

Concept of a Unit Circle and Unit Sphere as a Method of Expressing Respirator Physiological Function and Degradation— I: Vision*

Ronald A. Weiss

U.S. Army Chemical Research, Development and Engineering Center,
Individual Protection Division, Aberdeen Proving Ground, Maryland 21010-5423

The unit circle and unit sphere are a simple, but elegant, method of presenting both qualitative and quantitative information about any respirator physiological functions. The circumference of the circle represents normal physiological functional limits, or no physiological burden, for the average man. The focal point represents absence of physiological capability. Each physiological parameter is represented by a scalar radius. The radii must be in multiples of four to keep the symmetry of the circle. Each unit circle represents a specific physiological capability such as pulmonary function, vision, communications, thermal load, etc. This paper presents the parameters for the physiological and biophysical capabilities of vision in the form of two separate unit circles. A description, rationale for the selection, upper and lower limits and scalar intervals for each parameter are discussed. By connecting the parametric values for the mask being evaluated, a second inner circumference is formed. The closer the two circumferences come together, the better the mask. Any distortion of the circle is an area for improvement and investigation. Integration of the area of the inner circle and comparison with the area of the unit circle will give a percentage value for overall respirator performance or degradation. The unit sphere is a collection of unit circles along a vertical axis passing through the common focal point of each circle.

Introduction

One of the most difficult tasks asked of a scientist or engineer developing improvements to individual protection equipment is to show a non-specialist what those improvements are. In almost all cases the non-specialist is looking for, or only understands, coarse qualitative information (e.g., it is more comfortable, you can breathe easier, etc.). He has no idea of what the normal human response to the environment will be so he can not appreciate the amount of physiological degradation imposed by any protective equipment. To circumvent this

problem and at the same time impart quantitative information for those who can understand it in the same example, the concept of the unit circle and unit sphere are proposed. This paper will explain the concept and the parameters involved. An evaluation of the visual physiological function of the M17 military respirator will be used to demonstrate the concept. Future papers will describe this laboratory's use of the concept for evaluating communications (speech and hearing), pulmonary function, and thermal stress associated with individual respirators.

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UnitCircle

The unit circle consists of three basic elements: a focal **point**, an outer circumference, and a series of even numbered radii emanating from the focal point and touching the circumference (see Fig. 1).

The focal point represents the situation where the subject wearing the respirator has no physiological function at all.

The circumference represents normal limits of physiological function when the average person is not wearing a respirator. For example, when using the concept of the unit circle to explain the quantitative physiology of visual capability of a respirator, the circumference represents normal physiological visual operations. For ease of scaling, the circumference is located five centimeters from the focal point.

Each radius quantitatively represents a different physiological parameter. All radii present in any given circle are related to a specific physiological function such as vision or speech or pulmonary function. The number of radii must be multiples of four to form a symmetrical circle. Each circle must contain a minimum of twelve radii and a maximum of sixteen for best definition of the concept. The quantitative scale of each radius is so aligned that the further a value is away **from** the focal point, the more normal the physiological capability. The closer the value to the focal point, the greater the physiological degradation of that parameter caused by the mask. Any radius scale may be linear or logarithmic. The linear scale can be either an actual value or percentage.

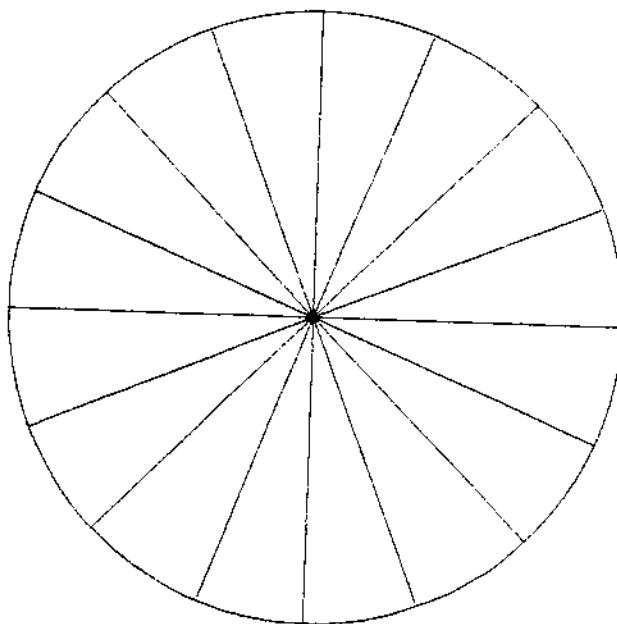


Figure 1. Concept of the unit circle to explain physiological capability of a respirator. The **circumference** represents normal physiological function. The **focal point** represents no physiological capability. The scalar radii each represent a **different** independent parameter. All radii in a unit circle depict a specific physiological capability (vision, pulmonary function, or communications, for example).

UnitSphere

Each unit circle represents a specific physiological capability (vision, communications, or pulmonary function, etc.). The unit sphere is nothing more than a three dimensional spacing of several unit circles around a central vertical axis bisected by their common focal point to give an overall picture of physiological function of a particular respirator (see Fig. 2). This axis is created by removing two opposing radial parameters from each circle at plus and minus 90° from the prime parameter of that unit

circle. The prime parameter of each unit circle is then automatically aligned along the horizontal equator of the sphere. The total number of circles making up a unit sphere must equal one half the number of radii on any unit circle. The more radii in a unit circle, the smoother the unit sphere will be. If 16 radii are used in a unit circle, then 112 parametric values can be demonstrated in a unit sphere consisting of 8 unit circles.

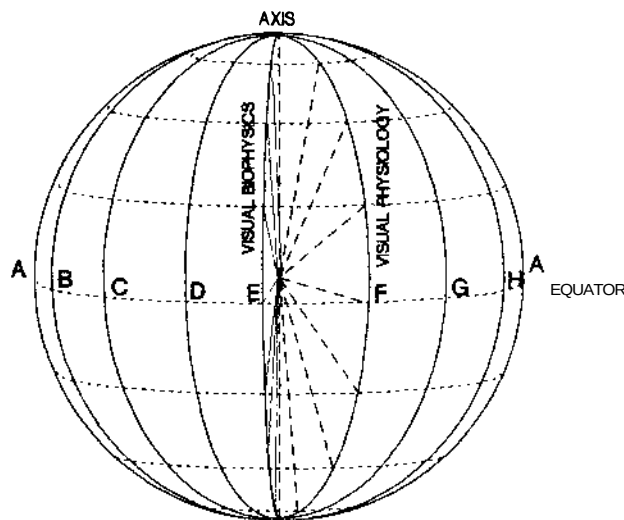


Figure 2. Concept of a unit sphere consisting of an even number of unit circles arranged around a common axis passing through the **focal** point of each unit circle. Each letter represents a **different** unit circle with parameters depicting a specific physiological capability.

Interpretation of Circle and Sphere

When each parameter of a unit circle has been marked on its appropriate **radius**, the marks are connected to form an inner circumference (see Fig. 3). If the area enclosed by this inner circumference is integrated using a **planimeter** and compared as a percentage of the area of the full unit circle (representing normal physiological function for a specific capability), it will give the percentage of average normal physiological function evidenced for that mask (see Fig. 4). Conversely, the area between the two **circumferences**, expressed as a percentage, will indicate the **level** of physiological degradation for that respirator for that specific physiological capability (see Fig. 5).

When the unit circle for a specific capability is shown to a non-specialist, it can easily be explained that the inner circumference represents the physiological capability of that mask. The closer this inner circumference comes to the outer circumference, the better the mask and the less burden it imposes in this specific physiological area. Any indentations of the inner circumference point out specific quantitative weaknesses of the mask that require additional work to correct. In the same fashion, when a non-

specialist is presented a unit sphere, it can be explained that the larger the ball and the smoother its surface, the less physiological burden imposed by the respirator. Because the unit sphere does not have the capacity for having a reference normal physiological function sphere immediately surrounding it, the north and south polar coordinates represent the landmarks for full functional capability.

If this unit circle concept is used to report the data of all respirators tested and evaluated, it becomes very easy to compare various masks and design concepts. All that is required is to superimpose the unit circles for a specific physiological capability of two different masks or concepts and compare the aligned parameters. For a specific **parameter**, the respirator having the marked value closer to the circumferential normal physiological performance would be the better mask. Not every mask will be superior to another in all parameters. To determine the better mask in this situation, compare the integrated percentages of normal physiological function. The higher the total integrated area percentage, the better the mask.

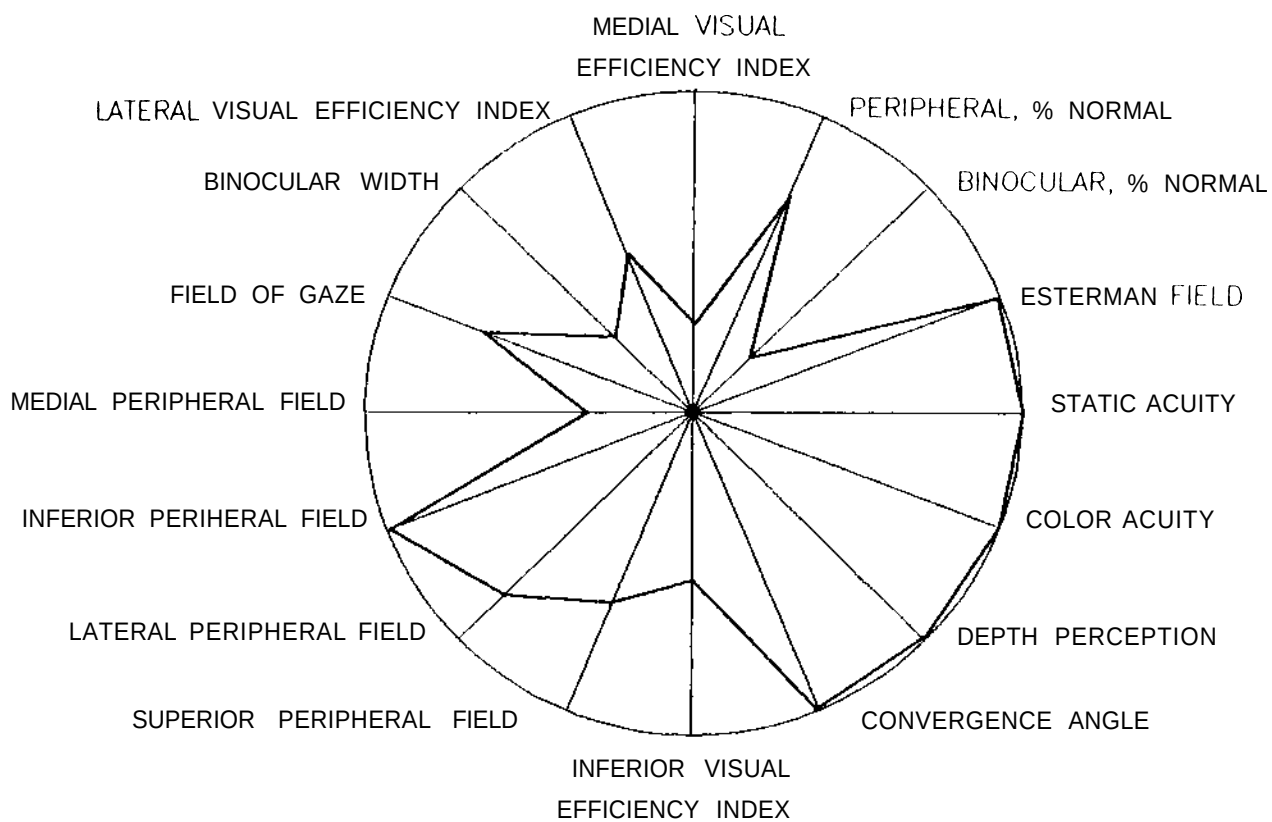


Figure 3. Functional visual capability of the M 17 mask presented in the form of a unit circle.

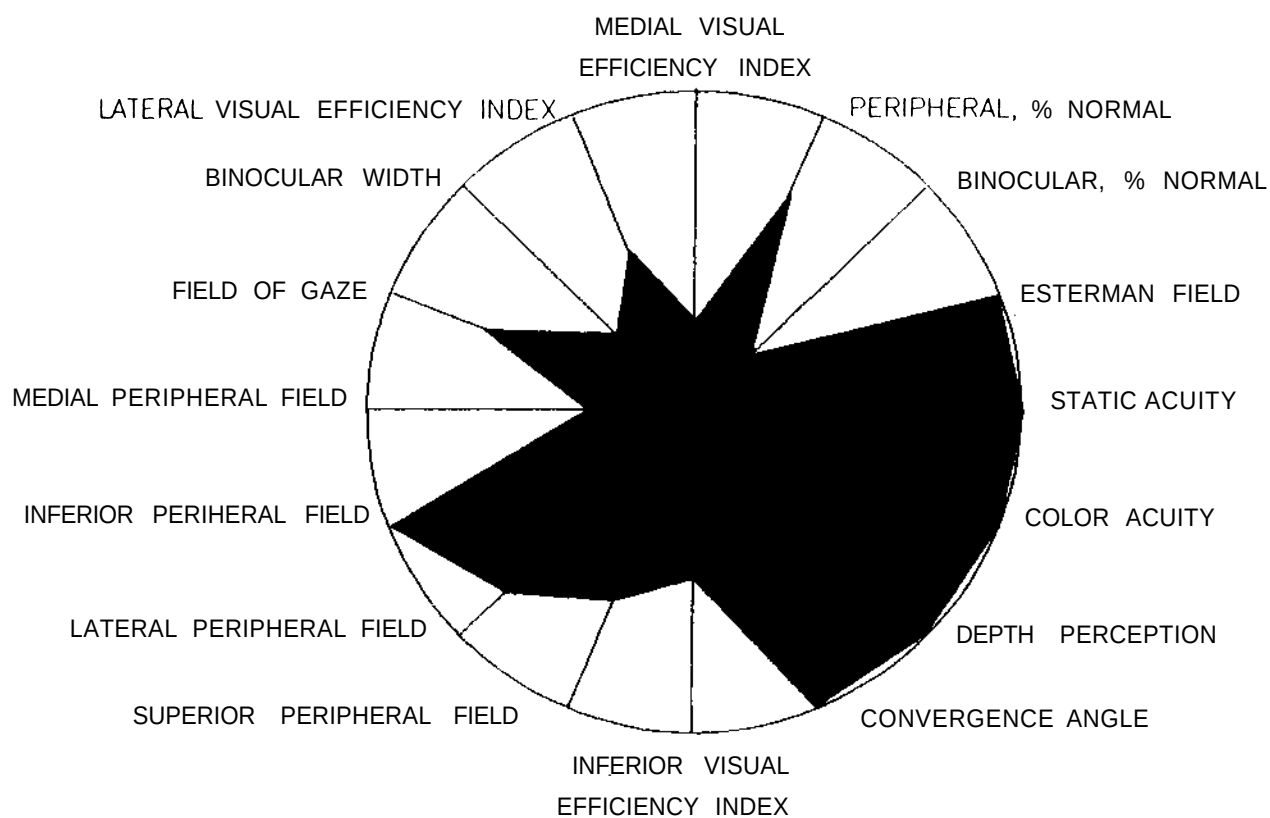


Figure 4. Functional visual capability of the M 17 mask presented as a percentage of normal visual physiological capability.

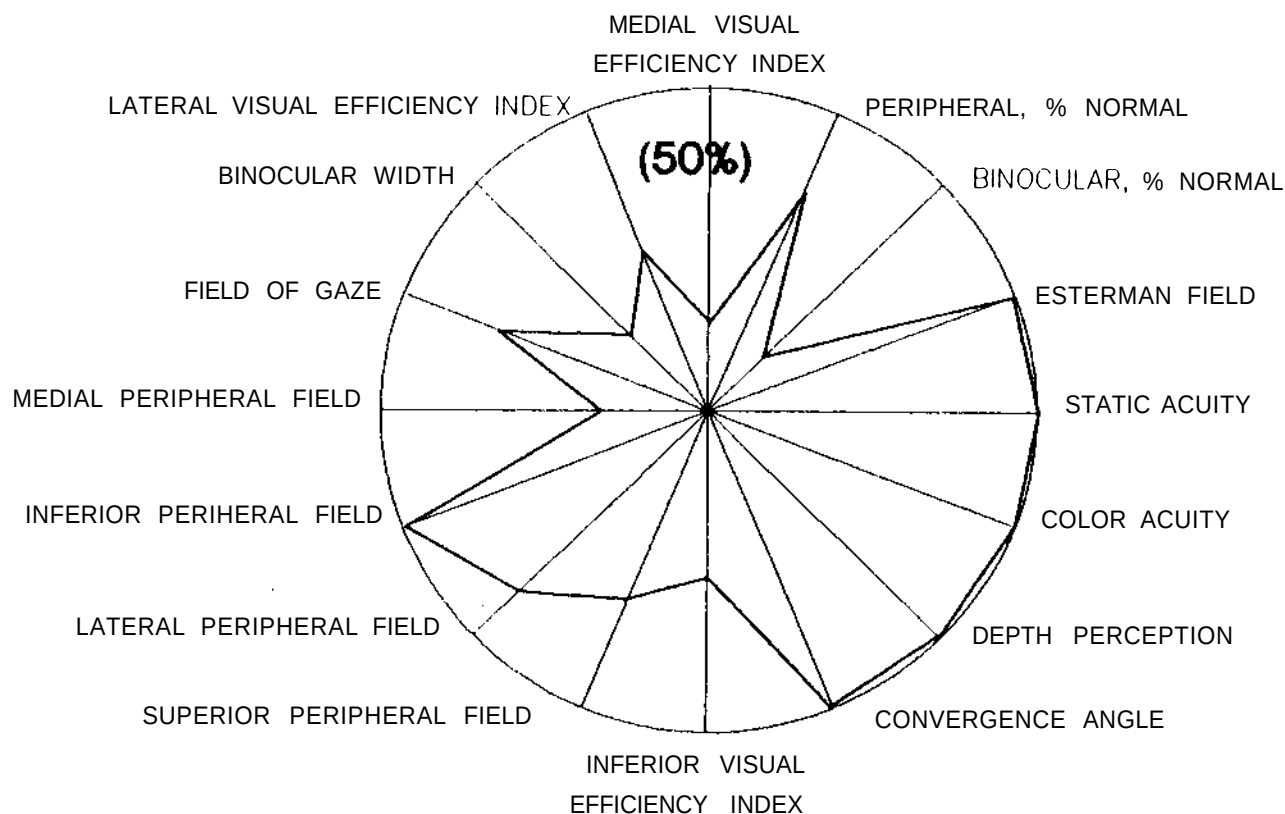


Figure 5. Degradation of visual capability of the **M 17** mask presented as a percentage of normal visual physiological capability.

Unit Circle Concept Applied to Respirator Vision

Vision, as detailed in this paper, is concerned only with the material and configuration of the lens built into the facepiece of the mask and the **wearer's** ability to see through that lens. Some masks have a binocular lens configuration while others use a single panoramic lens configuration. Since most masks are designed for use by anyone, no corrective vision capability (such as attached eye glasses or permanently mounted prescription lenses) is incorporated into the unit circle.

In the **author's** laboratory, each respirator is evaluated for the physiological and biophysical aspects of vision using 32 parameters. This large a number of parameters is too cumbersome to handle in a single unit circle making up only one plane of a unit sphere. Accordingly, they have been arranged into two convenient groups of 16 parameters,

thereby forming two unit circles. The parameters of one circle (Table 1 and Fig. 3) represent the visual physiological capability of the respirator while those of the second circle (Table 2 and Fig. 6) incorporate the biophysical aspects of the mask related to evaluating its physiological capability.

A description of each parameter, its rationale for inclusion, the normal physiological value (circumferential value), and the radius scale range are described in the attached appendices. Those parameters in the unit circle concerned with the physiological visual capability of a mask are presented in Appendix A. Those parameters in the second unit circle, concerned with the biophysical aspects of vision of the mask, are presented in Appendix B. The parameters are listed sequentially in each table with the prime parameter for each unit circle shown first.

Table 1. Unit circle parameters **for** mask visual physiological capability.

Parameters	Units	Circumference value	Focal point value	Scale	Intervals
Static acuity	ratio	1	0.1	logarithmic	0.1
Color acuity	ratio	15	0	linear	1
Depth perception	millimeters	0	30	linear	1
Convergence angle	degrees	15	0	linear	3
Esterman field	percent	100	0	linear	20
Superior peripheral field	degrees	60	0	linear	5
Lateral peripheral field	degrees	100	0	linear	5
Inferior peripheral field	degrees	60	0	linear	5
Medial peripheral field	degrees	60	0	linear	5
Field of gaze	degrees	120	0	linear	6
Binocular width	degrees	120	0	linear	6
Peripheral field , % normal	percent	100	0	linear	10
Binocular field, % normal	percent	100	0	linear	10
Lateral visual efficiency index	percent	100	0	linear	10
Inferior visual efficiency index	percent	100	0	linear	10
Medial visual efficiency index	percent	100	0	linear	10

Table 2. Unit circle parameters for mask visual biophysical capability.

Parameters	Units	Circumference value	Focal point value	Scale	Intervals
Eyere relief	millimeters	14	64	linear	1
Haze	percent	0.25	5.25	linear	0.25
Light transmission	percent	100	0	linear	5
Prism power	diopters	0.125	1.25	logarithmic	0.2
Spherical distortion	diopters	0	5	linear	0.25
Cylindrical distortion	diopters	0	5	linear	0.25
Cylinder axis	degrees	0	50	linear	5
Medial lens separation	millimeters	15	40	linear	2.0
Lens thickness	millimeters	2.0	5	linear	0.3
Equipment interfacing	number	5	0	linear	0.2
Exceptions to parameters	number	0	32	linear	1
Astigmatism	diopters	0	0.5	linear	0.1
Retroscopic (faceform) tilt	degrees	0	30	linear	6
Pantoscopic tilt	degrees	0	25	linear	5
Chromaticity , X	number	0	0.5	linear	0.01
Chromaticity , Y	number	0	0.5	linear	0.01

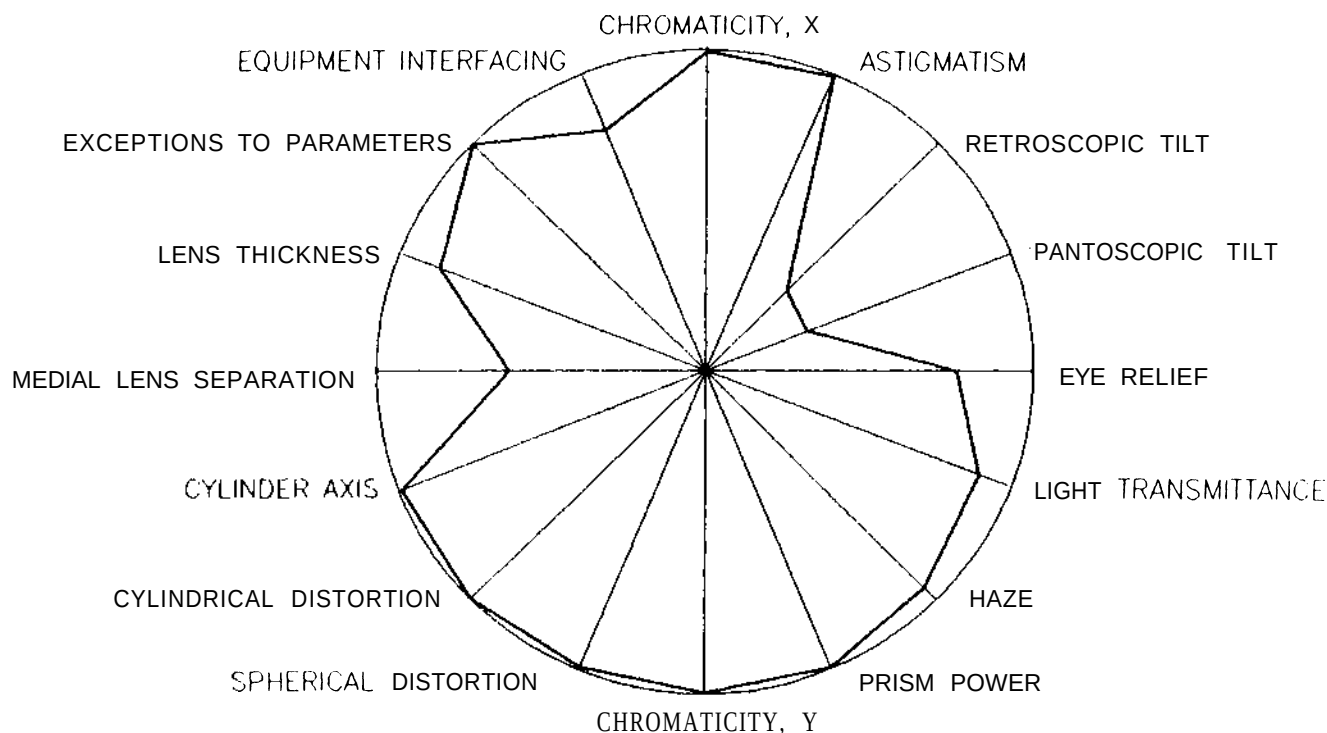


Figure 6. Visual biophysical capability of the **M 17** mask presented in the **form** of a unit circle.

Discussion

The unit circle and its multiple, in the form of a unit sphere, are simple but elegant ways of **diagrammatically** expressing large quantities of complex or poorly understood data that can easily be assimilated by both the specialist and non-specialist alike. Although this paper uses the visual physiological characteristics of masks as a means of presenting the concepts, the unit circle and unit sphere can be used for any descriptive data and situation, as long as it can be expressed quantitatively. A two or three dimensional graph displays a change in a dependent variable as one or two independent variables change. The unit circle and unit sphere, on the other hand, are a method of simultaneously expressing values of a group of related independent variables.

The unit circle concept makes it very easy to compare masks against one another. When each mask is marked on its own unit circle of the same specific capability, all that is required is to lay the circle of each mask on top of the same focal point with the parameters superimposed correctly. The inner **circumference** representing the capability of each mask can then be visually compared and the differences directly observed.

The circumferential and focal point values for each parameter have to be chosen very carefully to achieve the purposes intended for the unit circle. For the example used in this **paper**, the purpose of the circumferential values was to establish design criteria for mask designers related to the visual capability of a mask. The parameters were chosen to give the best physiological description of the visual capability of the wearer without the mask. If the circumferential values for each parameter are achieved in any mask design, the physiological burden with respect to vision of wearing the mask will essentially be eliminated. Any parameter not reaching the circumferential value can be considered a design area requiring improvement.

The scalar radius for each parameter can be expressed linearly, logarithmically, or as a quantitative accumulation of events. There is no interrelationship between radii. All the radii are grouped together, however, into a unit circle because of some underlying relationship to describe the functioning of a system. The values for each parameter are expressed as absolute deviations away from normal with no regard to direction. The direction of the deviation will

have to be determined from reading any accompanying reports. The circumferential values for each parameter are not the extreme value found in the literature, but rather the average of what can be found in a general population of young, healthy American men and women. By employing this **approach**, the circumferential design values to eliminate physiological burden can be achieved for most of the users of respirators. Any parametric value touching the circumference means, therefore, that that parameter has reached or exceeded normal physiological design requirements.

Note that each parameter is given equal weight in the unit circle to calculate percentage capability or degradation. While the unit circle on visual physiological capability may appear to place more emphasis on the peripheral visual **fields**, in essence four separate, but critical, parameters are represented by the visual fields. The visual efficiency indices define a narrow band area of vision rather than a specific limiting angle. When the unit circles are combined into a unit **sphere**, two of the visual efficiency indices are sacrificed with minimal effect on the measurement of integrated visual performance.

When data is not readily available to be marked on a particular parameter, the unit circle can still be used for mask comparisons or presentation of the data. The missing parameter is not marked at the focal point as would be expected, but rather at the equivalent of the ten percent value of this parameter unless it can be positively known that the missing data does not apply to that mask. By using the ten percent value for the parameter, it flags the fact that the data is missing or the mask has a critical shortfall in that parameter. Marking the value at the focal point could inadvertently give the impression that the parameter did not apply to the mask being reviewed.

The values marked on each unit circle are based on the assumption that the subject has been expertly fit in the mask being reported. If this is not done, the reported values may vary considerably from the left to right side of the face, etc., when it really is not inherent in the mask design.

Noticeably absent from the unit circle on visual physiology are the parameters of dynamic visual acuity and glare. Dynamic visual acuity is a measure of the ability to detect an object rapidly moving directly toward **you**.^{1,2} Under mental and/or physical stress this parameter is diminished because the object must be larger to see it at the same dis-

tance. The scattering of light due to the lens material or the scratching of its surface will produce a luminosity greater than that to which the eyes are **adjusted**. The resulting glare is both annoying and uncomfortable but it does cause a decrease in visual performance (blurring). Both parameters were dropped from the present unit circle either because of lack of space (for the dynamic visual acuity) **and/** or another parameter would give essentially the same information (the physical measurement of haze would give the same information as glare).

In the unit circle representing biophysical capability of vision in a mask, several other parameters have been deliberately **excluded**. These are **interpupillary** distance, refraction problems with multiple lens(es) configurations, problems of fogging and internal reflection, and lens color neutrality across the visible spectrum. Since the interpupillary distance can vary so widely (54–80 millimeters) between individuals, there is no optimal physiological design value to put on the circumference. This is acknowledged by most mask manufacturers when each mask is designed in several sizes or methods are incorporated to align the optical axis of the lenses with the interpupillary distance. Since there are many possible configurations for incorporating inserts, **outserts**, specialty lenses, and corrective eyewear into a mask, it was deemed less confusing to limit the unit circle presentations to only the lens(es) physically built into the face blank. While mask fogging and internal reflection characteristics could be handled on a qualitative basis similar to the way the equipment interfacing radius is used above, these parameters depend on too many other independent variables (environmental temperature, level of sweat production, air flow path, lens material, etc.) to give a single solid physiological/biophysical optimal value for the circumference. The lens color neutrality parameter has been **defined**³ but there was no room for its inclusion in the biophysical unit circle without substituting it for another parameter of higher priority.

Light transmission as identified in this paper is the average amount of light transmitted over the visual portion of the electromagnetic spectrum (380–770 nanometers). From a physiological standpoint, however, we should only be concerned with three narrow band frequencies which represent the ability of the human eye to see color. These band frequencies are 437–458 nm, 520–543 nm, and 562–583 nm.⁴ Between them, they account for about 15 percent of the total visible spectral energy used by the body to produce color visual sensation. If light transmission

through lenses is kept high (greater than 90 percent) in these three frequency bands, physiological vision will remain normal while all the other frequencies can be blocked with filters to prevent injury to the eyes with lasers or other high energy specific frequency hazards. On this basis the radius representing average light transmission can be used to report the average light transmission across the visible spectrum or the three physiologically specific narrow band frequencies. If the latter situation is reported, however, it should be indicated in the accompanying notes.

To make the unit circle concept for each specific capability interchangeable between laboratories, it is essential that the same sequence of parametric radii be used. The parameters reported for the unit circle on visual physiological capability have been numbered in sequence in order of importance to the function of the mask and grouped for ease of finding information. Static acuity is the most critical parameter because it lets the subject see out of the mask. The visual physiological capability unit circle is used as the foundation of the unit sphere. The static visual acuity parameter is the prime parameter reference alignment point for all the other unit circle planes.

The current parameters in the two unit circles described in this paper appear to adequately cover the physiology and biophysics of vision for masks. Future research and development on mask design concepts may result in a need to revise, expand, or change the number and values of the present parameters. Changing a circumferential or focal point limit on any parameter is not difficult but may require an upgraded change on all previously reported unit circles for this specific capability. Substituting a new parameter for one already in the unit circle may be more of a challenge because of the evaluation process to determine which one should be sacrificed so the new one may be added. This approach will also require caution when comparing

unit circles from different masks to make sure parametric results do not inadvertently become confused. Adding a parameter to the unit circle without substitution is the most difficult task because it affects the symmetry of both the unit circle and unit sphere. Ideally, four new parameters should be added at a time to each unit circle in the sphere. Addition of one or several (but not four) parameters to any one circle will destroy the symmetry and prevent a common axis and prime equator for the unit sphere.

When the unit sphere is formed, two apposing parameters from each unit circle incorporated in the unit sphere must be deleted to provide an alignment axis. The two parameters for each of the two unit circles presented here are the least critical in priority for each circle. The information provided by the medial and inferior visual efficiency indices can be extracted from the medial and inferior peripheral field angle. The X and Y chromaticity coordinates should represent the transparent portion of the chromaticity diagram and are expected to be zero. If any of these parameters show a deviation below the circumferential normal value, this can be flagged by a reduction in the exceptions to parameter radius.

This paper describes the parameters for two unit circles, i.e., visual physiological capability, and visual biophysical capability of respirators. With the number of parameters in each of these circles, the unit sphere must contain eight unit circles. Future papers will describe one unit circle with pulmonary function parameters, three unit circles describing the communication parameters, and a final unit circle that will cover thermal aspects, as well as some other miscellaneous parameters to complete the unit sphere for the design of the mask.

NOTE: Anyone who wishes a working copy of the two unit circles presented in this paper for evaluating masks in their own laboratory, can request it from the author.

References

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Appendix A

Unit Circle Paramaters Associated with Physiological Visual Capability

1. **Static Acuity**—A measure of the change in the respirator wearer's ability to see through the eye lens(es) in comparison to the non-masked condition. It does exclude deterioration of visual acuity due to an improper mask/face seal causing fogging. The effect of changes in oxygen and carbon dioxide concentration within the mask are included, however, because they would still be there even in the presence of an expert fit. The basic assumption is made that the wearer has 20/20 **uncorrected** vision,¹ and this becomes the circumference value of this radius. Any deviation from this 20/20 value, in either direction, is considered a mirror image deleterious effect on vision and is reflected in a one-way reduction of the static acuity radius toward its focal point of origin. The scale of this radius is logarithmic with 0.1 (i.e., 20/200 on the Snellen chart²) as the focal point and 1 (i.e., 20/20) on the circumference. The scale only goes to a value of 0.1, because in the United States, a person with visual capability that low is considered legally blind. The visual capability of 1.33 (20/15) is found in a few individuals, but it would require optical correction in most of the population to achieve it. Therefore, that value is not used as the circumferential normal.

2. **Color Acuity**—A measure of the loss of color perception due to the color spectral transmission, absorption and reflection characteristics of the lens(es) of the respirator. A **Farnsworth-Munsell** 15 color test^{3–5} is used. A person with normal color acuity will be able to correctly align all 15 colored caps in the correct sequence. This parameter is only

reported as the number of colored caps correctly identified and does not report what color problem is encountered. The circumference value is 15 and the focal point is 0. Complete color acuity through the respirator will be marked as 15 (on the circumference). Any loss of color vision will be identified by the number of correct caps identified along the linearly scaled radius representing this parameter.

In some laboratories the **Ishihara** "Test for Color Blindness"³ charts are used to determine changes in color acuity. This also can be reported on the same radius scale if the focal point represents eight of the correctly identified charts and the circumference represents the full 38 being correctly identified. This conversion from the Farnsworth-Munsell to Ishihara test result is possible due to the fact that the charts have duplicates and triplicates of certain test conditions while the colored caps are each different.

3. **Depth Perception**—A measure of the ability to distinguish two objects being in the same frontal plane when presented to the subject at a distance of infinite focal length (usually considered 20 feet from the subject). The pantoscopic and retoscopic tilt of the lens(es), their separation across the nasal bridge, as well as the way the mask is mounted on the face, can all cause the distortion of depth perception. While the Howard-Dolman depth perception instrument^{6,7} has the capability of measuring the position of the movable peg to the nearest millimeter over a range of 10 centimeters in front of, or behind the

fixed reference peg, for military pilots a deviation of three centimeters in either direction is considered disqualification from continued flight status.⁸ A person with good binocular vision should show no change in depth perception when not wearing a respirator. The linearly scaled radius representing this parameter has a 0 value on the circumference and 30 millimeters at the focal point to coincide with the current disqualification value. Again, like several other parameters described here in which there is the possibility of having both a positive and negative value, only the absolute number will be reported and subtracted from the circumference. The less the deviation from 0 the better the depth perception.

The Frisby Stereo Test⁹ is another depth perception test conducted at close range, usually 0.5 meter. It uses a series of three transparent plastic cards of different thicknesses containing four square random spot patterns printed on one side and only one pattern on the other to give one square an appearance of depth. The subject is asked to determine which square has the depth of field for each card. The level of resolution in this test is 2, 4, and 8 millimeters depending on the thickness of the card. If the subject identifies all cards correctly, this parameter is marked on the circumference. If the 8 millimeter card is identified but not the 4 millimeter card, then the radius is marked at the 8 millimeter position. Correctly identifying the 2 millimeter position qualifies for a mark on the circumference with this test.

4. Convergence Angle—A measure of the ability to focus upon an object at close range (e.g., to be able to read a document, work on a small object, etc.). In many cases where there are two lenses in a mask, a wide nasal separation and/or mounting the lenses further away from the eyes will necessitate that the object viewed be held further away from the mask than normal to bring it into binocular focus. The standard test described by Armstrong¹⁰ sets this focal point at 25 centimeters from the nasal bridge or maximum angle of 15°. If the object must be held further away from the face to be viewed, this angle would become smaller and, therefore, would be a reduction in visual capability. The radius for this linearly scaled parameter has 15° marked at the circumference and 0° at the focal point.

5. Esterman Field—A measure of the ability to see the whole field of view through the respirator lens(es) without distortion. Many single lens mask designs will try to have a flat surface for integration with other optical instruments. This necessitates a

sharp curvature at the side of the lens to wrap it around the face. This causes optical distortion in the visual field. For both single and multiple lens masks, the application of various coatings to the surface of these lenses can cause distortion in a normal visual field. The Esterman visual field test^{11,12} uses a grid to divide the binocular field into 100 units weighted to assign higher scores to those areas most useful to the subject—i.e., higher in the center than the periphery; higher in the lower than upper field; and higher in the horizontal meridian than the rest of the periphery. Because each of the 100 units equals one percent, a direct score in percent of useful field is obtained. The radius for this parameter is divided into 100 equal units with the full value on the circumference and the 0 value at the focal point.

6. Peripheral Field, Superior—An angular measure of the upper or superior boundary limit of a person's ability to obtain visual information while he is focused on one object at an infinite focal distance directly in front of him. This upper limit is usually reduced when the lens(es) of a mask extend some distance away from the face. Any reduction in this area becomes critical for personnel who must monitor instrumentation above their normal field of view because it necessitates increased fatiguing motion of the head in an awkward position and reduces concentration within the normal visual field. This parameter is measured by standard perimetry and only reported for white light using a target stimulus of size I-3b on the Goldmann Scale.¹³ Without a mask the upper peripheral field angle is usually 60° for young adults with normal vision.^{14,15} The outercircumference of this parameter is marked as 60° and the focal point of the circle 0°. The radius describing this parameter is marked linearly at 5° intervals.

7. Peripheral Field, Lateral—An angular measure of the lateral boundary limit of a person's ability to obtain visual information while he is focused on one object at an infinite focal distance directly in front of him. This lateral limit is usually reduced by the lens(es) of a mask extending some distance away from the face or bringing the lateral edges of the lenses forward to produce a flat surface to interface with sighting equipment. Any reduction in this area becomes critical for personnel who must obtain information from this visual region while focusing on other activities (e.g., soldiers on reconnaissance patrols). Like the superior peripheral field measurement, this parameter is measured by standard perimetry and only reported for white light using a target stimulus of size I-3b on the Goldmann Scale.¹³ Without a mask the lateral peripheral field

angle is usually 104° for young adults with normal vision.¹⁶ The outer circumference of this parameter is marked as 100° and the focal point of the circle is 0° . The radius describing this parameter is marked linearly at 5° intervals. Unfortunately, many clinical perimeters will not measure beyond $80\text{--}90^\circ$ to either side of directly in front of the subject because they are primarily used to detect pathology. When such an instrument is used to measure lateral peripheral fields, the actual upper limit must be marked correctly on the scale or it will imply greater visual capability than the mask may actually possess. The instrumentation limitation should be noted for any comments to the unit circle.

8. **Peripheral Field, Inferior**—An angular measure of the lower or inferior boundary limit of a person's ability to obtain visual information while he is focused on one object at an infinite focal distance directly in front of him. This lower limit is usually reduced for several different reasons in mask design, including the size of the nosecup, size and position of the canister and exhalation valve covers, and extending the lens(es) out from the face. Any reduction in this area becomes critical for personnel who must monitor instrumentation below their normal field of view because it necessitates increased fatiguing motion of the head in an awkward position and reduces concentration within the normal visual field. In a situation where the canister is mounted on only one side of the mask, there may be two different inferior peripheral field values. The unit circle will only present the worst value and does not indicate which side is being reported. This parameter is measured by standard **perimetry** and only reported for white light using a target stimulus of size 1-3b on the **Goldmann Scale**.¹³ Without a mask the lower peripheral field angle is usually 60° for young adults with normal vision.¹⁴ The outer circumference of this parameter is marked as 60° and the focal point of the circle is 0° . The radius describing this parameter is marked linearly at 5° intervals.

9. **Peripheral Field, Medial**—An angular measure of the medial or nasal boundary limit of a person's ability to obtain visual information while he is focused on one object at an infinite focal distance directly in front of him. The area enclosed by the medial limits of this parameter for each eye defines the binocular vision capability of the individual. This medial limit is usually reduced when the lens(es) of a mask extend some distance away from the face, the nasal bridge distance becomes too great or the nose cup extends high into the eye area. Any reduction in

this area becomes critical for personnel who require depth perception skills as part of their activity and/or must make rapid critical judgments based on the information in their surrounding environment. If this binocular area is small, the brain is essentially presented with two different views of the world simultaneously. It slows down decision making to choose which one is right or, in some cases when it can not decide, causes headaches and fatigue. This parameter is measured by standard perimetry and only reported for white light using a target stimulus of size 1-3b on the **Goldmann Scale**.¹³ Without a mask the medial peripheral field angle is usually 60° for young adults with normal vision.^{13,16,17} The outer circumference of this parameter is marked as 60° and the focal point of the circle is 0° . The radius describing this parameter is marked linearly at 5° intervals.

10. **Peripheral Field of Gaze**—A parameter conceived by this investigator to measure any degradation of the extended lateral peripheral visual field when the subject looks through the mask with his eye rotated laterally as far as his anatomical limits will allow. Under normal circumstances when a subject fixes his head in one position then rotates his eye laterally to its anatomical limit he can theoretically gain another 23° in his peripheral field of vision.¹⁸ It has been our experience however that 19° is the normal additional increase without a mask. When wearing a single lens mask or one with very small lenses mounted close to the eye, the subject will retain this increase in visual field. If the lenses of the mask extend away from the surface of the face to any appreciable extent, this peripheral field of gaze will actually be reduced. In a military situation, the masked soldier may not want to move his head for fear of giving his position away but it is critical to rotate his eyes to see any changes in his immediate surroundings. The circumference mark on this parameter is set at 120° while the focal point is set at 0° . The radius is divided into linear intervals.

11. **Binocular Field Width**—A measure of the width of the binocular visual field on the horizontal plane extending through the viewer's focal point. In double lens masks, the nasal bridge width and/or the lateral extensions of the nose cup may severely limit the binocular field at this level of vision while it may approach normal values at 30° above the focal plane. The unmasked normal binocular field width on the horizontal focal plane is 120° . The radius for this parameter has 0° at the focal point and 120° at the circumference and linear intervals between.

12. **Masked Peripheral Field as a Percent of Normal Peripheral Vision**—The ratio, expressed as a percentage, of the size of the masked visual field to the size of the visual field of the same subject in the unmasked condition. It provides a measure of the amount of total visual field loss produced by wearing a mask but it does not give any qualitative information about that visual field. The circumference mark for the linear radius of this parameter is 100 and represents the normal peripheral field of view without a mask. The focal point of the radius is 0, representing the absence of any visual field. This linear parameter is divided into 10 percent intervals.

13. **Masked Binocular Field as a Percent of Normal Binocular Field**—The ratio, expressed as a percentage, of the size of the masked binocular field to the size of the binocular field of the same subject in the unmasked condition. It provides a measure of the amount of total binocular field loss produced by wearing a mask but it does not give any qualitative information about that binocular field. The circumference mark for the linear radius of this parameter is 100 and represents the normal binocular field without a mask. The focal point of the radius is zero representing the absence of any binocular field. This linear parameter is divided into 10 percent intervals.

14. **Lateral Visual Efficiency Index**—The current method used among NATO countries to articulate any degradation of the lateral peripheral field of view produced by wearing a mask. A decrease in a lateral visual field severely limits the ability to observe what is happening around the subject at the same time. This causes the subject to rotate his head from side to side more often to obtain this information and results in neck muscle fatigue and less concentration on the specific objective at hand. It is the ratio, expressed as a percentage, of the actual size of the lateral field of view of the right eye between 70° and 135° when wearing a mask to that same field of view measured without a mask. This lateral angular area is integrated from the focal point of the subject's perimetry chart to the marked edge of his peripheral field of vision, with and without the mask. Zero degrees on this perimetry chart is at the top of the head and 90° is located to the lateral side of the body. The circumference mark for the linear radius of this parameter is 100, representing the normal physiological lateral field of view. The focal point of the radius represents 0 percent or a complete lack of lateral vision. It must be noted that the angular direction for this parameter is based on the European standard for reporting the visual field. Unlike the American physiological standard,¹⁹ which has the zero radial direction beginning from

the left side of the horizontal plane and rotating counterclockwise, the European system has zero radial direction starting at the superior perpendicular to the horizontal plane and rotating clockwise.

15. **Inferior Visual Efficiency Index**—The current method used among NATO countries to articulate any degradation of the inferior peripheral field of view produced by wearing a mask. Any degradation of the visual field in this area will affect the subject's ability to view instruments while operating equipment or the ability to move rapidly over rough terrain because he can not see where he is placing his feet. It is the ratio, expressed as a percentage, of the actual size of the inferior field of view of the right eye between 135° and 180° when wearing a mask to that same field of view measured without a mask. This inferior angular area is determined in the same manner as the lateral efficiency index except that a different angular region is integrated. The circumference mark for the linear radius of this parameter is 100, representing the normal physiological inferior field of view. The focal point of the radius represents 0 percent or a complete lack of vision below the horizontal focal plane. Again, it must be noted that the angular direction for this parameter is based on the European standard for reporting the visual field.

16. **Medial Visual Efficiency Index**—The current method used among NATO countries to articulate any degradation of the binocular field of view produced by wearing a mask. Any degradation of the visual field in this area will affect the subject's ability to determine distances accurately. It will also cause a decrease in the ability to respond rapidly in an emergency because the brain is essentially presented simultaneously with two different views of the surrounding environment and it must pause to determine to which one it will respond. This parameter is the ratio, expressed as a percentage, of the actual size of the medial visual field of view of the right eye between 250° and 310° when wearing a mask to that same field of view measured without a mask. This medial angular area is determined in the same manner as the lateral efficiency index, except that a different angular region is integrated. The circumference mark for the linear radius of this parameter is 100, representing the normal physiological medial field of view. The focal point of the radius represents 0 percent or a complete lack of binocular vision. As with the other two parameters of this type, it must be noted that the angular direction for this parameter is based on the European standard for reporting the visual field.

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Appendix B

Unit Circle Parameters Associated with Biophysical Aspects of Vision

1. **Eye Relief**—A measure of the distance between the center of the outer surface of the cornea of the eye and the interior surface of the lens(es) of the mask. The measurement is made by focusing a slit lamp on both surfaces in sequence and measuring the focal difference between them. If the lens(es) are too close to the eye, the lashes will touch the lens(es) when blinking and become very annoying. If the lens(es) are too far away from the eye it creates a problem of interfacing with optical devices and reduces visual capability for other parameters, notably peripheral fields. A minimum amount of space between the eye and lens(es) must be provided for permitting air to circulate through the area to remove moisture diffusing from the body surface and lachrymal glands. Because there is no corrective visual capability built into a generic respirator, actually placing the lens(es) at the reference spectacle point¹ located 14 millimeters in front of the cornea is not required. The circumferential value for this parameter is 14 millimeters while the focal point value of the radius is 64 millimeters, the furthest distance observed in a commercial mask. The linear radius is divided into millimeter intervals.

2. **Haze**—A measure of the transmitted light scatter produced by the lens(es) as a result of the material of construction, surface scratches, internal blemishes, etc. Using a standard method² and haze meter, the resultant value is expressed as a percent of the ratio of the scattered light to the transmitted light. In more familiar terms, the scattering or diffusion of light due to the lens produces glare or dazzling brightness which blurs the vision. The higher the haze, the more difficult it becomes to distinguish objects in the visual field. From a practical standpoint it is impossible to have 0 percent haze, due to current materials and the testing technique. It is possible however, to have values as low as 0.25 percent. Therefore, the circumferential value for the radius of this parameter is 0.25 percent. The focal point is set at 5.25 percent with the radius divided at linear intervals of 0.25 percent. Any value greater than 5.25 percent will be marked at that upper value. The rationale for limiting the scale to this upper value is that most manufacturers have recently been able to limit initial haze values on new masks to less than 3.0 percent.

3. **Light Transmission**—Defined as the ratio, expressed as a percentage, of the amount of transmitted light through a lens to the amount of incident light reaching the objective when the lens is not present. This parameter only measures the average amount of transmitted light through the visible range of 380–780 nanometers rather than at specific frequencies.² Light transmission in the ultraviolet and infrared region of the electromagnetic spectrum is not considered. If these additional frequency ranges are required for special purpose masks, they are presented in a special requirements unit circle of the unit sphere. This parameter also reports the average light transmission through only the standard optical lens(es) permanently mounted to the mask faceblank. Light transmission through a series of additional inserts, outserts, prescription corrective lenses and protective face shields is not included. Each one of these components, individually and collectively will further reduce the total average light transmission of the mask. Discoloration of the lens due to aging or chemical reaction will also reduce light transmission. The circumferential value of this parameter is set at 100 percent or full light transmission. The focal point of this radius is set at 0 percent, because the refractive index of some lens materials will minimize light transmission. The scale on the radius is linear and divided into 5 percent intervals.

4. **Prism Power**—A measure of the angular deviation, expressed in prism diopters, of a light ray after passing along the design viewing path through the lens (as defined in the American National Standard "Practice For Occupational and Educational Eye and Face Protection,"³). The design viewing path extends along the horizontal and vertical meridians radiating from the optical center of the lens. This parameter measures the amount of distortion—e.g., change in size (magnification) or position resulting from the light path being bent by traveling through a lens material with non parallel surfaces or varying curvatures as well as a different refractive index (i.e., air to plastic or glass back to air)—on its way to the eye.⁴ This bending is measured in diopters and represents the location of the new focal point for that particular lens. Since generic masks will have non-prescription or plano lens(es) suitable for use by the general population, the lens(es) should have no

distortion present. From a practical standpoint it is impossible to achieve this when mask lens(es) are manufactured in a mass production situation as well as when the surface of the lens is not always equidistant from the eye. If, therefore, the resultant lens prism power can be kept beyond the point of accommodation or infinite focus for the human eye, then the distortion in the lens would not have an effect on visual acuity. The point of infinite focus, where the lens of the human eye is completely relaxed, is considered to be 6 meters or 20 feet. By limiting the prism power of the mask lens equal to or greater than the 6 meters, distortion in vision should not be noticed by most individuals wearing that mask. The circumference value for prism power is set at 0.125 diopters or 8 meters. The focal point of this logarithmic scale is set at 1.25 diopters or 0.8 meters, the accommodation point for many older personnel.

When the mask lens(es) are very large (i.e., more than 5 centimeters in the vertical or horizontal plane), prism power is measured at the design viewing path and several points to either side in each of these planes. The deviation between the readings in each plane is determined and the plane with the highest prism power is reported.

5. Spherical Distortion—A measure, using a standard lensometer, of the spherical optical correction built into the mask. Masks to be used interchangeably among many people should contain no optical correction in the basic lens design. The presence of such a correction can magnify or distort the view of the wearer with normal vision resulting in improper decisions and maneuvering until he becomes adapted to the use of the mask. Spherical correction or refraction is the focusing of an image at a single point rather than in a plane.⁵ The circumferential value for this parametric radius is 0. The focal point end of the radius is set at 5 diopters, which represents the near point of accommodation or the widest convergence angle. The linear scale is divided into 0.25 diopter intervals. The diopter value reported is an absolute value and does not take into account convergence or divergence.

6. Cylindrical Distortion—A measure, using a standard lensometer, of cylindrical optical correction built into the mask. Masks to be used interchangeably among many people should contain no optical correction in the basic lens design. The presence of such a correction can magnify or distort the view of the wearer with normal vision resulting in improper decisions and maneuvering until he becomes adapted to the use of the mask. Cylindrical correction

or refraction is the focusing of an image in a plane rather than at a single point.⁵ Like the spherical correction parameter above, the cylindrical distortion circumferential value for this parametric radius is set at 0 diopters. The focal point end of the radius is set at 5 diopters, which represents the near point of accommodation or widest convergence angle. The linear scale of the radius is divided into 0.25 diopter intervals and represents an absolute value rather than an indication of convergence or divergence.

7. Cylinder Axis—When lenses have cylindrical distortion, the focal plane axis of the cylinder has an orientation which is expressed in terms of its radial direction with regard to the reference horizontal line of sight.⁵ The zero radial direction lies to the left of this horizontal line and any deviation is measured in a clockwise direction.⁶ Even though the lens(es) of a mask may not be designed with inherent cylinder correction, if they have any curve to them and are improperly mounted into the faceblank, a cylinder distortion may be observed along a specific axis. The circumferential value for this parameter is set at 0° and the focal point value is set at 50°. Although this latter value appears high, the bending curvature of a wrap-around lens of one mask has been observed very near this value. The scale of the radius is linear and marked at 5° intervals.

8. Medial Lens Separation—A measure of the internal non-transparent separation of two lenses across the bridge of the nose in a mask at the level of the horizontal plane of relaxed vision when the head is held in the Frankford plane.⁷ As this separation becomes wider, it will cause the convergence angle of vision to get smaller, thereby reducing binocular vision and forcing items to be held further away from the face to be read or examined. People with small interpupillary distances will have decreased binocular fields. Interfacing with various pieces of optical equipment will be difficult if the distance becomes too wide. The circumferential value for this parameter is set at 15 millimeters to accommodate the thickness of the nose at this level. The focal point value is set at 40 millimeters to encompass the full range of the interpupillary distance (i.e., 54 to 80 millimeters).⁸ The radius is marked at linear intervals of 2 millimeters.

9. Lens Thickness—This is important both for determining the physical strength of the lens(es) and the amount of refraction and distortion that can be expected as light traverses that material.⁸ Non-corrective plastic lenses can be made relatively thin to be light in weight while structurally strong.

Tempered glass lenses, on the other hand, must be relatively thick to retain the same mechanical strength. If physiological correction is required, the lenses will be even thicker. The thickness reported on this radius also includes the thickness of any coating, if present. The circumferential value for this parameter is 2.0 millimeters. The focal point value is set at 5.0 millimeters while the linear scale is marked at 0.3 millimeter intervals.

10. Equipment Interfacing—A measure of the ability of the mask to function with other equipment that must come in contact with it or be used while wearing it. Because the types and amounts of equipment will arbitrarily vary depending on the occupation and needs of the wearer, this parameter will only indicate a qualitative value for a fixed number of interfacing situations rather than being specific for any pieces of hardware. The total number of sequential qualitative items is set at five and is so represented on the circumferential value of this parameter. The focal point is set at 0 interfacing matches. The linear scale of the radius is divided into five major intervals which are, in turn, divided into 0.2 millimeter intervals. The smaller intervals represent the subjective evaluation, in percentage, of each of the five items reported. The total score for each of the items is summated and this total score is then marked on the radius. When selecting the five items for interfacing, they should be chosen to represent the major diverse duties the mask wearer will perform for this specific physiological capability represented by the unit circle. For example, in a military situation, the wearer must be able to interface with a rifle sight, binoculars or fixed target acquisition sight, night vision goggles, map/document/instrument gauge reading, and an item requiring color discrimination (a colored chemical agent test or television/computer screen, for example). In a civilian situation the examples will overlap with items substituted for rifle, target acquisition and night vision equipment interfacing. The user of the unit circle is left to choose his own interfacing requirements but as long as the same number of items is reported on the scale, the values from mask to mask should be fairly consistent.

11. Exceptions to Parameters—If there is any question about the value of any parameter reported, this radius serves as a qualitative flag to indicate that fact. The circumferential value will indicate zero exceptions while the focal point value of the radius indicates the highest number of parameters in the unit circle(s) associated with a specific capability. In

the case of vision, there are two unit circles with each containing 16 radial parameters. The radius is therefore divided into 32 intervals. The further the marking on this radius away from the circumference, the stronger the indication that the data reported is not "clear cut" and caution should be used when comparing unit circles between masks.

12. Astigmatism—The measure of local aberration observed in a lens due to unequal curvature along the different meridians in one or both of its refractive surfaces.^{9,10} The unequal curvature causes a difference in focal length for light rays coming from an off-axis object. The resulting image is smeared between the two sharp focal points representing the extremes of curvature. Using a lensometer, the lens is tested to determine if the lines in only one meridian are sharpest at a given focus. The meridian with the highest diopter reading is measured. The lensometer is then focused on the meridian with the opposite extreme diopter reading and the absolute difference between the two values is reported. The circumferential value for this parameter is 0 diopters. The focal point value is set at 0.5 diopters with the linear radius marked at 0.1 diopters.

Note that astigmatism, as defined in this parameter, is different from the physiological concept of astigmatism in which the lens surface is not rotationally symmetrical around the optical axis.

13. Retrosopic (Faceform) Tilt—A measure of the lateral/medial rotation around a vertical line through the lens where it crosses the focal plane of the eye when both eyes are focused at an infinite point normal to the plane of the face. When the lens is parallel to the normal of the facial plane, the retrosopic tilt angle is considered 0°. Having a zero degree retrosopic tilt can have its advantages as well as disadvantages. The flatter the angle, the better the ability of the mask to interface with other optical coupling equipment. The further the flat angle lens is away from the cornea, the greater the loss of peripheral vision. This can be compensated for by adding a slight amount of lateral posterior tilt to the lens or increasing the lens lateral length and curving it gradually to provide a 100° peripheral field without distortion. The retrosopic tilt is determined by using a slit lamp and attached caliper to measure the focal distance difference between two horizontal points (one centimeter to either side of the visual axis) on the lens. The circumferential value for this parameter is set at 0°. The focal point value is set at 30°. The linear scale of the radius is divided into 6° intervals.

14. Pantoscopic Tilt—A measure of the posterior/anterior rotation of the lens(es) of the mask around a horizontal line drawn at right angles through the focal plane of both eyes when the eyes are focused at infinity. When lens(es) are perpendicular to the focal plane, the angle of tilt is 0° . Any rotation posterior to this vertical position is measured in degrees of pantoscopic tilt. The more vertical the lenses, the better the ability to interface with other optical coupling equipment as well as minimize both the production of internal reflection and interference of distortion through haze and prism power. When the lenses of the mask are mounted at or near the spectacle point the pantoscopic tilt can be flat or 0° rotated posteriorly. As the lenses become larger or move further away from the spectacle point, they must develop a slight posterior tilt to accommodate the slightly anterior projection of the cheeks. The pantoscopic tilt is determined by using a slit lamp and attached caliper to measure the focal distance difference between two vertical points (one centimeter above and below the visual axis) on the lens. While pantoscopic tilt should not exceed 10° , in actual practice some masks have been designed with as much as a 30° posterior rotation. On this basis, the circumferential value for this parameter is set at 0° and the focal point value at 25° . The linear scale of this radius is divided into intervals.

15. Chromaticity, X—One of two Commission Internationale de l'Eclairage (C.I.E.) coordinates^{11,12} used to identify the color of lenses as the result of the intrinsic color of the material from which they are made and/or coated, as well as their light absorbent and reflective characteristics. The presence of any

color to the lens(es) may affect the ability of the wearer to distinguish the color of the object being viewed. This could be important trying to read a color change in chemical agent detector papers, reading a color chart on a computer monitor, or reading safety labels on chemical containers at spill sites. Complete transparency is taken as the presence of equal energy from all three primary colors in the Commission Internationale de l'Eclairage chromaticity chart. This value is set at 0 on the circumference of the unit circle and any deviation from that value represents the presence of a color in the lens(es). Since all colors can be identified by any combination of the percentage of the three primary colors equaling the whole color, identification of the X coordinate (red axis) and the Y coordinate (green axis) will automatically give the Z coordinate (blue) by subtraction from unity. The chromaticity diagram is set for unity on each axis. Since transparency is taken as one third the energy for each color, the maximum deviation from white (all colors equally) would be no greater than 0.66. In reality, the C.I.E. curve has a maximum deviation of 0.5 units in the green direction and .41 in the red direction from transparency. Therefore, for simplicity, the focal point is set for 0.5 units with intervals of 0.01 on the radius scale for this parameter.

16. Chromaticity, Y—The second coordinate for identifying the presence of color in a lens by using the C.I.E. chromaticity diagram. The explanation for establishing the values are defined immediately above for the chromaticity X coordinate. The circumference value for the Y parameter is 0, with the focal point at 0.5 and the radius divided into 0.01 intervals.

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While the references below do not deal directly with the optics of respirators, they will provide an in-depth background in geometric and physiological optics as well as visual physiology if the reader wishes to pursue a strong foundation for the visual aspects of mask design.

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