MONITOR-BASED, NON-COLLIMATED CPH DISPLAY FOR CCTT TANK TRAINERS

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ABSTRACT

Commanders in M1 and M2 tank vehicles have the capability to open the hatch to a protected open position, or "popped" position. In the commander's popped hatch (CPH) position the commander has a 360 degree view of the surrounding environment. The CCTT tank simulators require a display that simulates this popped hatch view.

A CPH display approach, which provides a 360 degree horizontal field of view, is a monitor-based, non-collimated display which uses a continuous single-piece acrylic beamsplitter. Ten 26-inch, high-resolution, monitors surround the beamsplitter. Five of the monitors are located directly behind the beamsplitter, in a horizontal orientation, and are viewed directly through the beamsplitter. The remaining five monitors are located above the beamsplitter, in a vertical orientation, and the monitor image is viewed as a reflection in the beamsplitter. The resulting display appears as ten horizontally juxtaposed monitors, with only a 0.5 degree gap between adjacent images.

The single-piece beamsplitter is composed of two types of regions or panels. Five flat, trapezoidal shaped, reflective panels are located directly beneath the vertical monitors to reflect the image back to the eyepoint. Curved direct view panels are located between the reflective panels to provide a smooth transition and to eliminate spurious reflections. The beamsplitter is fabricated from a single piece of molded acrylic. A vacuum deposited chrome coating is applied to the formed acrylic to create the beamsplitter mirror surface.

The 26-inch monitors are supported by an aluminum structure. The inside corners of the vertically oriented monitors are located within 1/8 inch of each other, requiring monitor ear repositioning.

The CPH display provides a 360 degree horizontal by 27.4 degree vertical field of view. The display resolution exceeds 6.5 arcmins/OLP. The brightness exceeds 8 ftL and the contrast ratio exceeds 15:1.

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INTRODUCTION

In the M1A1, M1A2 and M2M3 vehicles the commander has the capability to partially open his upper hatch into a protected open position or "popped" position. In this position, also known as the commander's popped hatch (CPH), the hatch is raised straight up to create a 3-5 inch gap between the bottom edge of the hatch and the top of the turret. This position provides the commander a full 360 degree horizontal view of the surrounding environment while remaining somewhat protected. From the popped hatch position the commander can also use binoculars or night vision goggles.

Since the popped hatch position provides the commander a 360 degree view of the surrounding environment, the Close Combat Tactical Trainer (CCTT) requirements specify that a CPH display be provided which fully renders a 360 degree horizontal image. The CCTT requirements further specify that gaps between adjacent images be no larger than two degrees.

A CPH display consisting of ten 26-inch monitors and a single-piece acrylic beamsplitter was developed to satisfy these CCTT requirements. The monitors and beamsplitter are arranged in a unique configuration to provide a nearly seamless 360 degree horizontal field of view.

CPH DISPLAY DESIGN CONCEPT

Clearly there are several approaches to implementing a 360 degree display for a commander's popped hatch view. Perhaps the most straight forward as well as least costly and least complex CPH display approach would be to simply place a set of CRT monitors side by side in a circle around the commander's popped hatch. CRT monitors provide a low-cost, low-maintenance, high-resolution display with excellent image quality when compared to the other display alternatives.

The problem with this approach, however, is that display suffers from large gaps between adjacent monitors. The CRT phosphor area where the image is actually rendered is typically located 1-2 inches from the physical sides of the CRT. Although the individual monitor cabinets can be removed to allow the monitors to be placed more closely together, the physical gap between the CRT phosphors for any two adjacent monitors will still be separated by 2-4 inches. For any viable monitor configuration that satisfies CCTT fields of view and resolution requirements, this equates to a 3-5 degree gap between adjacent images.

In order to decrease the 3-5 degree gap to two degrees or less it would be necessary to physically move the monitors into each other such that the edges of adjacent CRT monitors actually occupy the same physical space. This, of course, is not physically possible.

The same effect can be achieved, however, by rotating every other monitor into a vertical position and by adding a mirror, or in this case a beamsplitter, below the monitor as shown in Figure 1. By locating a beamsplitter directly below the vertical monitor a reflected image of the monitor can be viewed from the center of the monitor array or eyepoint.

The horizontal monitors are viewed directly by looking through the beamsplitter. The beamsplitter is continued in front of the direct view horizontal monitors to provide equal luminance attenuation and viewing characteristics for all monitors, both direct view and reflected.

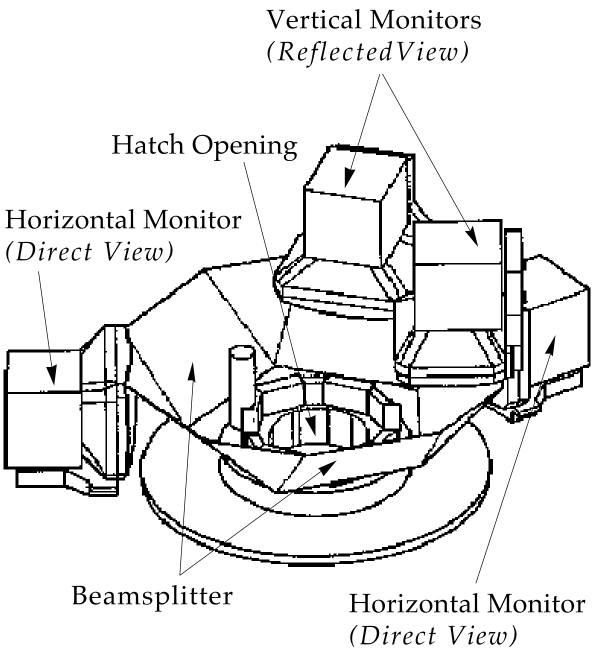

Figure 1. Cross sectional view of the CPH display design concept (only a portion of the total number of monitors are shown).

The horizontal and vertical monitors are arranged such that the reflected vertical monitor image appears to be the same distance away from the eye as does the directly viewed horizontal monitors. With each vertical monitor located physically above and between the horizontal monitors a virtual image of the vertical monitor appears to the observer as if it is positioned horizontally and located between the two adjacent horizontal monitors as shown in Figure 2.

With the horizontal and vertical monitors at physically different locations, it is possible to move them closer together laterally to significantly reduce the gap between adjacent monitor images. The array of monitors can be positioned such that the left and right edges of the individual monitors appear to physically occupy the same space (see Figure 2). This results in a display where the edges of the CRT phosphors appear to be much closer to each other than could be achieved by simply placing the monitors side by side.

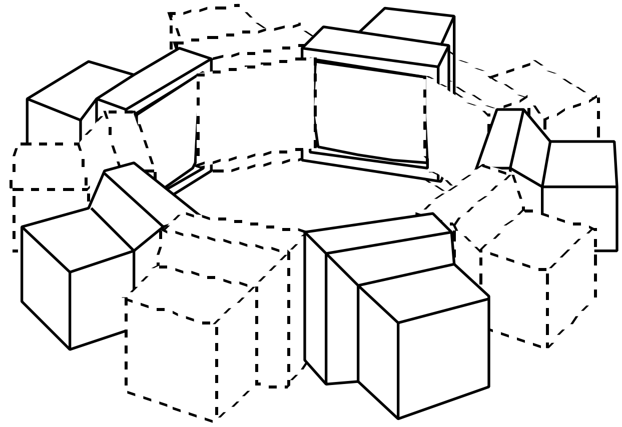

Figure 2. Virtual positions of the CPH display vertical monitors (dashed lines) with respect to the horizontal monitors (solid lines).

CPH DISPLAY OPERATION

Image Generator Configuration

In the CCTT configuration the ten monitor CPH display is normally connected to five separate video streams from the image generator. Each video stream is connected to two monitors 180 degrees opposite each other. The CCTT image generator configuration is capable of driving the monitors at 896 pixels per line by 768 lines.

Since the display can render a full 360 degrees a head tracker is required. The image generator in response to positional data from the head tracker drives the CPH display to render an instantaneous 180 degree horizontal field of view. As the user turns his head the five monitors most directly in front of him are active with the correct orientation and heading. The monitors behind the user, which obviously cannot be seen, are simply repeated views of the monitors in front of the user.

The CPH display configuration also incorporates an area of interest (AOI) feature where the two monitors most directly in front of the user are render with images at twice the resolution as the displays to either side. The high-resolution AOI images are switched from monitor to monitor as the user turns his head.

Parallax and Total Field of View

The beamsplitter does not provide any collimating effects for the monitor images. However, the CPH display provides many of the benefits of a collimated display since computation of the scene is based on the instantaneous eyepoint position as sensed by the head tracker. This provides a correct perspective for the observer throughout the scene despite the presence of a real image at a limited viewing distance. In effect, all objects retain the same relative bearing to the observer, regardless of head position, similar to the effects of a fully collimated display.

The head tracking capability used with the CPH display also gives the observer access to a larger vertical field of view than is available with the instantaneous field of view render by the CPH display alone. The user moves his head to access a greater field of view in the same way that the commander in an actual vehicle moves his head when attempting to gain a larger field of view.

CPH DISPLAY DESIGN CRITERIA

As with any display, there are several critical parameters that define the display. The CPH display design concept described above can vary in the number of monitors and in the size of the monitors required for the display.

The actual CCTT CPH display is based on CCTT visual requirements as well as physical interface requirements with the M1 and M2 training modules and trailers. Specifically, the key CCTT requirements which affect the size and number of monitors are as follows:

- Field of view
  - Horizontal: 360 degrees
  - Vertical: >20 degrees(1)
- Adjacent Images Gap: <2 degrees
- Resolution: 6.7 arcmins/OLP
- Minimum Inside Diameter: 34 inches

(1) In the normal popped hatch configuration, the maximum visible vertical angle measured from the hatch center, between the lip of the hatch cover on top and the outer edge of the vision blocks on the bottom is approximately 20°.

Gap Size Evaluation

As mentioned previously, the CCTT requirements specify that gaps between adjacent images be no greater than two degrees. The CCTT specifications further state that the design goal should be to minimize or eliminate gaps between images.

Although the CPH display concept described above has the capability to greatly reduce the gap size, analysis of gaps between monitor images has shown that it is desirable to maintain a small gap between adjacent monitor images rather than butt match the images.

Monitors tend to have a limited set of adjustments which result in some inherent mismatches between adjacent images in the CPH display. The beamsplitter adds some additional inherent misalignments as well. Although these misalignments are rather small, they become distracting to the observer when the adjacent images are butt matched. Deliberately creating a small gap of about 0.5 degrees tends to make these inherent misalignments non-distracting to the observer.

Determining the Number of Monitors

The CPH design concept dictates that an even number of monitors be used in the display. This allows every other monitor to positioned vertically. Each monitor in the CPH display renders a segment of the total horizontal field of view. Since each segment will be equal in size, the field of view rendered per monitor is determined by dividing the total horizontal field of view by the number of monitors. Once the field of view per monitor is known the resolution can be calculated (given that the number of available lines and pixels is also known).
The CCTT CPH display requires ten monitors to provide the required resolution. This results in

36 degrees field of view per monitor. The vertical field of view (for a monitor 4:3 aspect ratio) is 27.4 degrees as given by the equation:

$$\text{Vertical Field of View } (\theta_V) = 2\tan^{-1}\left[0.75\tan\left(\frac{\theta_H}{2}\right)\right]$$

$$= 27.4^\circ$$

where θ_H is the horizontal field of view per monitor.

The CCTT image generator configuration is capable of driving the monitors at 896 pixels per line by 768 lines. Given that each monitor must render a 36 degree horizontal by 27.4 degree vertical field of view, and assuming a 0.7 Kell factor, the horizontal and vertical resolutions are given as follows:

$$\text{Horizontal Resolution} = \frac{36.0^\circ \bullet 60\text{am}/^\circ}{896 \text{ pixels}} \bullet \frac{2 \text{ pixels/ OLP}}{0.7}$$

$$= 6.9 \text{ am/ OLP}$$

$$\text{Vertical Resolution} = \frac{27.4^\circ \bullet 60\text{am}/^\circ}{768 \text{ lines}} \bullet \frac{2 \text{ lines/ OLP}}{0.7}$$

$$= 6.1 \text{ am/ OLP}$$

The average display resolution for the ten monitor CPH display then is 6.5 arcmin/OLP, which satisfies the 6.7 arcmin/OLP CCTT requirement.

Note that if the number of CPH display monitors is reduced to eight, the horizontal and vertical fields of view per monitor increase to 45.0 and 34.5 degrees respectively. This would degrade the average resolution to 8.2 arcmins/OLP, which would be unacceptable for CCTT. (For an eight monitor display the horizontal resolution is 8.6 arcmins/OLP and the vertical resolution is 7.7 arcmins/OLP.)

Determining the Size of Monitors

The size monitors required for the CCTT CPH display is primarily determined by the minimum inside diameter required to position the display around the commander's hatch without interference. In the case of the M1 and M2 trainers this minimum diameter is 34 inches.

Since ten monitors are required to satisfy the resolution requirements, each monitor must cover 36 degrees horizontally. Figure 3 shows that the monitor must be positioned such that the phosphor area of the CRT completely fills this 36 degree field of view (less an allowance for the 0.5 degree gap). This places the monitor at a fixed distance from the eyepoint.

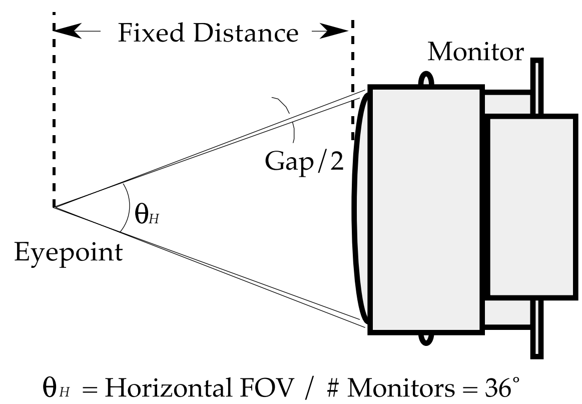

Figure 3. Top-down view of a single CPH display monitor with respect to the eyepoint. The monitor is positioned such that the phosphor area of the monitor fills the required field of view per monitor less the gap area.

The distance from the eyepoint to the CRT phosphor is given by the equation:

$$\text{Phosphor Distance } (d_P) = \frac{w_P}{2\tan\left(\frac{\theta_H}{2}\right)}$$

where w_P is the width of the phosphor and θ_H is the horizontal field of view (less the gap).

Of course, the minimum inside diameter of the display is not simply the distance to the horizontal monitors. Rather, the inside diameter is actually determined by the inside position of the beamsplitter. Beneath the vertically oriented monitors the beamsplitter is positioned at a 45 degree angle as shown in Figure 4. This represents the worst case extension of the beamsplitter towards the center of the display. Note that the position of the vertical monitors may actually form a smaller inside diameter than does the beamsplitter. However, since the vertical monitors are raised up above the hatch area, there is no vertical monitor interference with the hatch.

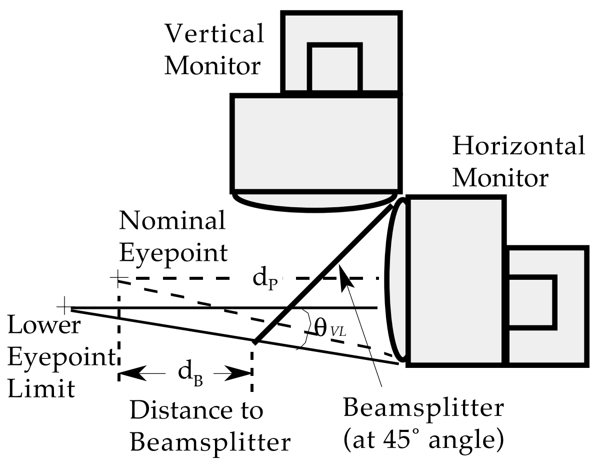

Figure 4. Beamsplitter inside diameter given the worst case eyepoint position.

The length of the beamsplitter is determined by the worst case lower eye position. For both the M1 and M2 commander, the worst case eye position is approximately two inches lower and five inches behind the nominal eyepoint. The beamsplitter needs to extend low enough to accommodate this lower eyepoint position (see Figure 4). Although the commander can move his eyepoint lower than this and still see the CPH display, he is unable to see the lower portion of the display because of other obstructions in the hatch.

Using trigonometric relationships the distance from the eyepoint to the front edge of the beamsplitter can be derived. Specifically, this distance is given by the equation:

$$\text{Distance to Beamsplitter } (d_B) = d_P - \frac{h_P}{\tan\theta_{VL} + 1}$$

where h_P is the vertical height of the CRT phosphor and θ_{VL} is the angle from the lower eyepoint to the bottom of the phosphor (see Figure 4). The distance d_P is the distance from the eyepoint to the phosphor (which equation was shown above). The vertical height of the CRT phosphor is a determined by the size of the monitor. The angle θ_{VL} can be found from the following equation:

$$\text{Angle to Phosphor Bottom } (\theta_{VL}) = \tan^{-1}\left\{\frac{\frac{h_P}{2} - 2}{d_P + 5}\right\}$$

where θ_V is the vertical field of view and h_P is the vertical height of the monitor phosphor.

Given that the phosphor must cover a horizontal field of view of 35.5 degrees -- that is 36.0 degrees less a 0.5 degree gap -- the CPH display requires at least a 24 inch monitor phosphor size (where the phosphor height is 14.4 inches). A 24-inch phosphor size leads to a display design where the distance from the eyepoint to the phosphor is 30 inches and the distance to the beamsplitter is 17.5 inches (providing a 35 inch inside diameter).

In the case of the CCTT CPH display, a 26-inch monitor was actually selected (in part because acceptable 24-inch monitors were not available). This monitor size results in an inside diameter of 38 inches. This also results in a display design in which the phosphor is 32.5 inches away from the nominal eyepoint, which provides comfortable eye relief.

BEAMSPLITTER DESIGN

The most critical component of the CPH display design is the beamsplitter. To provide a full 360 degree horizontal field of view the beamsplitter must be a continuous array of panels about eyepoint. Figure 5 shows the CPH display beamsplitter design concept. The beamsplitter is composed of two different types of regions or panels. In the areas under the vertical monitors, called reflective panels, the beamsplitter must be uniformly flat and set at a 45 degree angle with respect to the monitor. In the area located in front of the horizontal monitors, called direct view panels, the only requirement is that the beamsplitter allow an unobstructed and undistorted view of the monitors.

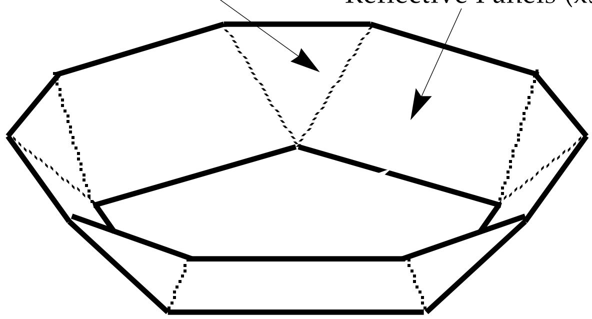

Figure 5. CPH display beamsplitter design concept.

As shown in Figure 5 the reflective panels are significantly larger than the direct view panels. As the observer moves his head side to side with respect to the reflected image, the beamsplitter panel must remain flat and at the 45 degree angle over a sufficiently wide area to provide a distortion free reflected image. The reflective panels are trapezoidal in shape since the distance from the monitor to the beamsplitter varies from the top to the bottom of the beamsplitter. From the nominal eye position, the observer views a horizontal monitor by looking through both the direct view panel as well as the left and right edges of the adjacent reflective panels.

BEAMSPLITTER FABRICATION

Perhaps the most straight forward approach for building a continuous beamsplitter array of this type is to bond together or in someway secure in place ten separate sections of glass (five pieces of each of the two panel types). However, early attempts to build a beamsplitter using this approach proved extremely difficult and costly. In order to position the panels accurately around the array each piece must be precisely machined. Any adjacent panels which did not match precisely created weak points in the beamsplitter structure. This approach also results in a beamsplitter with noticeable seams between adjacent glass panels.

Given the uniqueness of the beamsplitter design and the problems associated with creating a beamsplitter from individual panels, it was concluded that the least complex and cost effective approach would be to form or mold the entire beamsplitter as a single piece of glass.

Spurious Reflections

One of the significant advantages of forming the beamsplitter from a single piece of glass is that it allows the introduction of curved surfaces in the direct view regions.

One of the difficulties with the CPH display concept is that the vertical monitors not only produce a reflected image directly onto the reflective panel located below, it also produces reflected images on the direct view panels located to either side. These spurious reflections, which can be seen from some areas within the eye volume, are visible in the lower half of the direct view panel area.

To correct this problem, the direct view areas are formed into a curved panel section. In the bottom half of the direct view panel area where the spurious reflections occur, the beamsplitter is formed into a concave shape. This concave surface reflects the spurious images away from the eyepoint. The top half of the direct view panel area, where spurious reflections do not occur, is formed into a convex shape to provide clearance between the beamsplitter and the horizontal monitor.

The introduction of curved direct view panels also provides a means of making a smooth transition between reflective panels. The end result produces a beamsplitter in which there are no noticeable boundaries or seams throughout the continuous beamsplitter array.

Beamsplitter Glass Fabrication

There are two basic approaches for fabricating a complex single-piece of glass as required for the CPH display; injection molding and vacuum forming. Tooling for injection molding is extremely expensive, but given a large quantity of parts can be cost effective. The projected beamsplitter quantities for CCTT, however, were not sufficient to make injection molding a cost effective approach. Vacuum forming, on the other hand, has lower tooling costs and the CCTT quantities do support this method as a cost effective approach.

Vacuum forming suffers in that it is not a precise process. It can be difficult to hold tight tolerances and to achieve good optical performance. Scraping or scratching can occur during the forming process and, in addition, any defects or marks in the mold are transferred to the formed glass piece. These types of defects in the beamsplitter can lead to distortion or blur the images in the CPH display.

To improve optical clarity acrylic was selected for forming the beamsplitter glass. Acrylic tends to be more resistant to the scratching or marking that can occur during the forming process. In order to minimize defects or marks from the mold the beamsplitter is fabricated using a highly polished fiberglass male mold.

The forming process itself has also been designed to optimize optical clarity. As shown in Figure 6 heated acrylic is clamped to a vacuum box and then drawn down into the box with a vacuum until it forms a bowl shape. At this point, the mold is lowered down into the box and then the vacuum is released. With the release of the vacuum, the glass springs back up and contacts the mold and is formed into shape. Since the glass is already bowl shaped before it is released, it tends to minimize the surface scratching that can occur as the piece forms to the mold.

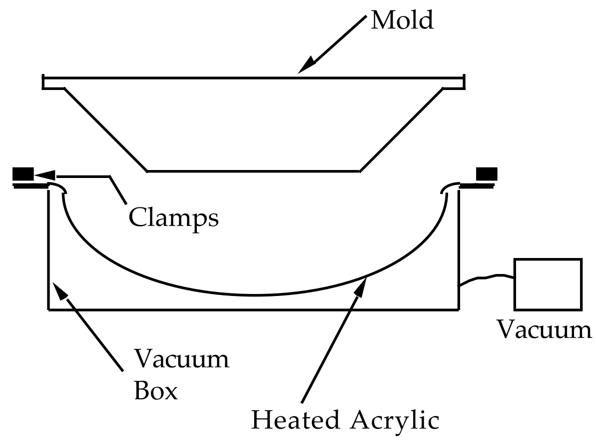

Figure 6. Vacuum forming process for single-piece acrylic glass.

Beamsplitter Assembly

The CPH display requires a beamsplitter that must be held to rather tight tolerances. In particular, the CPH display requires precise positioning and flatness for the reflective panels in order to provide a properly rendered image of the vertical monitor.

Although the proper selection of materials and the proper design of the vacuum forming process results in beamsplitter glass with good optical quality, it is not really practical to expect that the tight tolerances required on the beamsplitter could be achieved through the molding process alone. Therefore, the beamsplitter is designed as an assembly with support structures that hold the reflective panels in precise locations as shown in Figure 7.

Aluminum backing braces are bonded to the back surfaces of the reflective panels to help maintain flatness in this area. Since the user does not look through this part of the beamsplitter it can be blocked by the backing plate. The backing brace is attached to a support bracket which establishes the reflective panel at 45 degrees. The support brackets are tied to a common base which holds the entire assembly firmly in place.

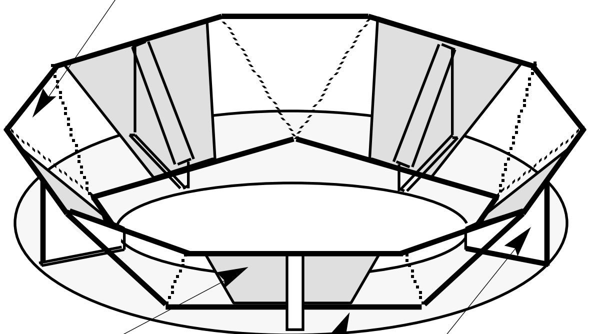

Figure 7. Beamsplitter assembly with formed beamsplitter glass and support structure.

The beamsplitter assembly is assembled on a tooling fixture. The formed acrylic glass is placed on the fixture and clamped into place to force the acrylic to conform to precise positions. The beamsplitter assembly is not removed until the entire beamsplitter has been assembled and locked in place.

The assembled single-piece acrylic beamsplitter results in a highly durable product which is inherently rugged. This is especially critical in trailer installations. Because of the durability of acrylic the CPH displays can be deployed in the trailers without any special packaging or handling of the beamsplitter.

Chrome Mirror Coating

To create the beamsplitter mirror surface, a chromium alloy film is applied to the formed acrylic by thermal evaporation in a vacuum chamber. The mirror coating is applied only after the beamsplitter glass has been formed and completely assembled with backing plates, support brackets and baseplate (as shown in Figure 7).

The chromium alloy film results in a beamsplitter with the following characteristics:

Transmission	27% - 33%
Reflection	27% - 33%
Absorption	34% - 46%

These characteristics are adequate for the CPH display since the vertical monitor images are only reflected once before reaching the eyepoint and the horizontal monitor images only pass through the beamsplitter once before reaching the eyepoint. Therefore, the total incident light that reaches the eye from either source is 27-33 percent. Clearly there are anti-reflective coatings and mirror alloys other than chromium which produce beamsplitters with better characteristics. However, not only are they not necessary to satisfy CCTT requirements, the cost of these anti-reflective coatings and other alloys are prohibitively high.

The chromium coating is reasonably resistant to abrasion. It can be cleaned with any non-abrasive liquid cleaner and soft cloths without scratching, rubbing off, or loss or reflectivity.

MONITOR DESIGN

As shown in Figure 8 brackets are added to the 26-inch monitors to allow the monitor to be installed in a vertical position. These vertical mounts are placed on all monitors such that any monitor may be placed in either a vertical or horizontal position.

In addition, the 26-inch monitor upper mounting ears are moved in about two inches from the upper left and right corners. To move the mounting ears, the CRT tension band must be removed and then reinstalled. This modification is necessary to allow the CRT monitors to come within 1/8 inch of each other when installed in the vertical position.

SUPPORT STRUCTURE DESIGN

The CCTT trailer requirements dictate that the support structure for the CPH display has resonant frequencies greater than 15 Hz and shock loading greater than 4 Gs. The CPH display concept precludes the use of structural elements that pass down vertically through the center portion of the display. Such elements would block the users view of the display in those areas. Therefore all structural elements must be located outside the beamsplitter area.

Figure 9 shows the design of the CPH display support structure. The entire structure is constructed of aluminum. The upper structure is a single piece casting and is held in place by five vertical supports located behind the vertical monitors. The vertical supports are also single piece castings. The vertical supports are all tied to a common base plate. The vertical monitors are attached to the upper structure while the horizontal monitors rest directly on the baseplate.

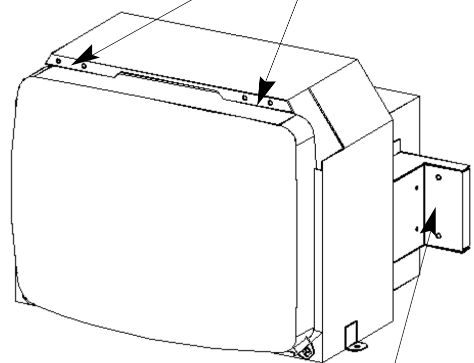

Figure 8. The 26-inch CPH display monitor with vertical support mounts and repositioned mounting ears.

DISPLAY PERFORMANCE

The CPH display meets or exceeds all CCTT performance specifications. Actual measured display performance is as listed below.

Horizontal FOV	360°
Vertical FOV	27.4°
Image Luminance	8 ftL
Image Contrast Ratio	Exceeds 15:1
Edge Match	
Luminance mismatch	Minimally noticeable
Color mismatch	Minimally noticeable
Geometry mismatch	Minimally noticeable
Eye Relief	30 inches
Image Resolution	6.5 arcmin/OLP
Gap Width	0.5°

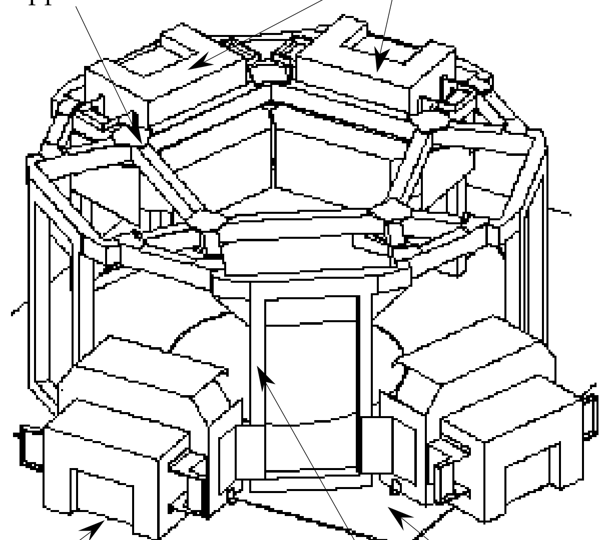

Figure 9. CPH display support structure.