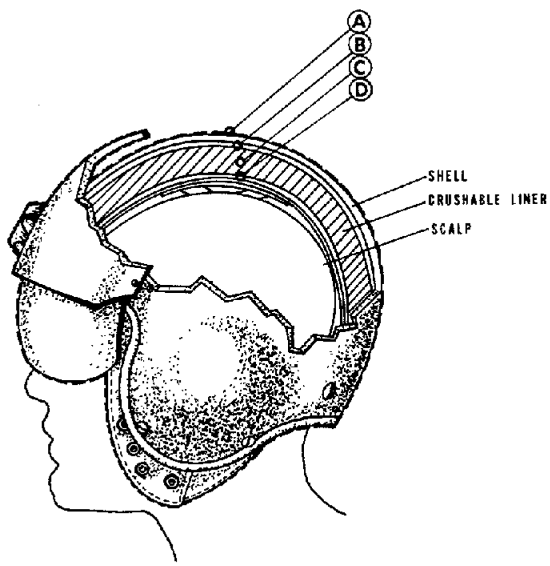
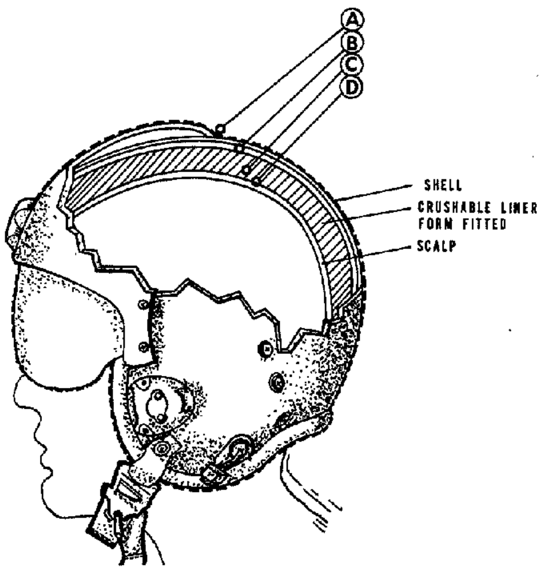


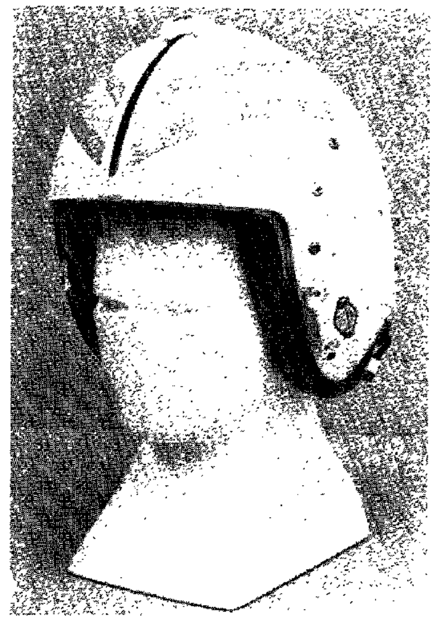
Fig. 1. (Above Left) Sling suspension helmet - structure and thermocouple locations.

Fig. 2. (Above) Sling suspension helmet - outside view.

Fig. 3. (Left) Sling suspension helmet - inside view.

The second type of helmet considered was a form fitted helmet. This helmet had an outer multilayered fiber glass shell with a 1.0 inch (mean thickness) crushable inner liner of polyurethane foam having a density of 3 lbs/cu ft. Separating this layer from head of the wearer was a comfort liner of leather backed with 0.2 inch layer of soft polyurethane foam. The structure of this helmet type, henceforth called "form fit", is shown in Fig. 4 through 6.





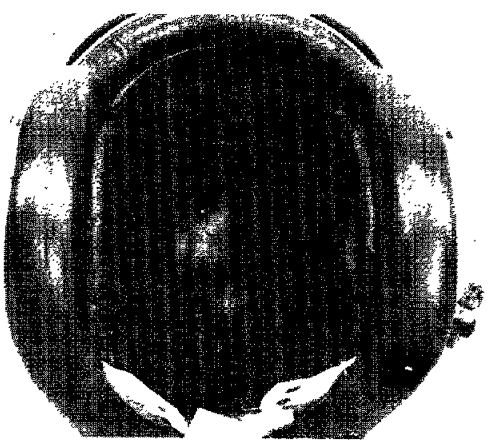
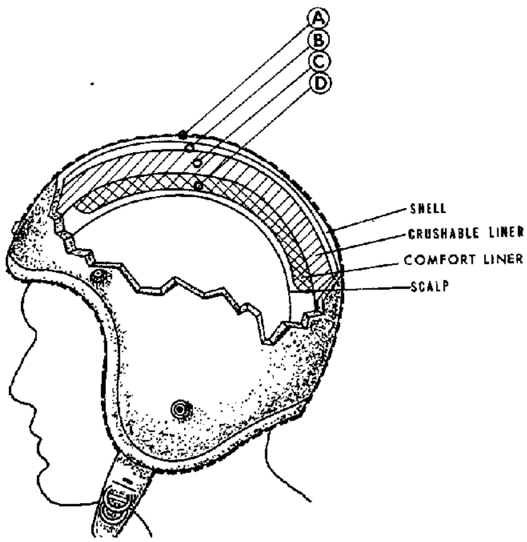


Fig. 4. (Above Left) Form fit helmet - structure and thermocouple locations.

Fig. 5. (Above Right) Form fit helmet - outside view.

Fig. 6. (Left) Form fit helmet - inside view.

The third type of helmet evaluated was a typical motorcycle helmet. This helmet had a polycarbonate outer shell with a 0.7 inch (mean thickness) crushable inner liner of expanded polystyrene having a density of 5 lbs/ cu ft. A 0.25 inch thick comfort liner was provided between the top of the wearer's head and the crushable inner liner. The structure of this helmet type henceforth called "standard motorcycle" (abbreviated "Standard M.C.") is shown in Fig. 7 through 9.



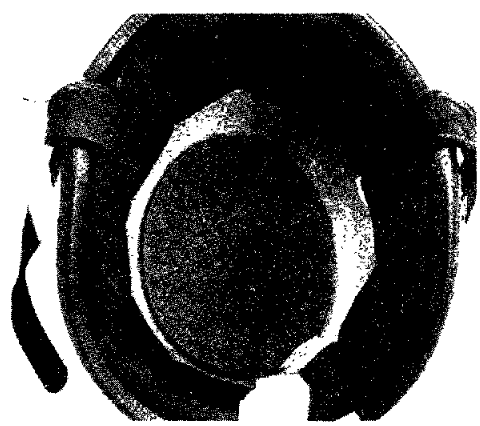


Fig. 7. (Above Left) Standard motorcycle helmet - structure and thermocouple locations.

Fig. 8. (Above Right) Standard motorcycle helmet - outside view.

Fig. 9. (Left) Standard motor cycle helmet - inside view.

The last type of helmet considered was a "shortie" motorcycle helmet which had a polycarbonate outer shell and a 0.6 inch (mean thickness) crushable inner liner of expanded polystyrene having a density of 5 lbs/cu ft. Unlike the standard motorcycle helmet the shell of the short helmet did not extend below ear level. This helmet also had a comfort pad of polyurethane foam between the top of the wearer's head and the crushable helmet liner. The structure of this "short motorcycle" helmet pictured in Fig. 10 and 11 is essentially the same as that of the standard motorcycle helmet shown in Fig. 7.

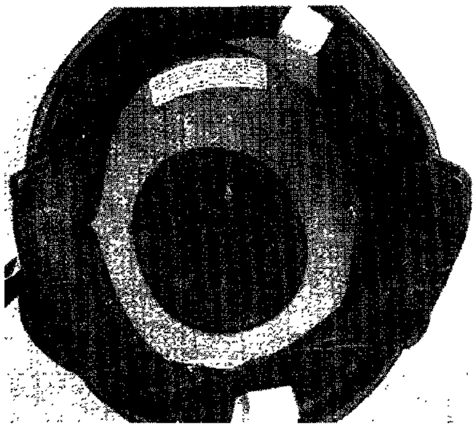


Fig. 10. (Left) Short motorcycle helmet - outside view.

Fig. 11. (Right) Short motorcycle helmet - inside view.

A summary of the helmet structure dimension is given in Table I.

TABLE I. NOMINAL THICKNESS OF HELMET STRUCTURES

HELMET STRUCTURE	HELMET TYPE			
	Sling Suspension	Form Fit	Standard Motorcycle	Short Motorcycle
SHELL	0.09"	0.08	0.16	0.15
CRUSHABLE LINER	0.46	1.00	0.67	0.63
COMFORT PAD	.25	.25	.25	.25

Two experiments were conducted in order to determine the relationship between helmet temperature distributions during actual use in a cold environment and during impact test procedures specified in standard helmet test methods. The first experiment simulated the temperature distribution which might be encountered by a helmet which was left in a parked vehicle (i.e. on the handle bars of a motorcycle or on the seat of a snowmobile) during winter for a long enough period of time that it came to thermal equilibrium with the cold environment. The cold helmet when placed on the head of the user began to warm from the inside as it absorbed body heat. In this experiment, each helmet was preconditioned for 12 hours in a walk-in freezer. The internal temperature of the helmet was monitored in the cold environment while the helmet was donned and worn by a test subject who remained in the chamber for the duration of the experiment; chill factor cooling can be discounted. The rise in helmet structure temperatures due to the subject's body heat was recorded until the helmet reached a thermal steady state condition.

The second experiment simulated the thermal conditions which would be encountered by a helmet undergoing impact testing in accordance with ANSI Standard Z90.1, Section 8.1 (1971).

The data train used in both experiments is illustrated in Fig. 12.

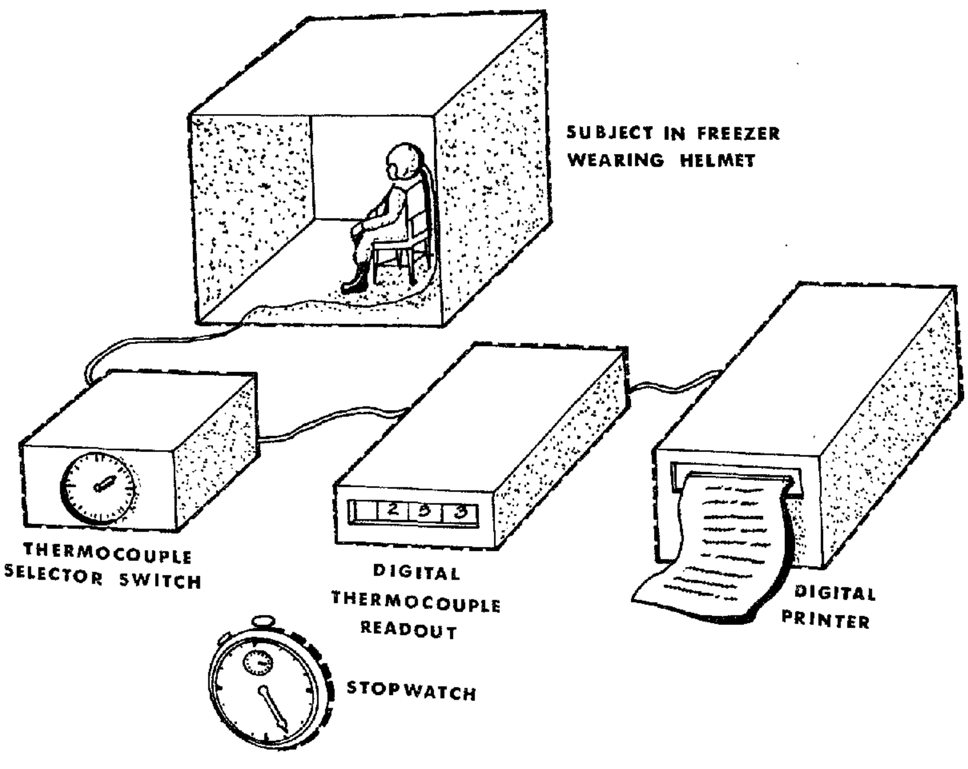


Fig. 12. Data acquisition system.

Chromel-alumel thermocouples, having a maximum error of ± 4°F, were used as temperature sensors. A thermocouple selector switch was used to serially select each thermocouple. A Newport digital thermometer was used to convert the thermocouple output to a digital temperature value in °F. A digital printer was used to record the value from the digital thermometer. Operation of the selector switch, setting time of the digital thermometer, and cycle time of the digital printer produced a maximum time skew of 1.5 seconds between thermocouple readings. In relation to the slow rate of change of the data, this error is insignificant.

The placement of thermocouples at four depths within the structure of each helmet is shown in Fig. 1, 4, and 7 for the sling suspension, form fit and motorcycle helmets respectively. The reference designators A, B, C, and D have been assigned to denote thermocouple depths as follows:

A - the topmost surface of the outer shell at the apex of the helmet.

B - the interface between the outer shell and the crushable liner immediately beneath it.

C - the center of the crushable liner.

D - the center of the comfort pad or in the sling suspension helmet, the bottom surface of the crushable liner.

RESULTS AND DISCUSSION

The temperature data obtained under simulated cold weather conditions is plotted as a function of time in Fig. 13 through 16.

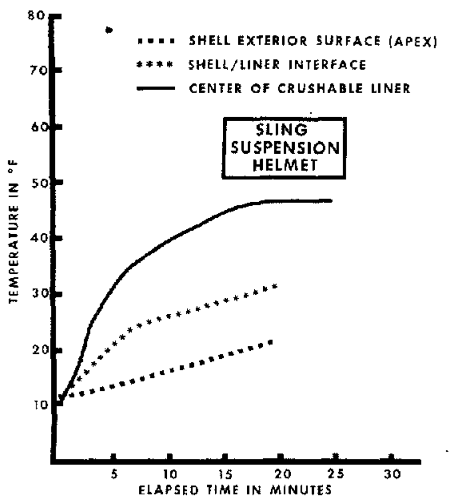


Fig. 13. Simulated cold use condition dynamic temperature response - sling suspension helmet.

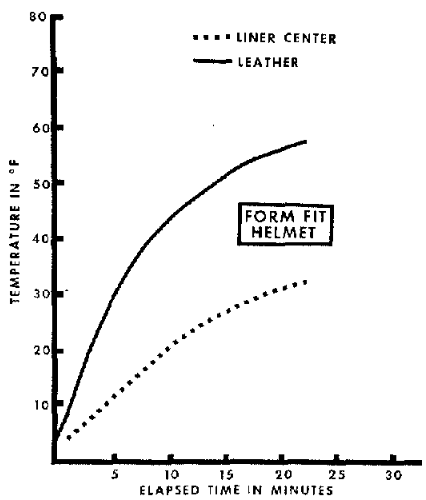


Fig. 14. Simulated cold use condition dynamic temperature response - form fit helmet.

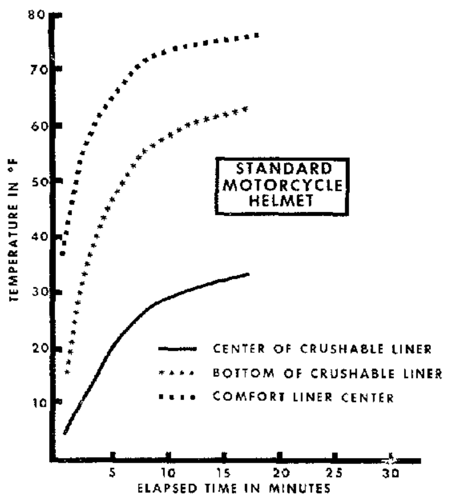


Fig. 15. Simulated cold use condition dynamic temperature response - standard motorcycle helmet.

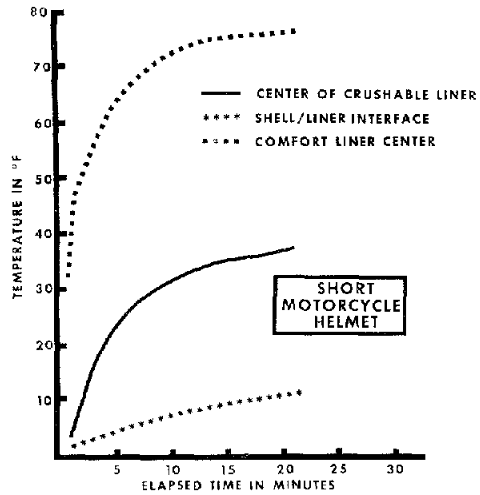


Fig. 16. Simulated cold use condition dynamic temperature response - short motorcycle helmet.

The temperature data obtained during simulated ANSI Z90.1 impact testing procedures is plotted as a function of time in Fig. 17 through 20.

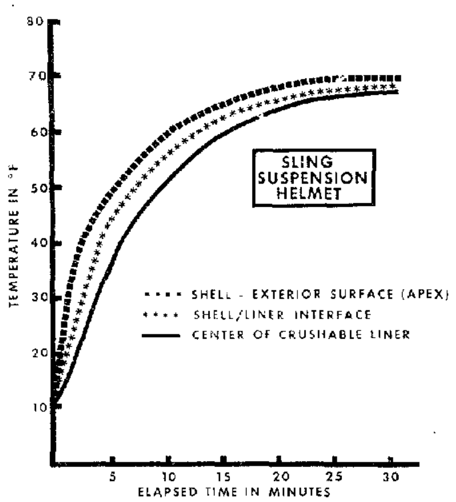


Fig. 17. ANSI Z90.1 cold conditioning dynamic temperature response - sling suspension helmet.

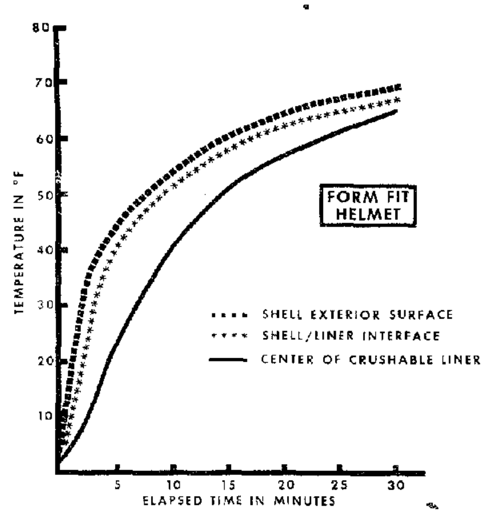


Fig. 18. ANSI Z90.1 cold conditioning dynamic temperature response - form fit helmet.

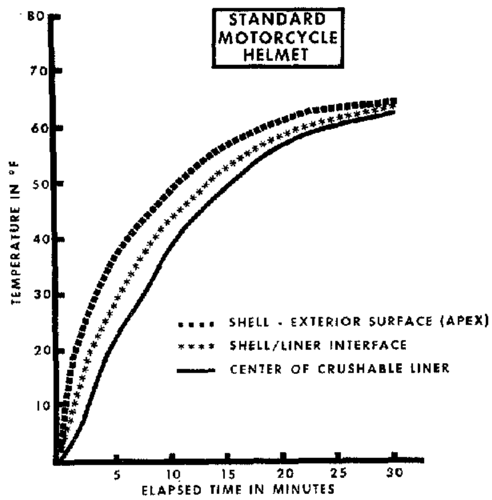


Fig. 19. ANSI Z90.1 cold conditioning dynamic temperature response - standard motorcycle helmet.

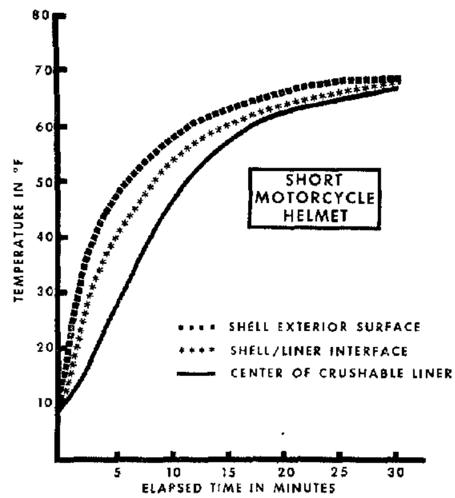


Fig. 20. ANSI Z90.1 cold conditioning dynamic temperature response - short motorcycle helmet.

The steady state temperature attained by each layer of each helmet during use by a subject in simulated cold weather conditions is shown in Fig. 21 through 23. The temperatures encountered by the same helmet two and five minutes after removal from the cold conditioning freezer and prior to impact testing are shown in the same graphs for comparison. The comfort pad in all four helmets very rapidly reached the temperature of the head within it. For this reason, the comfort liner is not given further consideration.

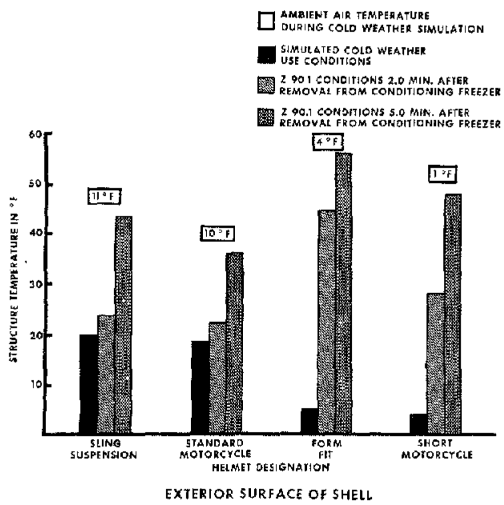


Fig. 21. Steady state temperatures on the exterior surface of the shell (thermocouple depth "A").

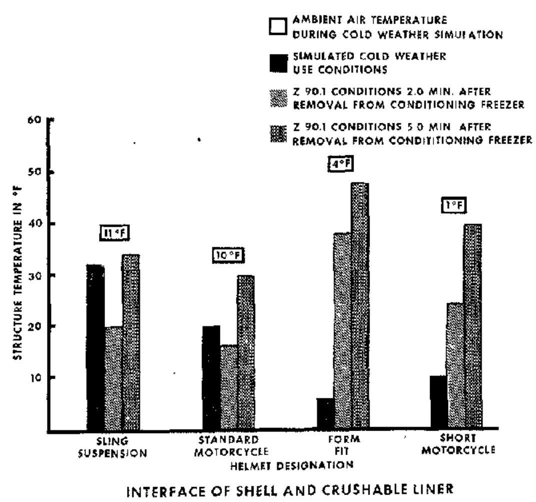


Fig. 22. Steady state temperatures at the interface of the shell and crushable liner (thermocouple depth "B").

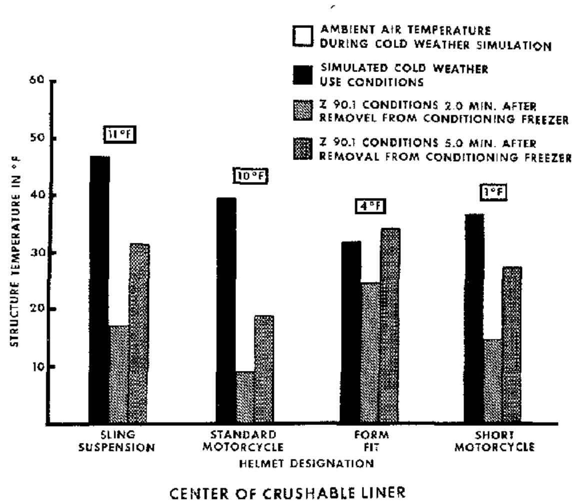


Fig. 23. Steady state temperatures at the center of the crushable liner (thermocouple depth "C")

If the temperature of the form fit helmet at the top surface of the outer shell is considered, see Fig. 21, a large discrepancy between the data acquired in simulated cold weather conditions and the data acquired under Z90.1 cold conditioning procedures becomes apparent. At the end of the maximum time allowed by the ANSI Standard, between removal of the helmet from the freezer and helmet impact (5 minutes), the helmet outer shell temperature had already risen 51°F above the temperature encountered in simulated cold use at an ambient temperature of 4°F. At two minutes after removal from the freezer the apex of the helmet was 40°F warmer than in the simulated cold use environment. The smallest discrepancy found for the outer shell of any helmet tested was the SPH-3 which was 3°F warmer at the apex after two minutes and 20°F warmer after five minutes when compared to simulated cold weather data (11°F ambient temperature). The graphs shown in Fig. 21 through 23 suggest that the discrepancy between the simulated cold weather use data and the Z90.1 was inversely proportional to the ambient temperature of the cold weather environment. That is, the colder the environment, the larger the discrepancy between actual use temperatures and temperatures encountered in the Z90.1 test conditions.

The temperature gradients for each helmet are plotted in Fig. 24 through 27. These graphs describe the temperature of the helmet as a function of depth in the helmet structure. Each of these plots contains three gradients:

a. The helmet structure temperatures at thermal steady state while worn by a test subject in a simulated cold environment.

b. Helmet structure temperatures at two minutes after the helmet had been removed from the preconditioning freezer during a simulated ANSI Z90.1 cold conditioning impact test.

c. Helmet structure temperatures at five minutes after removal of the helmet from the preconditioning freezer during a simulated ANSI Z90.1 cold conditioning impact test.

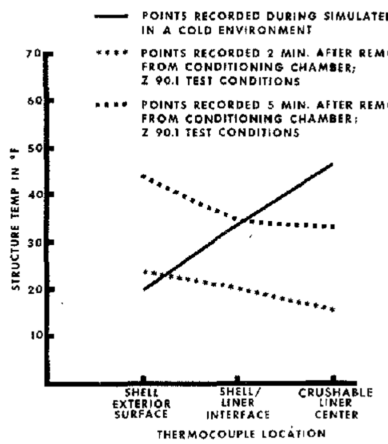


Fig. 24. Temperature gradients in both thermal environments - sling suspension helmet.

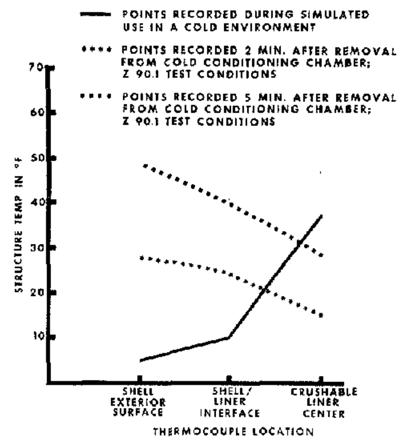


Fig. 25. Temperature gradients in both thermal environments - form fit helmet.

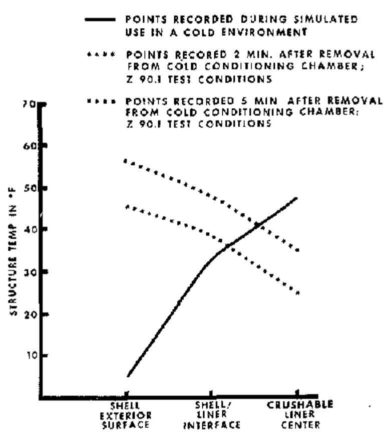


Fig. 26. Temperature gradients in both thermal environments - standard motorcycle helmet.

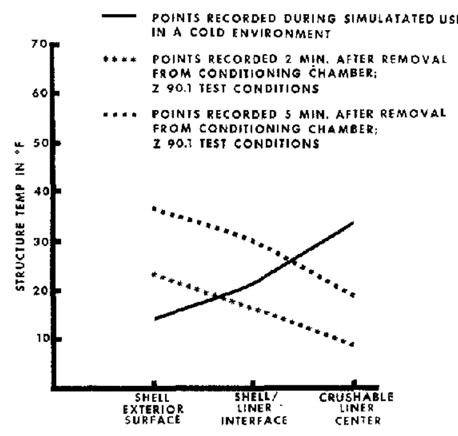


Fig. 27. Temperature gradients in both thermal environments - short motorcycle helmet.

These graphs indicate that within each helmet the temperature gradients were opposite in direction under these two different thermal conditions: simulated cold use and ANSI Z90.1 cold conditioning. All of the helmets preconditioned under ANSI Z90.1 procedures developed negative temperature gradients, while the same helmets in simulated cold weather use conditions developed positive temperature gradients.

The explanation for this phenomenon is straight forward. In actual cold weather use a thermal potential exists between the inside of the helmet which surrounds the exothermic head of the wearer (approximate temperature, 98^{0}F) and the outside of the helmet which is exposed to the cold atmosphere. A cold conditioned helmet placed on a magnesium headform for impact testing will experience a totally different thermal potential: a metal headform at ambient temperature (nominally 72^{0}F) on the inside and ambient air on the outside.

The reaction of the helmets to these differing thermal environments is predictable. In the case of actual cold weather use, the warm head of the wearer will cause heat to flow in the direction of the cooler temperature, at the outer shell of the helmet. As this occurs, a continuous temperature gradient will be established. If the thermal characteristics of the system remain constant (i.e., ambient temperature, wind, scalp temperature, etc.) this temperature gradient will reach a steady state in a form similar to that of Fig. 21 through 24. The shape of the temperature gradient depends upon the helmet structure.

The same helmet under ANSI Z90.1 cold conditioning constraints will experience totally different thermal effects. In this procedure a cold helmet of theoretically uniform temperature is placed on a magnesium headform which is at room temperature (nominally 72^{0}F). Thus, heat will flow into the helmet both from the warm atmosphere and from the warm metal headform. Because of this, the innermost and outermost surfaces will warm up more rapidly than the center of the crushable liner. This produces a "U" shaped temperature gradient as the helmet warms up from heat sources on both the inside and outside. The outer half of this temperature gradient (from the center of the crushable liner to the outer shell) is shown in Fig. 21 through 24. Sufficient data was not taken from the innermost layers to the helmets to show the upward swing of this temperature gradient.

Composite polymer materials, laminates, polycarbonate, and most expanded or chemically molded polymer foams used in helmet construction are temperature sensitive. Under static compression stress the foam characteristically stiffens and the minimum level of stress required for plastic deformation rises. The more elastic materials, i.e., nitrile rubber and polyvinylchloride blended foams, exhibit greater temperature sensitivity than do less elastic materials such as expanded polystyrene. Composites and laminates used in shells seem to have a temperature sensitivity related to the characteristics of the matrix and binder and to the ratio of their combination. Under the dynamic loading characteristics of crash impacts, the rate of stress can be close to impulsive. Any condition that alters either the yield point for plastic deformation or the rate of deformation of the foam will alter the amount of energy transmitted through the helmet to the head. In all accepted helmet test methods this energy transmission characteristic of the helmet is measured as some function of the acceleration imparted to the headform during impact. Helmet shells that stiffen under cold conditions will deform less at the point of impact, thus, spreading the applied load over a much larger area of the liner. Assuming the liner is also stiffer it will take a greater load to cause deformation, thus transmitting a greater force to the head. In general, it is the plastic deformation of the liner that absorbs impact energy during compression, thus, dissipating the impact energy over a finite period of time. If the shell and liner stiffen due to thermal sensitivity to cold, the test headform accelerations resulting from a given impact load will rise in proportion to the increased stiffness.

CONCLUSIONS

The pass/fail acceleration criteria of accepted helmet test standards must eliminate helmets that are unusually temperature sensitive. Based on the data derived in this series of experiments the authors conclude that standard helmet impact test methodologies do not simulate potential real world impact conditions in a cold climate. The standard methodologies are inappropriate for the determination of the cold temperature dynamic response of a helmet system.

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