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The optical properties of smoke-protective devices.

THE OPTICAL PROPERTIES OF SMOKE-PROTECTIVE DEVICES

INTRODUCTION

Optimum visual performance for aviation personnel wearing smoke-protective goggles or fullface masks requires that conditions in two general categories be met: (i) the wearer's visual integrity should be maintained relative to the parameters of visual acuity, including a proper fit of corrective lenses when worn with the devices, adequate peripheral visual fields, and normal depth perception, and (ii) the quality of the optical properties of the facepiece of the device must be high enough to permit rather than negate good visual performance.

The tests conducted during this study include measurements to determine the optical characteristics of 13 smoke-protective devices (goggles, fullface masks, and hoods) and include the following: (i) light transmission, (ii) optical haze, (iii) prismatic deviation, (iv) refractive power, (v) optical distortion, and (vi) surface curvature. These measurements provide a comprehensive description of the optical properties of each test device but do not necessarily delineate the effects on human visual performance.

This study was designed to quantify optical defects of the 13 test devices. Evaluation of the visual performance of these smoke-protective devices worn in combination with several respirators has been reported elsewhere (1).

MATERIALS AND METHODS

Optical evaluations made for eight goggles and five fullface oxygen masks are shown in Table 1. Of the latter, three were rigid one-piece masks, one was a flexible experimental polyurethane hood, and one was a flexible fabric/polyurethane hood with a Kapton facepiece. Measurements of all optical parameters were made through the C-areas, as determined by the C-points, and marked on the facepiece of each test device. C-points are imaginary points on a transparency through which the visual axis of each eye passes when the line of sight is straight ahead and fixating on a distant object.

Each device was positioned at the wear angle and secured with a laboratory clamp. The wear angle is defined as the angle between the vertical (frontal) plane of the head and the plane of the transparent facepiece when the device is worn

TABLE 1. Smoke-Protective Devices

NO.	
	GOGGLES
01	Sierra 322-01
02	Sierra 322-20
03	Puritan 118071
04	Robertshaw 595-900
05	American Allsafe G202-13R
06	H. L. Bouton 1970
07	Welsh 1083
08	H. L. Bouton 552
	FULLFACE (One-Piece) OXYGEN MASKS
09	Robertshaw 900-002-066
10*	Robertshaw 900-700-062-01
11	Scott 10100 C2A
12	Sierra 651-100-1
13**	Robertshaw 900-700-062-02

* Flexible hood, polyurethane.

** Flexible hood, Kapton facepiece.

correctly. The technique for determining the wear angle is described in the report on the visual evaluation of the test device (1).

A. Light Transmission. Light transmission is defined as the difference in percentage between the amount of light entering a material and the amount of light reflected, scattered, and absorbed by the material. Transmission was determined with a Gamma Scientific (Model 2020-1) photometer with the scale adjusted to read 100 when directed toward the center of a 100-fL Gamma Scientific standard luminance source. The test device was clamped in the position of the wear angle, and the C-area was positioned between the light source and the photometer. The amount of light passing through the transparent facepiece was recorded as the percent transmission. Figure 1 shows the photometer (facing camera) and other instruments used in the optical evaluation.

B. Optical Haze. Optical haze results from random scattering of light by particles suspended in an optical medium. A Gardner Hazemeter (Model PG5500) measured the percentage of light scattered off-axis when a parallel beam of light passed through the C-area of each test device.

C. Prismatic Deviation. Prismatic deviation is the change in direction of light as it passes through a transparent body with nonparallel plane surfaces. Prismatic deviation will cause an apparent displacement of objects from their true position, may place stress on the binocular fusion system and, if varied throughout a transparent medium, will create distortion or rippling in the field of vision.

With the test device again secured at the wear angle, a 1.0-mm (0.04-in) beam from a helium-neon gas laser (Figure 1) was positioned in the center (0.0, 0.0) point of a grid chart. The right, then left, C-area of each device was then aligned with the laser beam and the coordinates of the beam were recorded with each millimeter on the grid equal to 1.0 arc minute at a goggle-to-grid distance of 3.45 m (11.32 ft).

D. Refractive Power. Refractive power is the amount of bending of light rays as the wave fronts pass between two transparent media having different refractive indices. Refractive or lensing power, as measured in this study, is created by curved and/or nonparallel opposing surfaces in the optical transparency. Refractive power was measured with an American Optical focimeter with a range from -0.25 to +0.25 diopters (D) in 0.01-D increments. The power of fullface oxygen mask No. 09 (Table 1) could not be measured because the bulky material surrounding the facepiece prevented

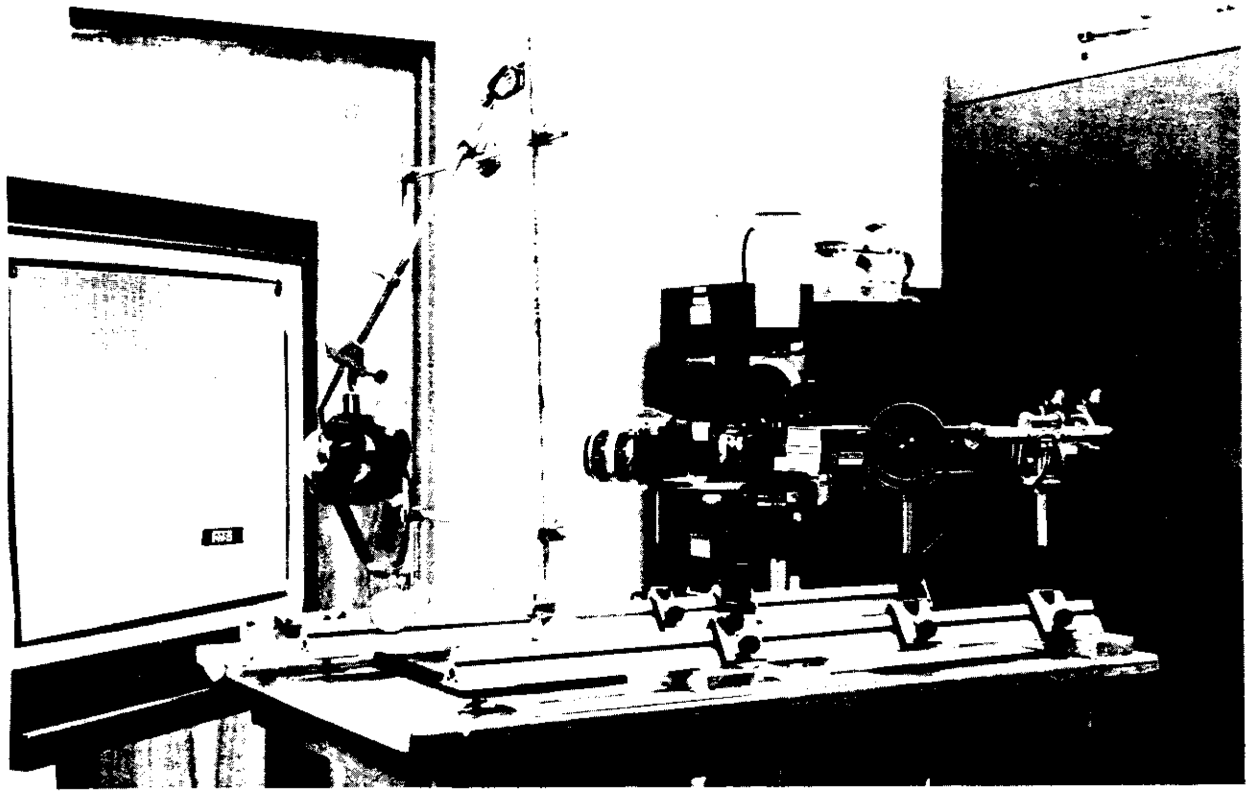

FIGURE 1. Apparatus for measuring optical characteristics of the smoke-protective devices.

positioning the transparency in the optical light path of the focimeter. Two hoods (Nos. 10 and 13) were not evaluated for refractive power because their thin, flexible surfaces would not maintain a uniform curvature in the instrument.

E. Optical Distortion. Distortion is defined as a condition in which the image is not a true-to-scale reproduction of the object. Distortion was recorded by taking photographs through each transparency of a plastic grid. The grid, 48 by 60 cm (18.9 by 23.6 in) in size, consisted of horizontal and vertical lines spaced 2.0 cm (0.8 in) apart, and located 67 cm (26.4 in) from the film plane of the camera. The grid was held evenly on a vertical, translucent, acrylic panel by reduced pressure supplied by a vacuum pump. Gridlines were illuminated from behind the acrylic panel by a series of parallel fluorescent tubes. The camera and grid are shown in position in Figure 1. The photograph of the grid taken through the facepiece of each test device was then analyzed to determine optical distortion. First, the right and left C-points were marked on the photograph 32 mm (1.26 in) on each side of the centerline of the device and at an elevation approximating the location of a subject's pupils. The horizontal gridline passing through or nearest to the right and left C-points determined optical distortion. A reference line, established by aligning a straightedge on an adjacent gridline, extended beyond the test device to determine whether the gridline and straightedge were parallel (indicating no optical distortion). The distance between the gridline and the straightedge at two points along the straightedge was measured with a 6.0-power optical reticle. The two points were separated by 10 grid squares, equally spaced five squares to each side of the C-point. Measurements were taken to the nearest 0.1 mm (0.004 in), and the difference in the two readings was recorded. The same method was used to measure a vertical gridline across the right and left C-areas of the facepiece. Final values were obtained by averaging the measurements taken by two investigators working independently.

F. Surface Curvature. The curvature of the front surface of each test item was measured with a Robinson-Houchin surface measuring gauge. Readings were taken in the horizontal and vertical planes over the right and left C-areas. Final values were the averages of the readings taken by two investigators who were experienced in the measuring technique.

Similar techniques for measuring light transmission, optical haze, prismatic deviation, and distortion by gridboard photography have been used in the optical evaluation of windshields on military aircraft (2).

RESULTS

The mean and standard deviation of five readings of the amount of light transmission through the facepiece of each device is presented in Table 2. Only one reading was taken on the flexible hoods (Nos. 10 and 13) because the material prevented repeated accurate measurements through the C-areas. With the exception of device No. 13, 78 to 94 percent of the light was transmitted through the devices.

The results for optical haze are shown in Table 3. Higher numerical readings indicate a proportionally greater amount of haze. The mean haze value for all the devices was 2.3 percent and ranged from 0.2 to 18.8 percent.

Results of measurement of prismatic deviation are presented in Table 4. Column 6 lists the total horizontal prismatic deviation for which the binocular fusion system must compensate to maintain binocular fusion. Column 11 displays similar information for the vertical prismatic deviation. Larger amounts of total horizontal deviations were found in fullface oxygen masks Nos. 09, 11, and 12.

The degree of refractive power caused by nonparallel optical surfaces measured in the right and left C-areas of each device is shown in Table 5. The refractive power for all the devices measured was less than 0.25 D for both the spherical (range 0.00 to 0.10 D) and the cylindrical (range 0.04 to 0.23 D) components.

The numerical values of optical distortion shown in Table 6 represent deviations from vertical or horizontal of the gridlines used in the test. A 0.0 value indicates that the gridline photographed through the transparency and the reference line are parallel. The mean range of distortion extended from 0.0 to 0.45 mm (0.0 to 0.018 in) in the horizontal plane, and from 0.0 to 0.48 mm (0.0 to 0.019 in) in the vertical plane. Values greater than 0.0 indicate a slope of the gridline with higher values representing increased distortion in the C-areas on the transparency. Optical distortion was most pronounced in the goggles having curved facepieces (Nos. 01 and 02) but the goggles with the flat transparencies and the fullface devices (Nos. 09, 11, and 12) showed little or no distortion. The two flexible hoods (Nos. 10 and 13) were not evaluated because they could not be photographed or analyzed by this method.

The surface curvatures of the 13 test devices are presented in Table 7. Readings ranged from minus values (concave surfaces) to plus values (convex surfaces) that approximated the

TABLE 2. Light Transmission

Test Device	Mean Transmission (%)			
	CR*	S.D.	CL*	S.D.
01	89.0	2.3	89.0	2.6
02	89.4	2.3	89.6	1.8
03	79.8	0.8	80.4	1.1
04	78.4	1.4	79.0	1.4
05	91.0	1.3	90.9	1.8
06	82.2	1.7	82.0	1.6
07	89.3	1.5	90.0	1.6
08	84.0	0.0	83.8	0.8
09	92.0	0.7	92.0	0.7
10	94.0	0.0	94.0	0.0
11	92.2	2.2	91.2	1.9
12	91.2	1.1	91.2	0.4
13	59.0	0.0	59.0	0.0

* Right and left C-areas, respectively.

TABLE 3. Optical Haze

Test Device	Haze (%)
01	CR* 4.2 CL* 3.5
02	CR 4.7 CL 4.9
03	CR 1.8 CL 1.8
04	CR 2.1 CL 2.4
05	CR 0.2 CL 0.3
06	CR 1.0 CL 1.3
07	CR 1.7 CL 2.3
08	CR 1.3 CL 1.6
09	CR 0.3 CL 0.3
10	CR 18.8 CL 17.7
11	CR 0.4 CL 0.3
12	CR 0.2 CL 0.3
13	CR 4.6 CL 4.8

* Right and left C-areas, respectively.

TABLE 4. Prismatic Deviation (arc min)

Test Device	HORIZONTAL					VERTICAL				
	CR*	S.D.	CL*	S.D.	Total	CR*	S.D.	CL*	S.D.	Total
01	2.8L	7.2	1.9R	7.1	4.7	17.6D	14.6	16.9D	13.7	0.7
02	0.8R	4.5	3.2L	4.8	2.4	14.8D	5.0	17.2D	8.3	2.4
03	0.8L	0.4	0.6L	0.5	0.2	0.4U	0.5	0.6U	0.5	0.2
04	2.3R	0.6	3.5L	2.6	5.8	1.6D	0.5	1.7D	0.6	1.0
05	2.4L	0.9	1.9L	1.0	0.5	2.3D	0.9	2.3D	0.8	0.0
06	1.2L	0.4	0.8L	0.5	0.4	1.8U	1.1	1.8U	1.2	0.0
07	1.1L	0.2	1.1R	0.2	2.2	1.4U	1.0	1.3U	0.8	0.1
08	0.2R	0.4	0.4L	0.5	0.6	0.4U	0.5	0.0	0.7	0.4
09	13.2R	1.3	16.2L	1.8	29.4	2.0D	0.7	1.8D	0.8	0.2
10	N/E**	--	N/E**	--	--	N/E**	--	N/E**	--	--
11	17.2R	2.2	14.6L	0.5	31.8	3.2D	0.4	3.0D	0.5	0.2
12	13.2R	2.6	13.0L	1.2	26.2	0.8D	0.8	0.6D	0.5	0.2
13	N/E**	--	N/E**	--	--	N/E**	--	N/E**	--	--

* Right and left C-areas, respectively.

** Not evaluated because of flexible facepiece.

TABLE 5. Refractive Power

Test Device		Spherical Power (Diopters)	Cylinder Power (Diopters)	Cylinder Axis (Degrees)
01	CR*	+0.01	-0.23	06
	CL*	+0.02	-0.14	180
02	CR	-0.02	-0.19	179
	CL	-0.10	-0.10	180
03	CR	+0.01	--	--
	CL	+0.01	--	--
04	CR	+0.07	--	--
	CL	0.00	-0.23	167
05	CR	-0.03	--	--
	CL	-0.02	--	--
06	CR	-0.03	--	--
	CL	-0.03	--	--
07	CR	+0.01	+0.08	25
	CL	+0.02	+0.08	165
08	CR	-0.02	--	--
	CL	-0.02	--	--
09	CR	N/E**	N/E**	N/E**
	CL	N/E**	N/E**	N/E**
10	CR	N/E**	N/E**	N/E**
	CL	N/E**	N/E**	N/E**
11	CR	+0.01	+0.04	75
	CL	+0.03	+0.06	95
12	CR	+0.02	-0.10	88
	CL	0.00	-0.09	90
13	CR	N/E***	N/E***	N/E***
	CL	N/E***	N/E***	N/E***

* Right and left C-areas, respectively.
** Not evaluated because bulk prevented positioning in instrument.
*** Not evaluated because of flexible facepiece.

TABLE 6. Optical Distortion

Test Device	HORIZONTAL (mm)		VERTICAL (mm)	
	CR*	CL*	CR*	CL*
01	0.38	0.45	0.36	0.48
02	0.30	0.35	0.30	0.45
03	0.05	0.05	0.05	0.05
04	0.05	0.08	0.05	0.05
05	0.02	0.02	0.00	0.05
06	0.04	0.02	0.04	0.02
07	0.02	0.02	0.02	0.02
08	0.05	0.00	0.00	0.00
09	0.00	0.00	0.00	0.00
10	N/E**	N/E**	N/E**	N/E**
11	0.05	0.00	0.00	0.05
12	0.00	0.00	0.05	0.05
13	N/E**	N/E**	N/E**	N/E**

* Right and left C-areas, respectively.

** Not evaluated because of flexible facepiece.

TABLE 7. Surface Curvature (Diopters)

Test Device		Horizontal Meridian	Vertical Meridian
01	CR*	+7.50	+17.12
	CL*	+8.75	+17.00
02	CR	+8.25	+16.50
	CL	+9.25	+17.12
03	CR	+1.50	+ 0.38
	CL	+1.00	+ 0.75
04	CR	+4.38	+ 1.12
	CL	+4.12	+ 1.12
05	CR	-0.12	+ 0.25
	CL	-0.12	0.0
06	CR	-0.50	- 0.12
	CL	-0.12	+ 0.12
07	CR	+1.12	- 0.12
	CL	+1.25	- 0.25
08	CR	-0.50	+ 0.25
	CL	-0.12	- 0.12
09	CR	+5.62	0.0
	CL	+5.62	+ 0.25
10	CR	N/E**	N/E**
	CL	N/E**	N/E**
11	CR	+5.25	+ 0.12
	CL	+5.62	+ 0.25
12	CR	+5.50	+ 0.25
	CL	+5.25	+ 0.25
13	CR	N/E**	N/E**
	CL	N/E**	N/E**

* Right and left C-areas, respectively.

** Not evaluated because of flexible facepiece.

curvature of a tennis ball (+16.00 to +18.00 D). As expected, the steepest curvatures occurred with the curved goggles (Nos. 01 and 02) and ranged from +7.50 D to +9.25 D in the horizontal meridian and from +16.50 D to +17.12 D in the vertical meridian. The horizontal curvatures of the fullface oxygen masks (Nos. 09, 11, and 12) showed moderate but consistent slopes ranging from +5.25 D to +5.62 D. Goggle No. 04 showed a moderate convex curvature, particularly in the horizontal meridian.

Table 8 lists the devices with optical properties that meet or exceed requirements of the USA Standard for eye and face protection (3) and the U.S. Air Force specifications for the optical characteristics of lenses, goggles, and helmets (4). All optical properties were compared with the two standards except surface curvature, which was not specifically listed. All of the transparencies exceeded requirements for light transmission. The four test devices with tinted facepieces (Nos. 03, 05, 06, and 13) did not conform to the transmission requirements for clear standard lenses of Class I (90 percent luminous transmittance) of the military specification, but all exceeded standards for Class II (neutral gray, 15 percent luminous transmittance) and Class III (1 percent luminous transmittance) (4). All devices except the polyurethane hood (No. 10) exceeded standards for optical haze. Horizontal readings of prismatic deviation of the three fullface oxygen masks (Nos. 09, 11, and 12) and vertical values of deviation for two goggles (Nos. 01 and 02) did not meet either the USA Standard or U.S. Air Force specifications of 2 arc min or 6 arc min, respectively.

Values of spherical refractive power exceeded standards in all but 2 of the 10 devices tested (Nos. 02 and 04).

Table 8 reveals that only 4 of the 11 devices evaluated met the standards for optical distortion when compared with the results of the grid-board photographic method of analysis.

DISCUSSION

Differences in optical properties of the 13 smoke-protective devices generally correspond to visual evaluations conducted on five test subjects during the same time period (1). Optical characteristics of the devices had the greatest effect on visual acuity and stereoscopic depth perception. Visual acuity was moderately impaired (more than 20/20) with the curved facepieces of goggles Nos. 01 and 02, particularly at the distance of 0.4 m (1.3 ft). These goggles also showed the highest values of optical distortion (Table 6), surface curvature (Table 7), and vertical prismatic deviation (Table 4)

TABLE 8. Smoke-Protective Devices That Meet or Exceed Optical Standards

Optical Characteristic	USA Standard Z 87.1	Test Devices That Meet or Exceed Standard Z 87.1	Military Specification MIL-L-38169 (USAF)	Test Devices That Meet or Exceed MIL-L-38169 (USAF)	Data Source
LIGHT TRANSMISSION	≥ 89%	(CR)* 01, 02, 05, 07, 09-12 (CL)* 01, 02, 05 07, 09-12	≥ 90%	(CR)* 05, 09-12 (CL)* 05, 09-12	TABLE 2
OPTICAL HAZE	≤ 6%	01-09, 11-13	≤ 5%	01-09, 11-13	TABLE 3
PRISMATIC DEVIATION					
Vertical	≤ 2 arc min (0.06 D)	(CR) 03, 04, 06-09, 12 (CL) 03, 04, 06-09, 12	≤ 6 arc min (0.18 D)	(CR) 03-09, 12 (CL) 03-09, 11, 12	TABLE 4
Horizontal	≤ 2 arc min (0.06 D)	(CR) 02, 03 06-08 (CL) 01, 03, 05-08	CR + CL ≤ 25 arc min (0.75 D) CR - CL ≤ 6 arc min (0.18 D)	01-08 03, 05, 06, 08	

* Right and left C-areas, respectively.

TABLE 8. Smoke-Protective Devices That Meet or Exceed Optical Standards (Continued)

Optical Characteristic	USA Standard Z 87.1	Test Devices That Meet or Exceed Standard Z 87.1	Military Specification MIL-L-38169 (USAF)	Test Devices That Meet or Exceed MIL-L-38169 (USAF)	Data Source
REFRACTIVE POWER	± 0.06 D	(CR)* 01-03, 05-08, 11, 12 (CL)* 01-04, 05-08, 11, 12	± 0.06 D	(CR)* 01-03, 05-08, 11, 12 (CL)* 01-04, 05-08, 11, 12	TABLE 5
OPTICAL DISTORTION					TABLE 6
Vertical	0.0 mm	(CR) 05, 08, 09, 11 (CL) 08, 09	0.0 mm	(CR) 05, 08, 09, 11 (CL) 08, 09	
Horizontal	0.0 mm	(CR) 09, 12 (CL) 08, 09, 11, 12	0.0 mm	(CR) 09, 12 (CL) 08, 09, 11, 12	
SURFACE CURVATURE**					

* Right and left C-areas, respectively.

** Surface Curvature was not compared because it was not in the above standards.

of all the devices tested. In addition to the optical properties of the transparencies, factors inherent in the design, geometry, and fit of the smoke-protective device may contribute to impaired vision to varying degrees. Displacement of the spectacle frame, opaque material surrounding the lens, or a fit that does not permit line of sight to be perpendicular to the lens are some of the factors that can be additive and reduce visual acuity and visual fields. Deviation in line of sight is related to the thickness and curvature of the lenses. When lenses are thin and flat, as in test devices Nos. 03 through 08 (Table 7), each eye looks through similar lens sections at similar angles, so that each eye is similarly affected, and differences between the deviations will be small. If the lenses are thicker and steeply curved (as is the case of goggles Nos. 01 and 02), each eye looks through different lens sections at different angles, and deviations are larger and will fluctuate as the wearer scans the field of view (5). These larger differences in deviation cause disparities in spatial perception. Flexible facepieces (devices Nos. 10 and 13) also cause similar disparities.

The all-plastic hood (No. 10) was simply two sheets of clear polyurethane with bonded seams on three edges, an elastic neckband, and a port for the oxygen supply. Of all the devices tested, this hood demonstrated the highest light transmission (94 percent), but the anterior seam prevented line of sight perpendicular to the hood and severely limited stereoscopic depth perception and visual acuity at all distances (1). The remaining hood (No. 13) had an outer part made of opaque fire-resistant material that draped around the shoulders. It enclosed a smaller polyurethane liner and had an amber-colored facepiece made of Kapton, which is thin and flexible but more rigid than polyurethane. Line of sight was kept perpendicular to the facepiece and visual acuity, particularly at 6 m (20 ft) or more, was good, but distortion degraded stereoscopic depth perception to some extent. This hood is employed by ground crews for activities that do not require sharply focused vision or quick donning procedures.

Light transmission values lower than 85 percent may create visual difficulties, especially with dim light, whereas unusually high levels of transmission cause the binocular vision system to be stressed by bright light, resulting in photophobia and lacrimation. The tinted facepieces of devices Nos. 03, 05, 06, and 13 reduced light transmission to some degree (Table 2), although color tests using the Dvorine Pseudoisochromatic plates conducted while the subject was wearing these devices revealed no decrements in visual performance associated with color (1).

Table 3 indicates that, excluding device No. 10, values of optical haze ranged from 0.2 to 4.9 percent and exceeded both standards. An observation by the authors, using calibrated haze panels, indicated no loss in distant or near visual acuity with haze levels up to 75 percent. However, when haze effects are combined with other optical anomalies in the facepiece, visual performance may be significantly impaired.

The data of Table 8 reveal that only 4 of the 11 devices measured met the USA Standard or U.S. Air Force specification for optical distortion (i.e., no optical defects in either C-area). The U.S. Air Force specification for evaluating lens distortion (par. 3.5.4) states that no visible distortion or optical defects detectable by the "unaided eye" (defined in the specification as 20/20 or better visual acuity with or without correction) at the typical "as worn" position shall be visible (4). The authors viewed a target under these conditions and, wearing the identical smoke-protective devices used in this evaluation, found no visible distortion in devices that measured from 0.00 to 0.10 mm (0.00 to 0.004 in) (Table 6). If this criterion of visible distortion may be used, 9 of the 11 devices tested (Nos. 01 and 02 excluded) by the grid-board photographic method of this study conform to the U.S. Air Force specifications. The USA Standard lists only general requirements and states that the lenses shall be free from visible defects and flaws which would impair the optical quality of the lenses (par. 6.3.2.1) (3). When considered separately from the other optical characteristics, the ranges of refractive power and optical distortion of the devices tested have only a slight effect on visual acuity.

The data in Table 7 suggest that the moderately steep surface curvatures and the thick lenses (approximately 1.5 mm (0.06 in)) of goggles Nos. 01 and 02 and of fullface oxygen masks Nos. 09, 11, and 12 were the probable causes of the higher values of prismatic deviation (Table 4).

In summary, with the exception of the experimental polyurethane hood (No. 10), optical properties of the 13 smoke-protective devices were generally compatible with acceptable visual performance of the tasks for which they were designed. Effects of the smoke-protective devices in relation to flying performance can only be determined subjectively by experienced personnel tested during actual or simulated flight conditions.

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