Development and Manufacture of Visor for Helmet Mounted Display

David Krevor[a*], Gregg McNelly[a], John Skubon[b], Robert Speirs[c]
[a]Kaiser Electronics, a Rockwell Collins Co.; 2701 Orchard Prkwy, San Jose CA 95134;
[b]MXL Industries; 1764 Rohrerstown Road, Lancaster, PA 17602;
[c]Plastics & Rubber Department; Ferris State University, Big Rapids, MI 49307

ABSTRACT

The manufacturing design and process development for the Visor for the JHMCS (Joint Helmet Mounted Cueing System) are discussed. The JHMCS system is a Helmet Mounted Display (HMD) system currently flying on the F-15, F-16 and F/A-18 aircraft. The Visor manufacturing processes are essential to both system performance and economy. The Visor functions both as the system optical combiner and personal protective equipment for the pilot. The Visor material is optical polycarbonate. For a military HMD system, the mechanical and environmental properties of the Visor are as necessary as the optical properties. The visor must meet stringent dimensional requirements to assure adequate system optical performance. Injection molding can provide dimensional fidelity to the requirements, if done properly. Concurrent design of the visor and the tool (i.e., the injection mold) is essential. The concurrent design necessarily considers manufacturing operations and the use environment of the Visor. Computer modeling of the molding process is a necessary input to the mold design. With proper attention to product design and tool development, it is possible to improve upon published standard dimensional tolerances for molded polycarbonate articles.

1. INTRODUCTION

1.1 The Visor in the Helmet Mounted Display

The visor is an essential element of a Helmet Mounted Display (HMD) system. The visor is the optical combiner, which displays information from the relay optics to the user. For tactical aircraft, the visor must also provide personal protection, such as in the case of ejection, where the mechanical stresses on the pilot are extreme. The JHMCS visor is shown in Figure 1.

This paper discusses the manufacturing development of the injection molding process to produce a visor for the JHMCS system.

1.2 The Joint Helmet Mounted Cueing System (JHMCS)

Moffett and Melzer provide an excellent introduction to HMDs in their monograph (1).

The JHMCS system is the first mass-produced HMD system for the U.S. military (2). It is currently flying on F-15, F-16 and F/A-18 aircraft, for the Navy and Air Force. Initial deployment is on the F/A-18E/F Super Hornet, manufactured by Boeing.

[*] dhkrevor@rockwellcollins.com; (408) 532-4760

2. REQUIREMENTS

2.1 Optical requirements for the visor

The optical properties of the visor include both the reflective and transmissive properties. For see-through, maximal transmission and minimal haze are obviously desired. Transmission characteristics of the visor may be modified by additives in the polymer resin. Examples are neutral gray filters, which provide a sunshield; and short wavelength-blocking dyes to provide UV protection or high contrast.

Figure 1. The JHMCS Visor, with attached mounting hardware.

Reflective properties of the visor are also essential. The display image source is reflected on the visor surface. The inner, concave surface (i.e., towards the pilot) is the optical combiner for the display. The Fresnel reflection, due to the air-visor interface, is not adequate to provide a bright display to the pilot. Therefore, the visor reflectivity is enhanced in the region of the display by depositing a thin-film beamsplitter coating on the visor surface. Marasco (3) describes the balance between environmental characteristics, visor transmission and reflectivity, and performance.

2.2 Mechanical Requirements for the visor

The visor is protective equipment for the pilot. This mechanical requirement determines the choice of optical resin. Polycarbonate is the preferred material because of its superior impact resistance. The impact strength of polycarbonate compensates for its reduced transmission and birefringence properties, relative to other optical resins (i.e., acrylic, polystyrene and cyclic olefin polymers). Polycarbonate is also the preferred material for less sophisticated protective optical visors, such as for ice hockey and motorcycles. [Polycarbonate is also used for non-optical products which require strong impact resistance, such as ice hockey helmets.]

Figure 2 shows the visor and HMD after ejection sled testing. The system is mounted on a crash-test dummy.

Figure 2. The visor and HMD after ejection sled testing.

2.3 Hardcoat

The injection molded visor requires coatings to enhance both mechanical and optical properties. A protective hardcoat (4) is used to provide abrasion and scratch resistance, which is the primary wear and failure mode for the visors. Typically, these hardcoat materials are thermally cured polysiloxane materials, although urethanes and other chemistries have been used. These materials may be dip-coated or spray-coated. Thicknesses are on the order of 0.0001".

The hardcoat itself provides a partial anti-reflective coating. This is because the refractive index of the hardcoat is typically less than that of the polycarbonate (RI = 1.58). Refractive indices of available hardcoats vary from about 1.42 to about 1.53, depending upon chemistry.

2.4 Optical Coatings and Secondary Reflections

Thin film optical coatings provide an AR (anti-reflective) coating on the exterior surface, and a beamsplitter coating on the interior, concave imaging surface. As noted above, the beamsplitter coating is necessary to provide sufficient image intensity to the pilot. The display source intensity and the beamsplitter coating reflectivity determine the luminance to the pilot.

Note that the AR coating on the exterior surface is superfluous to allow sufficient light to transmit to the pilot from the outside environment. The purpose of the AR coating on the exterior of the visor is to reduce secondary reflections (i.e., "ghosts") to the pilot from the display source.

The ghost image is a result of the reflections from both interior and exterior surfaces of the visor. The display is imaged on the interior surface of the visor. However, some light passes through the visor and is reflected off of the exterior surface, back to the pilot. This reflection, off the exterior surface, causes the ghost or secondary reflection.

The secondary reflection is optical noise and could be a distraction to the pilot. It is desired to minimize the secondary reflection, with respect to the display image (i.e., the primary reflection). Therefore, the exterior anti-reflective coating is applied. Figure 3 diagrams the problem.

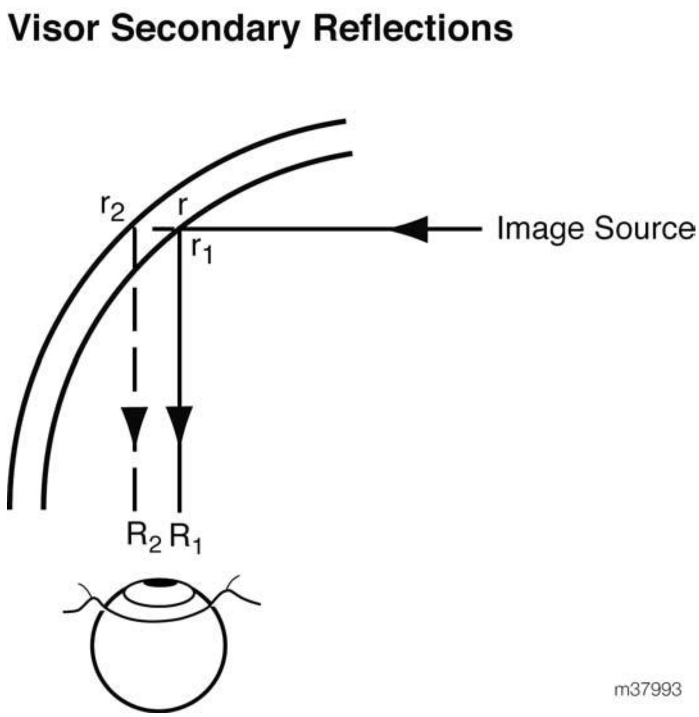

Figure 3. The secondary reflection, i.e., "ghost image", is the reflection off of the outer surface of the visor. The inner, concave surface is the combiner for the primary display image.

The intensity of the secondary reflection, relative to the primary reflection (i.e., display image) may be approximated by

$$R_2 / R_1 = [\, t^2 \; r_2 \; (1 - r_1)^2 \,] / \; r_1$$

where

R_1 is the intensity of the primary display image to the pilot;
R_2 is the intensity of the secondary reflection or ghost image;

t is the transmission of the visor;
r_1 is the reflectivity of the interior, concave visor surface;
r_2 is the reflectivity of the exterior, convex visor surface;

This expression neglects the effect of the hardcoat and other second order effects. The balance between visor transmission, image intensity and optical noise intensity dictates the design choices for the visor. This balance is dictated by the environmental conditions (i.e., day or night), the intensity of the image source and tolerable level of optical noise. This balance between image intensity and transmission in the display region, together with the outside environment, determine the pilot's visual acuity, as described by Marasco (3). The secondary reflection is an additional factor.

Manufacturing tolerances of the thin film optical coatings must also be considered when calculating intensity of the secondary reflection. Due to standard manufacturing variances, the reflectivity of the beamsplitter coating can vary by several per cent, from article to article.

3. MOLD DESIGN

3.1 Injection Molding Tool Design and Dimensional Tolerances

Injection molding has existed as a technology for more than a century. Plastics injection molding became prevalent after World War II. General Electric commercialized polycarbonate as a molding resin in 1955. Bryce (5, 6) and Speirs (7) provide good introductions to injection molding and injection mold design.

The prerequisite to successful molding is to design and build a good tool (i.e., the injection mold, shown in Figures 4, 5 and 8). Design-for-manufacture and concurrent engineering are essential.

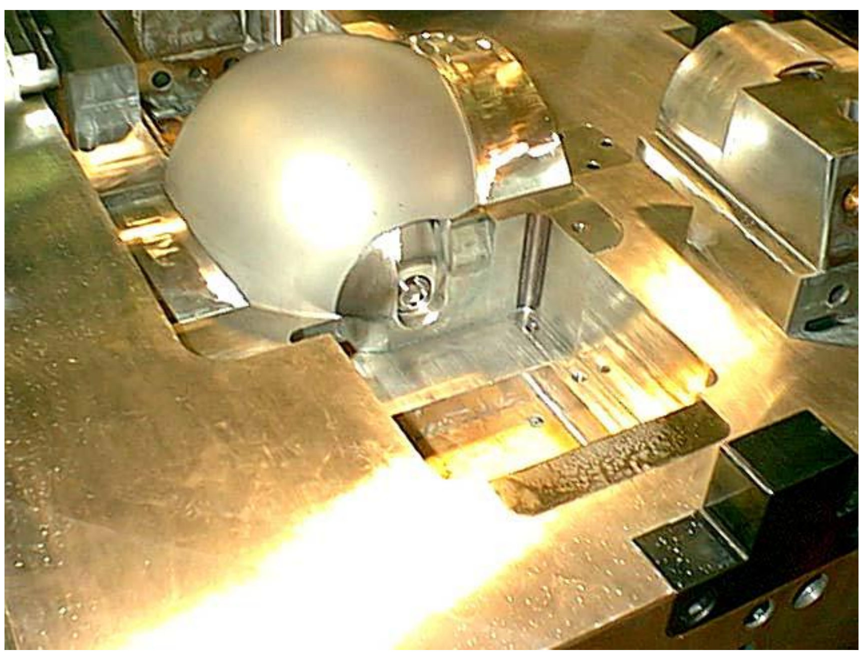

Figure 4. The core-side of the mold, showing internal action and cavity for external action.

Unique features of this visor mold are the internal core actions. Two visor mounting features are toward either ear, on the interior and exterior surfaces of the visor. To mold the interior mounting features, internal core actions are necessary, shown in Figure 4. These actions are pneumatically activated.

The alternative to molding these features would be a secondary operation to affix these mounting features to the visor after molding. This could be done by use of an adhesive, or by sonic or solvent welding. However, the dimensional tolerance requirements of the system design could not have been satisfied by any method other than molding-in these mounting features.

The visor dimensional tolerances derive from the functionality of the HMD system. In addition to the display providing information to the pilot, there is also a camera which records what the pilot is viewing. The camera provides documentation, recording what the pilot sees in the display and in the environment. Fidelity between the display and the camera is critical.

The visor contributes to the optical fidelity between the display and camera. Specifically, the visor dimensions must be within a narrow tolerance to ensure that camera/display fidelity is maintained, when replacing one visor for another (such as when changing from Day Visor to Night Visor when the sun goes down). The position of the visor in space, with respect to the display optics and camera, should be constant. Two factors affect the position of the visor: the mounting points and the visor shape. It is these two factors that should be the same, from visor to visor.

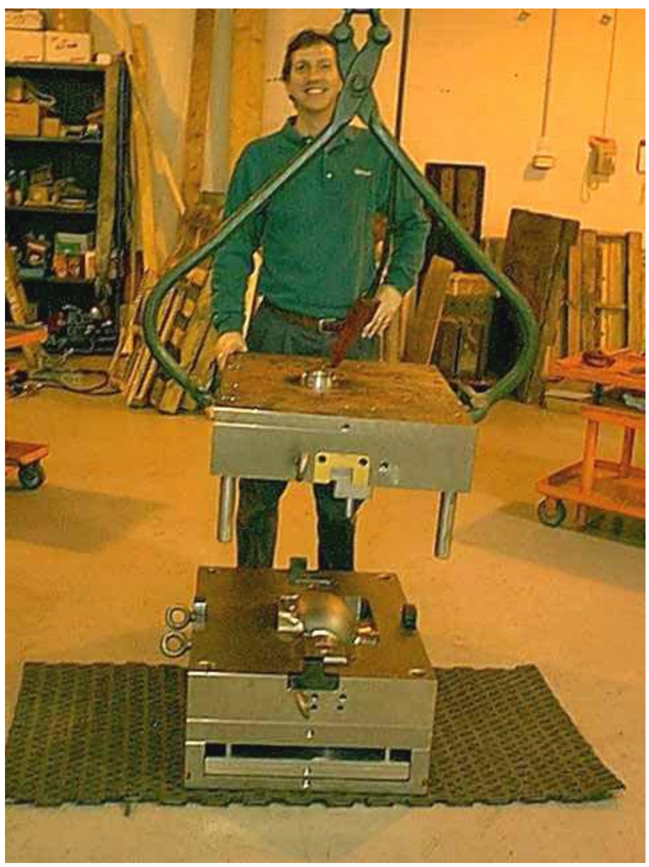

Figure 5. The injection mold.

Typical injection molding manufacturing tolerances for polycarbonates (and other resins) are available in trade publications (8). Closer (i.e., tighter) tolerances can be achieved, with greater attention to detail, multiple metrology checks during the mold build process and optimization of the injection molding process parameters. Iterative checks, between machining and metrology are necessary. Trial molding is done before final finishing of the tool, to check for dimensional fidelity and allow for adjustment. During the manufacture of this visor mold, such greater attention to detail was devoted.

Such greater care during the mold design and build process necessarily increases the cost of the mold. However, it does not increase the recurring cost of the visor. Manufacturing the visor, once the processing parameters are established, is no more costly than an analogous commercial commodity.

Figure 5 shows the completed mold. It is a combination of sheer mass - the mold weighs in excess of 3,000 lbs. and is designed to operate in a 300-500 ton press – and intricate mechanical and pneumatic actuators, capable of reproducibly molding precision features as fine as 0.001". Bryce (6) and Speirs (7) discuss the intricacies of components and mechanisms used in such sophisticated molds.

The well-manufactured visor saves time and money for the designer, the manufacturer, the customer and the user. To ensure low cost system manufacture and low-cost system maintenance, we want all visors to be identical, within tolerance. If visors are identical, less adjustment latitude is necessary for design into the system; less adjustment is necessary during the system manufacturing process; and less system adjustment is necessary when the user changes a visor.

3.2 Concurrent Engineering and Transition to Manufacturing

Contract award for the injection molding tool was made after a national search and review of competitive bids. Both cost and technical capability - explicitly including technical risk - were primary downselect criteria. Several companies were considered capable of making the tool and manufacturing the visors. This visor mold was designed and built by MXL Industries.

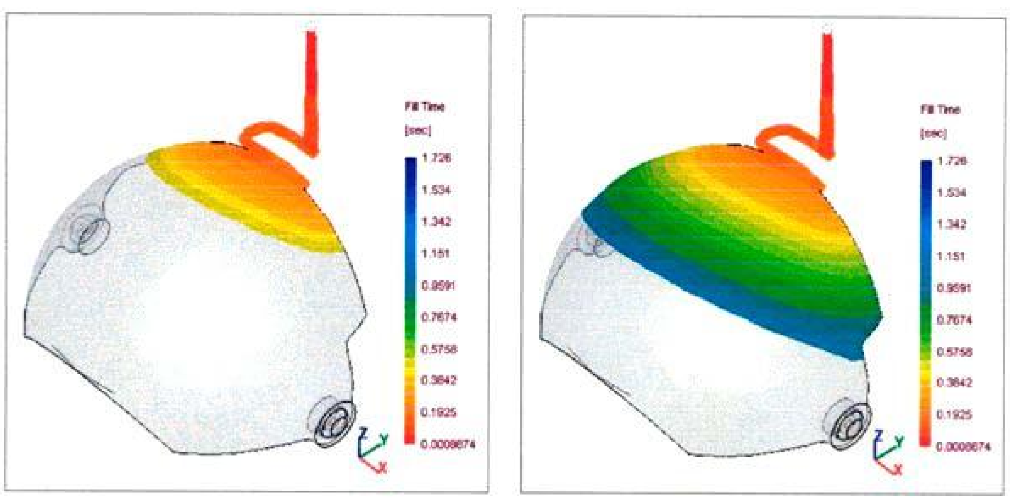

Figure 6. MoldFlow analysis showing melt front advancement during cavity fill

System requirements and design reviews were necessary to ensure that the tool was made correctly the first time. Following contract award, a Systems Design Review was held to clarify the product requirements and ensure that the requirements were consistent with the toolmaker's capabilities. Some design changes were made to the visor in order to improve manufacturability. A Preliminary Design Review was held to present the toolmaker's design concept, including the strategy to ensure that all dimensional requirements were met. The Critical Design Review presented the final tool design for evaluation, along with all modeling and simulation results to justify the design choices. The product design was necessarily frozen prior to the CDR. All modeling and simulation work were complete prior to CDR, and provided input to the design.

Design Reviews were attended by all major shareholders. In addition to MXL and Kaiser Electronics (HMD designer), also represented were VSI (JHMCS integrator), Boeing (the system/aircraft integrator, and manufacturer of the F/A-18 and F-15), the U.S. Air Force (flying the F-15 and F-16) and the U.S. Navy (flying the F/A-18). Attendance by all major shareholders at the design reviews was essential to ensure that all viewpoints were considered, from designer to fabricator to integrator to end-user.

3.3 Modeling of Molding Process

Computer modeling is an important tool in design for manufacture of precision plastic parts. For the JHMCS visor mold, the computer analysis was provided by CAE Services (Batavia, IL), using the MoldFlow Plastics Investigator software. The mold simulations included cavity fill, gate design, pressure distribution, weld line prediction, shrinkage, and per cent polymer frozen at shut-off. The flow properties of two candidate resins were compared. A fill analysis is shown in Figure 6.

Of critical importance to this development was the cooling analysis. To achieve uniform dimensions and meet design tolerances, it is essential that the mold be at a uniform temperature and that there are no significant temperature gradients across the mold.

The cooling analysis emphasized the need for the copious cooling lines that were machined into the mold. This was particularly important for the core side and actions, where space constraints made it challenging to add sufficient cooling lines. Cooling line temperature modeling is shown in Figure 7.

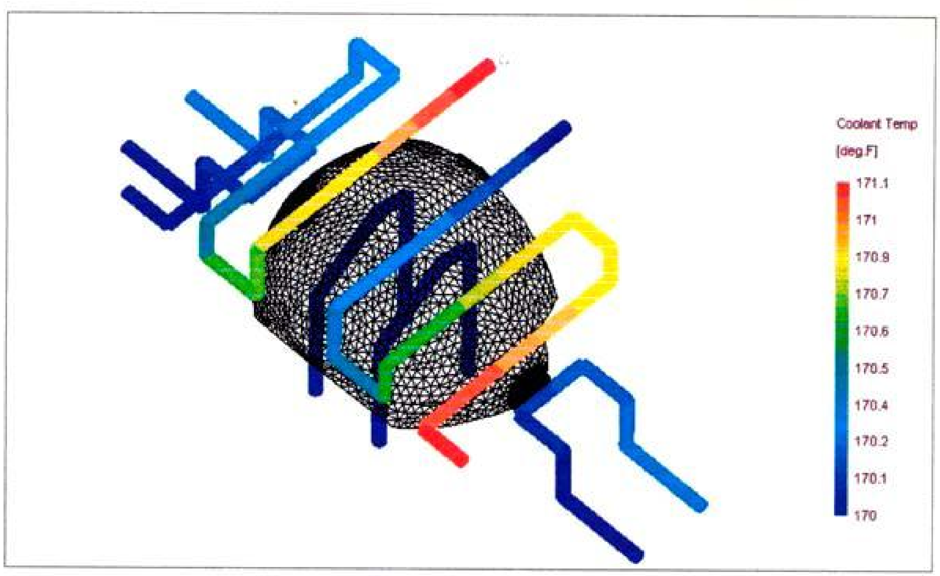

Figure 7. MoldFlow analysis showing mold coolant temperature calculations.

3.4 Optical Finish

Excellent surface properties are essential for optical quality. The fine quality surface of the mold is a prerequisite to surface quality of the part, which is prerequisite to optical quality. It is noteworthy that this surface quality for optical molds exceeds those specifications listed in trade society publications (9). Mold surface quality is achieved by hand polish with fine grits, after the best achievable machine-polish with diamond tools. The fine polish of the cavity side of the mold is shown in Figure 8.

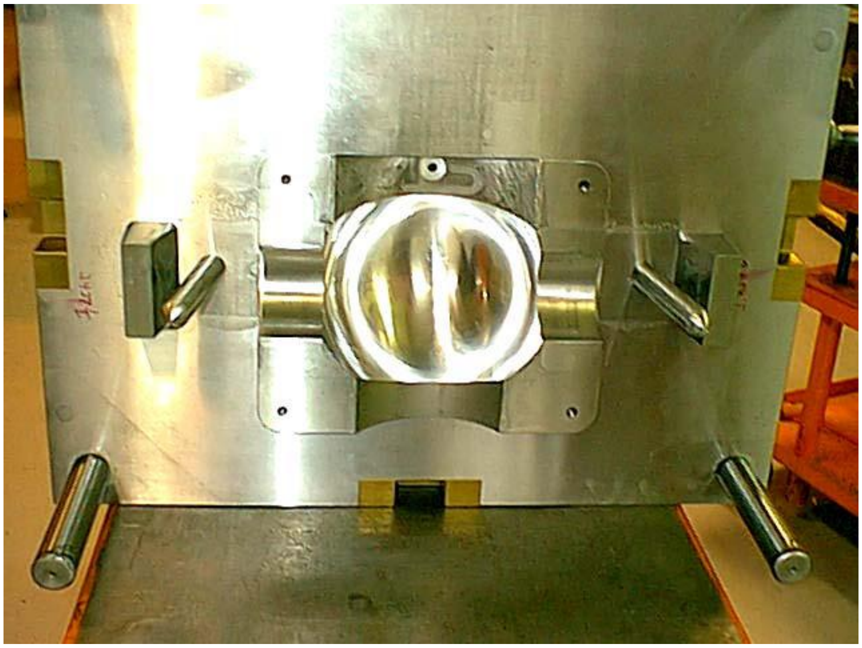

Figure 8. Cavity-side of mold, showing polish of optical surface.

4. MANUFACTURE

4.1 Polymer Resin

The resin is provided by General Electric: Lexan OQ2720. GE provides processing information – including recommended injection press settings and temperatures - for its injection molding resin. These suggested parameters are the usual starting point when the mold is first used. Processing is then optimized for the specific press and mold, including screw temperatures, press temperature, screw speed and pressure.

4.2 Design of Experiments

A Design of Experiments was performed, to determine the optimal processing parameters for the visor. The variables evaluated included cycle speed, residence time of the part in the mold, and injection speed. [A note on terminology: some injection molders use "cure time" for the time the part spends in the mold and use "residence time" for the length of time that the resin melt is in the screw cavity).

4.3 Results

The molded visors met the requirements to which they were designed. Dimensional tolerances on mounting features were as close as 0.001", which was better than expectations. Such precision exceeds the published standards for fine dimensional tolerances for injection molded polycarbonate.

An interesting result of the process design of experiments was that dimensional fidelity was not increased by residence time in the mold, relative to that normally used for commodity products. As a starting point, a residence time of sixteen seconds was used; increasing this to eighteen seconds did not increase part quality.

The JHMCS system is now flight qualified. First deployment is on the F/A-18E/F Super Hornet aircraft.

ACKNOWLEDGEMENTS

For their assistance, we thank Rick Lucasik and Patrick Murray of the U.S. Navy; Ken Fresh, Ed Matheson and Albert Ojeda of the U.S. Air Force; Pat Corbett and Bill Kirk of Boeing; Pat Farrance, Bob Foote and Sharon Kedem of Vision Systems International; Matt O'Connell, Mike Van Treese, Randy Stauffer, Tom Nemec and Tom Shissler of MXL; Chuck Balogh, Rob Bekker, Muh-fa Chen, Paul Hack and Steve Kramm of Kaiser Electronics; Rick Wheeler and Charles Bottieri of AOtec; and Deborah Francome of General Electric. We thank Bob Maes of MXL, a strong contributor and fine teammate, who has since passed away; we miss you, Bob!

REFERENCES

1 James Melzer and Kirk Moffett; *Head-Mounted Displays; Designing for the User";* McGraw-Hill Professional, 1996.
2 Kaiser Electronics website : www.kaiserelectronics.com (see HMDs and Press Releases).
3 Peter Marasco; *"The Impact of Helmet-Mounted Display Visor Spectral Characteristics on Visual Performance";* SPIE Volume 4711; C.E. Rash and C. E. Reese (editors), *HMDs VII*; 2002.
4 MIL-C-83409 (USAF); *"Coatings, Visor, Polycarbonate, Flying Helmet";* 5 February 1974.
5 Douglas Bryce; *"Plastics Injection Molding… manufacturing start-up and management";* Society of Manufacturing Engineers; Dearborn, MI; 1999.
6 Douglas Bryce; *"Plastics Injection Molding… mold design and construction fundamentals";* Society of Manufacturing Engineers; Dearborn, MI; 1998.
7 Robert G. Speirs; *"Injection Mold Development and Design",* a short course for the Plastics Molders and Manufacturers Association of Society of Manufacturing Engineers; 2000.
8 "*Standards and Practices of Plastics Molders,"* Guidelines for Molders and their Customers; The Society of the Plastics Industry; Washington, D.C. 1998.
9 "*Cosmetic Specifications of Injection Molded Parts";* Specifications for Molders and their Customers; The Society of the Plastics Industry; 1994. And, *"SPI Mold Finish Guide";* catalog AR-106.