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RESEARCH ON PHYSICAL AND PHYSIOLOGICAL ASPECTS OF VISUAL OPTICS IN SPACE FLIGHT

FINAL REPORT

30 JULY 1971

Contract NAS 9-11085

National Aeronautics and Space Administration
Manned Space Craft Center
Houston Texas

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FOREWORD

This report was prepared by the Life Sciences Division of Technology Incorporated for the Manned Spacecraft Center of the National Aeronautics and Space Administration under Contract NAS 9-11085, and covers the period 28 May 1970 to 28 May 1971. Dr. W.H Shumate and Dr. R. Fitch were the Contract Monitors, and Dr. Brian Ward was the Principal Investigator.

Acknowledgement is made of the assistance provided by the Contract Monitors throughout the period of the study

The research effort involved five distinct phases, each of which was performed and reported as a separate unit. This Final Report will continue this approach by summarizing the entire program.

INTRODUCTION

The work described in this report refers to tasks which have been performed during the period 1 June 1970 to 31 May 1971 under the terms of Contract NAS 9-11085.

Research on physical and physiological aspects of visual optics in spaceflight has involved five task areas, which may be conveniently grouped under the following headings.

1. Retinal temperature calculations for the specification of adequate eye protection at the lunar surface
2. A survey of hazardous visual perceptions in spaceflight
3. Measurement of the optical properties of new and used visual transparencies
4. Analysis of visual problems in spaceflight
5. Direct support to the neurophysiology laboratory, NASA, MSC, Houston

The text of this report is similarly subdivided.

TABLE OF CONTENTS

PAGE

LIST OF FIGURES

1. RETINAL TEMPERATURE CALCULATIONS FOR THE SPECIFICATION OF ADEQUATE EYE PROTECTION AT THE LUNAR SURFACE

1.1 Introduction

The infrared region of the spectrum is generally considered to extend from approximately 700 nm to some 100 μ It is chiefly known for the heating effects produced when radiation in this wavelength band is absorbed by the body.

The eye is heated in common with other surfaces of the body. The retina of the eye however, is particularly vulnerable to the heating effects of both the visible and the infrared spectral regions,-because radiation in the wavelength bands below 1400 nm is focused upon a retina which is backed by the highly light absorbing, retinal pigment epithelium. Above 1400 nm, the ocular media are virtually opaque and the chorioretinal structure is protected.

Man is ordinarily protected from solar retinal burns by his aversion to intense lights, by blinks, pupil contractions, and the attenuation of radiation by the atmosphere. Yet on the moon, without an atmosphere, heating due to the increased irradiation is much greater, For this reason, the astronaut requires optical protection in both the visible and the infrared regions of the spectrum It is desirable that this protection should be provided while providing for optimum visual performance.

1.2 The Model Described

A mathematical model(1) constructed under a previous contract has been modified and employed to calculate the retinal temperature increase caused by direct observation of the solar disc by an unprotected astronaut situated on the lunar surface. Such calculations, based upon considerable experimental data, allow the calculation of the minimum attenuation of the solar radiation required for safe exposure on the lunar surface Data on the radiant output of the sun(2) is used, and the worst-case condition is considered in which the astronaut directly observes the sun for 100 seconds. The pupil of the astronaut's eye in this calculation was assumed to be 3 millimeters in diameter, an appropriate size for a terrestrial observation of the sun. The resulting temperature rise is shown in Figure 1.

The total irradiance from the sun, called the solar constant, is approximately 2.0 calories per square centimeter per minute. Infrared radiation contributes about half of the solar constant, 0.98 calories per square centimeter per minute. Pre-retinal ocular media absorb much of the near infrared and practically all of the radiation of wavelengths greater than 1400 nanometers. As a result, only about 27 percent of the retinal temperature rise is caused by infrared radiation Table I shows the temperature rise associated with each of fourteen wavelength bands used in the calculation.

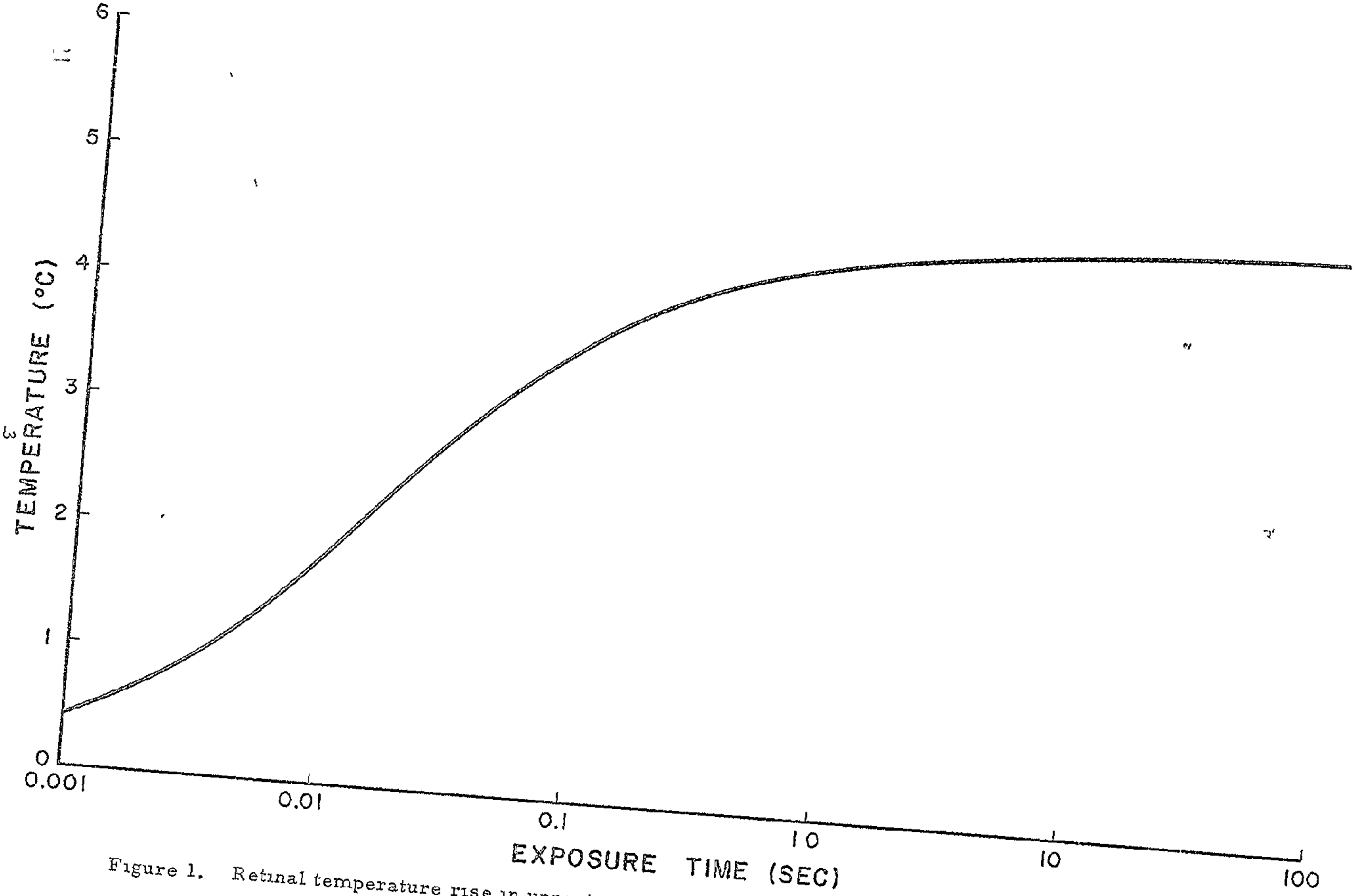


Figure 1. Retinal temperature rise in unprotected lunar observation of the sun with a 3 millimeter pupil

TABLE I

Wavelength Band (nm)	Temperature Rise (°C)	
355- 381	0.0090108	ULTRAVIOLET
381- 413	0.043509	VISIBLE
413- 451	0 3099	
451- 496	0.6808	
496- 545	0.7382	
545- 591	0.6321	
591- 636	0.5821	
636- 689	0.4486	
689- 751	0.4949	INFRARED
751- 827	0.3565	
827- 918	0.2519	
918-1033	0.096649	
1033-1181	0.086086	
1181-1377	0.013878	

The temperature rise considered to be safely tolerable is 5°, (3) and from Figure 1 it is seen that retinal damage will not occur for a 3 mm pupil diameter. There are situations however, in which the sun may be imaged on the retina when the pupil size is larger than 3 millimeters, and the solid curves in Figure 2 show the temperature rise associated with the various pupil sizes of the human eye. Curve (C) is concerned with infrared and visible spectra reaching the retina, (D) is concerned

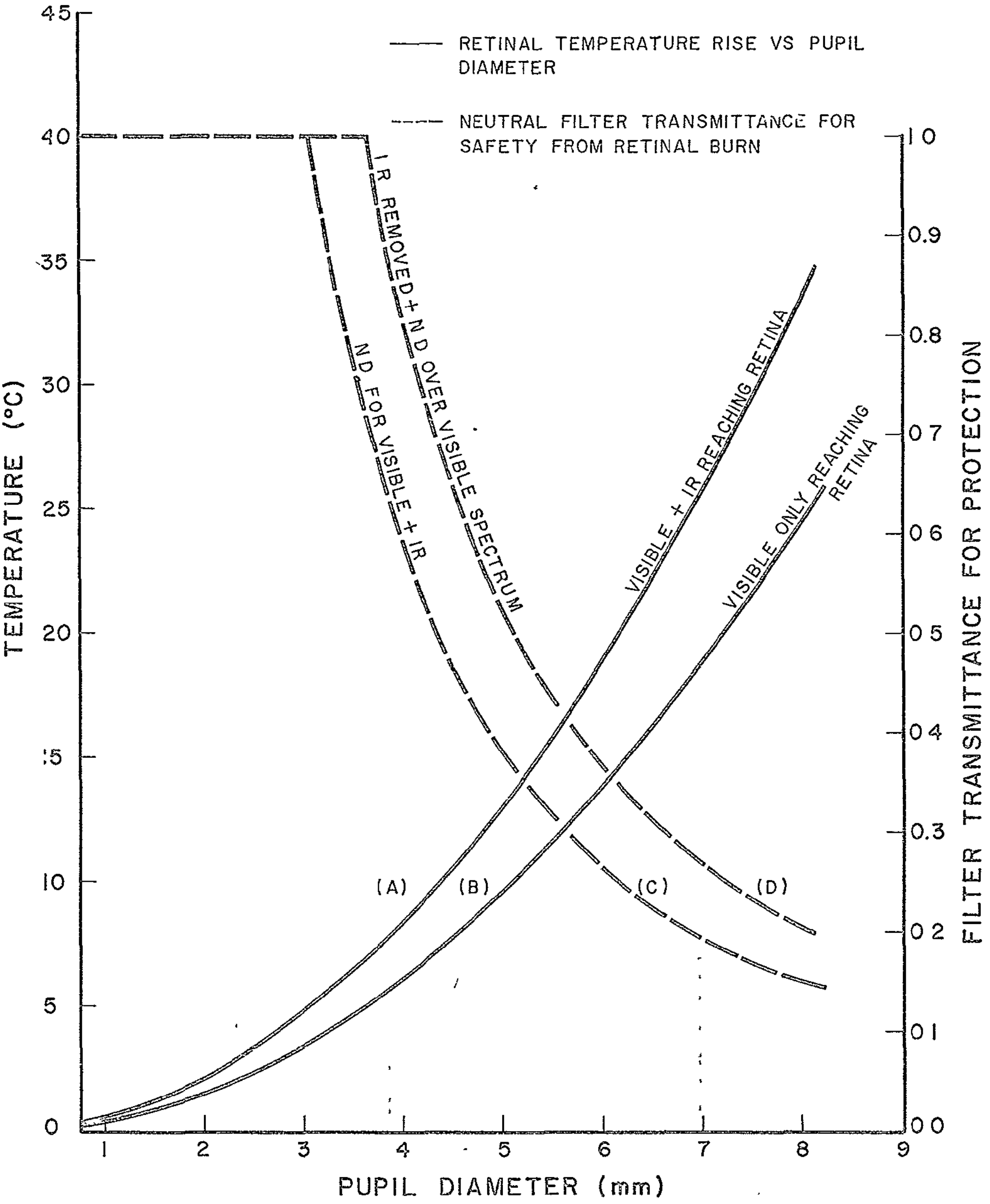


Figure 2. 100 second unprotected lunar viewing of the sun

with the visible spectrum alone. The corresponding dashed curves (A) and (B) predict the degree of neutral density filtering required, over the visible and infrared spectra, for the safety criterion stipulated of a retinal temperature rise of 5°C or less, for pupil diameters of 1 to 8 millimeters.

It is apparent from Figure 2 that filtering of some kind is required in the astronaut's helmet and visor system in order to protect against retinal damage. Even in an accidental exposure, the retinal temperature rise attains over 80 percent of the 100 second value before the eye can blink. The design of protective filtering involves a decision about the spectral distribution of the filter transmittance. The simplest filter is a neutral filter in which the transmittance is the same at all wavelengths of importance. The transmittance of a neutral filter which would prevent the temperature rise in the retina from exceeding 5° is given in Figure 2 by the dashed curve, as a function of pupil diameter.

Using Figure 2 and Table I, a suitable filter may be designed for various situations or mission objectives. The total temperature rise and temperature rise in each wavelength band in the Table are directly proportional to the pupil area or the square of the pupil diameter. A possible filter would be one which filtered out most of the infrared radiation but was very transparent to the visible wavelength radiation The retinal temperature rise in this case is shown for various pupil diameters by the solid curve in Figure 2 labeled (D). A safe visible light neutral filter worn with a filter opaque to the infrared would be one with the transmittance shown by the dashed curve in Figure 2 labeled (B). It is seen that with the infrared filter and a 20 percent neutral filter, the astronaut would have adequate protection against retinal burn from the sun. Standard Air Force sunglasses, for example, provide adequate safety as they have a 15 percent transmissivity in the visible range and about 2 percent in the infrared out to at least 1400 nm

2 A SURVEY OF HAZARDOUS VISUAL PERCEPTIONS IN SPACE FLIGHT

2.1 Introduction

Three Apollo missions have successfully landed on the moon and returned to earth. To date, visual problems associated with lunar missions have not prevented the successful completion of these missions. It is, however, possible and desirable to identify some potentially hazardous perceptual conditions which could affect performance on future lunar missions and in other space programs. This task is difficult because of the paucity of research on the type of perceptual tasks demanded in these situations The visual problems described in this report must, therefore, be viewed as conjectures and possibilities. Through a systematic research program it should be possible to determine which of the perceptual problems described in this report are most likely to occur during lunar missions. A program of this nature would also permit the identification of additional areas of concern and would provide information about methods of reducing the dangers from such phenomena.

Voyage in a space vehicle introduces conditions which may produce aberrant perceptions which could constitute a serious hazard during critical phases of operation. This section discusses these conditions and the illusions that may arise from them. Some of the topics discussed below will perhaps not be applicable to the Apollo program, but may be pertinent to future space activities.

2.2 Survey of Illusions

2.2.1 The Visual Effects of Restricted Perceptual Environments

During the space flight the astronauts are exposed to a visual environment which is restricted in a number of ways. This environment contains few, if any, of the cues to distance and depth normally associated with earth terrain. Such cues include texture density gradients, which are important for judgments of both distance and slant, linear perspective cues and gradients of light and shading, which produce the impression of depth and elevation. Furthermore, there is a limited visual expanse within the cabin, and while space outside the cabin extends to optical infinity, there is no natural visual ground at any "middle-distances" -- distances between perhaps 10 feet and one mile. The perception of objects at such distances is of primary importance for the lunar landing operation and lunar surface explorations. The possibility arises that this restricted environment could cause inappropriate and confusing perceptual responses.

Few studies have been directly concerned with the effect that deprivation of a particular depth clue might have on tasks requiring later utilization of that clue. One experiment reported that deprivation of binocular vision by alternating monocular occlusion at 2 - 3 hour intervals for a 24-hour period resulted in a deterioration of depth perception.(5) There appear to be no analogous studies for the monocular clues to depth and distance.

Hence, the effect of a lack of opportunity to utilize certain depth cues, or to make perceptual responses to certain distances, is unknown.

It is known that various perceptual systems can be altered by introducing a systematic bias, in humans these systems appear to be quite labile or plastic.(6) Since perceptual systems are capable of modification, it is plausible to hypothesize that they are also susceptible to degradation if they are not continuously recalibrated or re-tuned. If this is true, the lack of any opportunity to calibrate various systems during the space flight may have adverse consequences during the lunar landing. It is a reasonable hypothesis that any system capable of being changed requires frequent input to remain calibrated.

If subjects make active movements while wearing wedge prisms in spectacles, they rapidly adapt to the visual displacement by altering the positional sense of a body part such as an arm, head, or eye. Essentially, the proprioceptive sense is recalibrated to align it with visual ego-centric localization of the part.(7, 8) One of the first consequences of looking through lenses which reverse or invert the visual field is that when the head or eyes move, the field of view does not remain stable or stationary, as it would under ordinary conditions However, with time these perceived movements become less pronounced. Again, it is as if the systems signaling movement in the world become adjusted so that a change in the position of a retinal image, which formerly produced the sensation of object movement, no longer does so In a similar fashion, the absence of an opportunity during the duration of the space flight to calibrate movement of images of objects across the retina with distance, for distances greater than 10 feet, may result in the degradation of the "motion parallax -- distance perception linkage."

Similarly, the relationship between convergence and distance can be experimentally altered. It is also possible that this relationship may become degraded without an opportunity for calibration. Although convergence is not usually considered a major clue to depth, it is important for the accurate perception of the absolute depth associated with a given magnitude of stereopsis or binocular disparity. To determine the absolute distance between two objects, an observer must take into account both the disparity of the images of the objects on the retinas and the degree of convergence of the two eyes.

The possibility that the perceptual systems responsible for distance judgments may become decalibrated during the space flight has not yet been empirically validated. The hypothesis could be tested in a straightforward manner under simulated space flight conditions. If degradation were to occur, it might be possible to provide "exercise" devices to be used within the spacecraft to simulate distances between 10 feet and one mile and to produce a variety of depth clues associated with objects at such distances. It would be difficult to make provision for the active movements necessary for recalibration and possibly necessary for the prevention of degradation, nevertheless, in a visually rich environment, several clues together might sufficiently reinforce or bolster each other, and reduce the tendency toward degradation.

2.2.2 The Visual Effects of Alteration in Sleeping Patterns

A continuing problem for the astronauts is the lack of adequate sleep, due to such factors as stress, excitement, noise, the novel environment, and cramped quarters. Lack of sleep may result in perceptual and cognitive malfunctioning The decrement in performance on vigilance tasks with an increase in drowsiness has been documented,(9) such a decrement can be reduced by appropriate motivational increases. It has also been reported that sleep deprivation is frequently associated with the production of hallucinations (10)

Another possible consequence of altering normal sleeping habits, and one which has only recently been hypothesized, is a deterioration of binocular depth perception. It has been suggested that one function of REM (rapid eye movement) sleep is to provide a mechanism for maintaining precise binocular coordination so as to prevent a degradation of binocular vision immediately upon awakening.(11) After a period of sleep deprivation, non-REM sleep takes precedence over REM sleep, so that an individual does not innervate his eye muscles during sleep while he is recuperating from the lack of sleep. If an astronaut were in a state of sleep deprivation so that almost all of his sleep were of the non-REM variety, and if he were required to perform a task demanding binocularly coordinated eye movements shortly after awakening, it is possible that his visual performance would be seriously impaired. This is an intriguing and potentially important area in which the necessary confirmatory research has yet to be performed.

2.2.3 The Visual Effects of Angular and Linear Accelerations

Illusory visual and spatial perception may arise as a result of angular acceleration (affecting the semicircular canals) or linear acceleration (affecting the otolith organs). A frequent outcome of angular acceleration is known as the oculogyral illusion. If a subject is seated in a rotating chair, viewing a target which rotates as he does, an acceleration to the left will cause the target to seem to move leftward, without appearing to be greatly displaced. The illusion may also occur when viewing a moving target in darkness, so that the effects of real and apparent motion may either summate or cancel each other. (12)

A second effect of angular acceleration is the Coriolis effect, occurring when a subject who is rotating in one plane tilts his head in a different plane. The results can be severe dizziness, nausea, and spatial disorientation, as well as illusory target motion.

A linear acceleration causes target displacement in a direction consistent with the resultant gravitational force vector. This effect is known as the oculogravic illusion. If a pilot accelerates his plane during straight and level flight, the resultant G-vector is mistakenly interpreted as a cue to verticality, causing the pilot to feel that he is tilting backward. A fixed target would then appear to rise as the pilot appeared to tilt.

A special case of the oculogravic illusion involves a change in the magnitude of the G-vector, but not in its direction. When the G-vector increases in magnitude, as when a high speed elevator ascends, a target fixed relative to the observer appears to rise. Conversely, during a decrease in G-force, a fixed target appears to descend.

The illusions described above are not simply laboratory phenomena, but do occur in high performance aircraft, and are considered a potentially serious hazard to flight safety (12) To minimize problems caused by the oculogyral and oculogravic illusions, a good visual frame of reference outside the vehicle should be maintained.(13) Difficulties of this nature resulting from spacecraft maneuvers are not anticipated during lunar landings occurring in the daylight. However, during space flight, or, more likely, in extravehicular space activities where the astronaut may be in a position to see only black space and stars, false clues to motion might result from certain accelerations, and might produce inappropriate and dangerous corrective actions.

2.2.4 The Visual Effects of Weightlessness

While a variety of authors have suggested that certain visual anomalies might occur in a weightless environment,(14) no serious difficulties have been encountered in the U. S. space program. Although future experimentation may reveal subtle effects of a zero-G environment, current evidence does not suggest this poses a serious threat to lunar missions.

With respect to visual acuity, although slight decrements have been found during some zero-G flights in airplanes, these were too small to be of practical significance.(15) Furthermore, the testing of astronauts during Gemini flights 5 and 7 produced no evidence of any such degradation (16)

One illusion which has been observed under certain conditions in transient weightlessness experiments is the "inversion" illusion.(17) Upon entering the zero-G state, subjects sometimes report the feeling of suddenly being turned upside down. Similarly, if they were "standing" on the ceiling of the plane during the parabolic maneuver, they might report the feeling that they were standing upright and that the plane was flying upside down. Although some Russian cosmonauts have experienced this illusion in space flight,(18) astronauts of the U. S. space program have not reported it.

In general, the evidence to date indicates that the oculovestibular system does not react to weightlessness in a manner foreseeably hazardous to space travel or lunar landing operations. This is doubly true for experienced pilots trained to recognize and, where possible, avoid many situations where illusory perceptions may occur.

2.2.5 Autokinesis

The autokinetic effect consists of the apparent random movement of a light viewed without an adequate visual frame of reference. If the interior of a spacecraft were dimly illuminated, objects viewed through the windows could occasionally appear to move in an erratic fashion. Such movement could also occur for dim signal lamps within the craft. This apparent movement is a compelling phenomenon, and is difficult to abolish While thorough parametric research has not been conducted on the subject of minimizing the illusion, there is evidence that it is reduced when multiple lights are visible, and when a visual frame of reference, such as the border or a window, is introduced into the field of view. (18)

2.2.6 Perspective Reversals

If the only clue to the nearer and farther sections of a space station is the retinal angle subtended by the two sections, a perceptual reversal of near and far is then possible When an object is seen in this reversed fashion, it appears to move laterally along with a laterally moving observer. As long as it remains reversed, corrective movements will be reversed. (A fore and aft runway reversal in darkness or fog has been suggested as the probable cause of some aircraft accidents in which the pilot lands well short of the actual runway. (19) Because of this reversal of corrective movements, an astronaut would probably approach a perceptually reversed space station on an erratic course. Perspective reversals could also occur when viewing a girder-like structure, such as a partially constructed space station, against the blackness of space. (This can be demonstrated in the laboratory by viewing a luminescent wire model of a cube in an otherwise dark room.) This phenomenon is viewed as a serious potential problem in space activities, and one not easily solved.(20)

It is difficult to prevent the occurrence of this illusion, to do so it is probably necessary to introduce other clues to distance. For example, differential illumination of the near and far portions of the space station might reduce the frequency of the reversal effect. It may also be possible to train astronauts to recognize its occurrence and to avoid approaching the station when it is spatially reversed. If the shape of the object being viewed were well known, the illusion's existence should become apparent, since shapes become distorted as objects reverse This is a consequence of the mechanism of size constancy, by means of which the apparent size of a portion of the object is determined by its apparent distance from the observer.

2 2. 7 Reduced Size Constancy

As we walk toward an object it remains approximately constant in perceived size. Such constancy of size will be reduced, however, when an object is approached in space. Research has shown that when an observer is wheeled at a constant velocity toward a luminous disc in an otherwise completely dark room, the disc appears to expand in size.(20) The increase in size with a decrease in distance is enhanced if the observer views the disc through a simulated window frame dimly lit by luminous paint. In this case, the observer apparently compares the retinal image size of the disc with that of the window. As he approaches the disc, it expands relative to the window and is perceived as becoming larger. These viewing conditions are similar to spacecraft conditions in which the observer has no subjective impression of his own motion. Possible phenomenological experiences include the perception that the viewed object is increasing in size and/or the perception that it is moving toward the observer. Methods to reduce this illusion have been explored, one possible technique is to provide the observer with non-visual information about distance.(20) If one is trained to associate tones with distances under normal illumination, the tones may help to maintain partial size constancy in the reduced illumination conditions. Also, placing a fixed reference light next to the object being viewed has been found to aid the viewer considerably in maintaining constancy.(19) It may be necessary to introduce such techniques for visually guided space rendezvous.

2.2.8 Brightness Difference Illusions

Another perceptual anomaly which might arise in space involves the problem of estimating the relative distances of two objects differing in brightness. Normally, the brightness of a surface is not a cue to its distance from the observer, since although the intensity of a point of light diminishes with distance via the inverse square law, the luminance of a surface does not. This is because as a surface recedes, its theoretical "points" become more densely packed, so that the total amount of light per unit solid angle at the eye remains constant. Paradoxically, however, when two luminous objects are viewed against a black background, the brighter object does, in fact, appear to be closer.(21) It is not difficult to conceive of situations (such as when astronauts are freely moving in space, or possibly are engaged in a rendezvousing maneuver) where the blackness of space could give rise to this illusion. This phenomenon has not been extensively investigated, so it is not clear whether training procedures can reduce its effects. Furthermore, it is possible that a dark background is not a necessary condition for its occurrence, and that it may arise in other situations where there is a reduced number of normal distance cues (e g., in orbit with the earth or moon as a background, or possibly on the lunar surface itself).

2.3 Potentially Hazardous Illusions in Lunar Landing

The descent to the surface of the moon may be the most critical and potentially dangerous portion of the lunar mission. Since, in the Apollo program, this descent is visually guided, any impairment in perceptual functioning could have severe consequences. Even if the perceptual systems of the astronauts are in normal condition after the flight from earth, the lack of sufficient visual information regarding features of the lunar surface and the presence of conditions producing visual illusions during the descent and landing may result in non-veridical perceptions.

Perceptual tasks essential to the mission include the recognition of the pre-designated landing site, the choice of a safe area in which to land, the determination of altitude above the lunar surface, and the alignment of the lunar module with the selected touchdown point during the final descent to the surface.

2.3.1 Recognition of Landing Site

The effects of set or expectancy are known to play a significant role in visual perception. The fact that people are prone to see what they anticipate seeing, or what they hope to see, sometimes produces embarrassing, or even catastrophic, results. For example, there are occasions each year when experienced pilots unknowingly land their aircraft at the wrong airport. (22) In the lunar landing situation, a slight course deviation of which the pilot was unaware could cause him to misperceive lunar features and, possibly, to commit himself to landing at a site more dangerous than the one originally chosen.

This problem can be minimized, first, by thorough training with accurate simulations and photographs of the selected landing area. With regard to this point, the Apollo 12 astronauts commented that their training photographs were inadequate for visual orientation immediately after pitchover, in terms of detail and field of view (23) Second, training should emphasize not only the distinctive features of particular landmarks, but also the spatial relationships between several of these landmarks. (For example, Apollo 12 astronauts looked for a cluster of craters which resembled a "snowman".) Finally, with two persons searching independently for critical features, the probability of misperception due to set should be reduced.

2.3.2 Selection of a Safe Landing Area

Perceptual problems associated with the selection of a safe area are more likely to occur during future missions scheduled for areas more rugged than those in which landings have already occurred. When the astronaut attempts to select a landing area visually, certain features of the lunar surface may cause him to make a poor choice The shadows cast by mountains illuminated at low sun angles would obliterate most surface details. These details would not be illuminated by the scattering of light from atmospheric particles as occurs on earth. Mounds, craters, and boulders may be hidden by such lunar shadows. No attempt should be made to land in or near such a shaded area without adequate illumination from the spacecraft itself, or the provision of masking of brightly illuminated features so that the eye could see shaded detail receiving indirect lighting.

The slope or slant of the lunar surface cannot always be determined accurately from the perceptual input available during the final descent. There are, on the surface of the earth, certain features which are known to have a constant orientation with respect to gravitational forces and which contribute to the determination of slant. These earth features include horizontal bodies of water and vertical trees and buildings. In addition, roads and rectangular fields provide information about surface slant via the perceptual clue of linear perspective. This information is not available on the lunar surface. In the absence of these or other clues, two general assumptions are likely to enter into the assessment of surface slant. First, a large and apparently smooth area, in the absence of contradictory cues, will be assumed to be flat. And, second, mountains and crater walls will be assumed to be regular or symmetrical. A problem might arise if an area were bounded on two sides by mountains which rose at different angles to the true horizontal, for the assumption that they were actually symmetrical would be likely to cause a misjudgment of the slant of the area which they bounded.

Accurate perception of slant will be aided at lower altitudes by the gradients of texture density. The texture of a surface becomes finer as that surface recedes in the distance. The rate, or gradient, of this texture change can provide information about slope. People can perceive slant when presented with pictures of surfaces composed of elements such as small rocks. However, they tend to underestimate the actual slant by approximately 50%(24). Furthermore, the height at which this cue becomes effective depends on particle size. Virtually no information could be obtained from texture density when flying over an area composed mainly of dust particles. The absence of this cue is a serious problem, not only for perception of slant but also for judgment of height, and has often caused difficulties for pilots flying over fresh snow or a glassy-smooth lake.

In addition, it should be mentioned that judgments of surface slant based on the distribution of texture elements involves the assumption that the elements are the same size. Thus, a particular gradient produced by a surface composed of uniform elements slanting away from the observer could also represent a level surface with smaller objects at a greater distance from the observer. A visual array with such characteristics could be produced, for example, by rocks being scattered about a crater by eruption or meteoric impact.

The lunar surface should be carefully examined for the presence of conditions likely to produce such terrain illusions. It would probably be difficult to train an astronaut to overcome these illusions because the assumptions producing them are adaptive for the perception of slant in most situations. They become maladaptive in the presence of unusual or atypical surface characteristics.

Further problems associated with the selection of the landing site are the astronauts' lack of knowledge of the exact sizes of specific objects on the lunar surface and the failure of size constancy mechanisms to operate above vertical distances of any appreciable extent. An area a mile away might appear smooth because it was relatively smoother than adjacent areas, yet still be too rough for a safe landing. Practice in judging the size of vertically viewed objects from the length of their shadows should reduce the likelihood of committing the spacecraft to land in an unfavorable area.

2.3.3 The Perception of Altitude

The judgment of vertical distance is a difficult perceptual task. The primary distance clue available to the astronauts in the lunar module is the differential rate of expansion of elements on the lunar surface as the craft approaches the surface. The rate of expansion increases as distance to the surface decreases. There is apparently no research on the adequacy of this clue for mediating veridical judgments of absolute distance. Texture density itself is a cue to height only if the size of the surface elements is well known. Other available clues to distance are convergence (probably limited to distances closer than 60 ft.) and motion parallax produced by the observer's head and eye movements. These cues are presumed to be relatively ineffective for vertical distance judgments.

Fortunately, cognitive input in the form of altimeter readings is available to compensate for the lack of adequate perceptual information. Were the perceptual and cognitive information to conflict, it is possible that the perceptual input would take precedence, although experienced pilots are trained to avoid this error.

The surface of the moon may be hidden by a dust cloud during the final moments of the descent. This was a particular problem during the landing of Apollo 12, when vision of the ground was totally obscured for the last 50 feet.(23) This lack of visibility forces reliance on instruments at a time when visual input might provide adequate and usable information about depth.

2.3.4 Alignment with Touchdown Point

During the final moments prior to landing a sensation of drifting could occur due to the illusion of induced motion This illusion (analogous to the sensation of motion induced by the movement of an automobile beside one's own stationary vehicle) could be caused by the drifting of the dust cloud which is generated by the descent rocket, and the change in the position of the shadow of the lunar module's legs on this cloud. The pilot's view of the dust cloud, which is moving away from him, could induce the illusory perception of backwards motion. The sensation of drifting to one side could be induced by the appearance of the shadow of the lunar module's legs on this dust cloud. If the sun were slightly to the pilot's left, the shadow would be displaced to the left relative to his viewing window as the craft approached the surface. (In the absence of the dust cloud, the shadow would appear to move with respect to features on the surface and therefore be less likely to induce motion) If both backwards and rightwards motion were induced, compensation would result in a 'hook' forward and to the left just prior to touchdown.

Induced motion is a compelling perceptual phenomenon. It is possible that simulation training would reduce the tendency to make a compensatory response, although it is unlikely that the illusion itself could be reduced. This illusion occurs because a viewer is moving in most situations when he and the background alter their relative positions, thus, attributing motion to oneself is usually the correct decision.

2.4 Potentially Hazardous Visual Illusions in Lunar Surface Exploration

Illusions occurring once the astronauts are on the surface of the moon are likely to involve the misperception of distance (and therefore size), depth, and terrain slant. These misperceptions are unlikely to introduce hazards during limited excursions on relatively flat terrain. They may cause more serious problems when vehicular exploration is undertaken. Perceptual performance may also be impaired by factors associated with the lack of atmospheric scattering of sunlight. These factors include the difficulty of coping with the wide range of luminances that will occur between illuminated and shaded portions of the lunar surface, and the presence of glare from reflecting surfaces and the sun itself.

2.4.1 Distance and Depth Perception

It is probable that far distances will not be accurately perceived by lunar explorers. The absence of aerial perspective, present on earth due to atmospheric haze, will result in an underestimation of distance. distant features will appear closer than they are. However, a feature located on or near the horizon may be judged to be farther than its actual distance. This would occur if the shorter distance to the moon horizon was assumed to be equal to the distance to the earth horizon. These factors may partially cancel each other, however, the general tendency, confirmed in the Apollo 11, 12 and 14 explorations, will be one of distance underestimation.(23, 25, 25a)

The effectiveness of other distance clues may be reduced on the lunar surface. The use of texture density gradients as a clue to absolute distance requires knowledge of element size. Such knowledge may require more familiarity and experience than would be provided by an inspection of a small segment of the lunar surface The effectiveness of this clue would probably be further reduced by the presence of rocks of all sizes on the lunar surface, the elements are more irregular than those on the surface of the earth due to the absence of weathering. Another factor weakening the effectiveness of this clue is the low contrast on the lunar surface at higher sun angles, which may make the perception of element size more difficult

Illusions of distance result in the misperception of size a mound inferred to be closer than it actually is will therefore be judged smaller than it actually is. Although distance and size may be perceived in an illusory fashion, such misperceptions will probably not be hazardous in most situations. If accurate distance judgments were required, a rangefinder could be utilized for this purpose. It should be noted that knowledge obtained in this fashion is unlikely to result in veridical size perception. Size constancy is set by registered distance, not by known distance. (6)

Judgments of crater depth may be impossible to make when the sun is low in the horizon. Since the inside of the crater will be in shadow and, except where significant amounts of reflected light enter it, its details will not be visible to the outside observer. The depth of the crater might then be estimated from its diameter, and if an incorrect judgment were made, an astronaut's decision to step or drive into a crater, believed to be shallow, could result in serious consequences. Headlights or portable lights may be necessary under certain circumstances.

In conclusion, the lunar lighting conditions, the lack of atmospheric light scattering, the absence of haze, the general unfamiliarity of the terrain or the lack of objects with familiar shapes at known distances, will contribute to uncertainty and to systematic errors in the perception of distance, size, and depth on the lunar surface. It is impossible at present to estimate accurately the extent of such a perceptual degradation A large scale lunar surface with appropriate lighting would provide invaluable information about these problems.

2.4.2 Judgment of Terrain Slant

Terrain slant is usually judged by a ground observer from a combination of vestibular clues caused by gravitational pull and visual clues such as the assumed verticality of buildings and natural objects such as trees. These clues are minimal or absent on the surface of the moon. A large flat area may tend to be judged as level, regardless of its actual slant. The difference in effort required to traverse a slope as opposed to a level surface may not be noticed because of the reduced gravity. Lighting conditions will also affect perception of slant, as happened during Apollo 12 where a slope that appeared to be tilted 35° when it was in shadow seemed to be only 10° - 15° (closer to the actual value) when directly illuminated by the sun.(23) It may be desirable to equip surface exploration vehicles with a level to indicate the vehicle's slant, and to incorporate self-leveling devices on equipment which must be positioned vertically.

2.4.3 Visibility under Lunar Lighting Conditions

The wide range of luminances encountered by the astronaut on the moon can impair visual performance since the dark and light adaptation processes are not instantaneous. If an astronaut switches from a task requiring him to look at a highly illuminated area on the surface of the moon to a task requiring him to look in a shadow or towards the black sky, he may require several minutes to dark adapt sufficiently to perceive small details. A switch from a dark area to a light area will be accompanied by dazzle and an inability to see adequately for some 5 seconds to 2 minutes. The visibility of an object in a dark area which adjoins a bright area will be further diminished due to a border contrast effect resulting from lateral interactive effects within the visual system (26)

Another possible major problem is that of temporary flashblindness due to an accidental visual encounter with a highly reflecting surface such as a portion of the lunar module or an excursion vehicle, or with the sun itself. Due again to the lack of atmospheric scatter, and to the small number of vertical objects in the field of view, the astronaut may not always be aware of the sun's exact position in the sky. There may therefore be a danger of his inadvertently looking into the sun, with severe visual impairment lasting for perhaps a minute or more.

In general, the effects of continuously viewing a highly contrasted field are not known and should be studied. Reports from the short lunar excursions to date indicate that the most serious visibility problems involved the necessity of using one hand to shield the eyes in order to reduce glare when looking up-sun, a slight problem in scanning the bright zone at the zero-phase point down-sun, and the need to dark adapt a short while when entering a shadow.

2.5 Conclusions

This section of the report has reviewed present-day knowledge concerning visual illusions pertinent to lunar missions and to spaceflight in general. It has also pointed to areas where further research is desirable. The approach has been designed to identify possible hazards, some of which may be found to be of little consequence in the foreseeable future. However, it is also true that some of the problem areas discussed may prove to be serious enough to merit detailed investigation.

It should also be stated that illusion problems should not be disregarded on the strength of their non-occurrence to date in the space program. Future missions will become more difficult and demanding for the human observer, for example, when different areas of the moon are chosen as landing targets, when maneuvering in space must be done without the extensive computer aid available to date, and when longer missions introduce more severe conditions of fatigue. In the decades to come, it seems highly probable that error in the human visual system will produce hazardous consequences, or will cause a hazardous situation to become more so, and the better understanding of such problems is the only basis for their prevention.

3. MEASUREMENT OF THE OPTICAL PROPERTIES OF NEW AND USED VISUAL TRANSPARENCIES

3.1 Helmet/Visor Transparency Wear and Tear

Under Contract NAS 9-6865, an experimental program of research was conducted, designed to determine the feasibility of setting special optical specifications for helmets and visors, appropriate to the manufacturing techniques currently employed.(27) It was shown that the accepted optical quality tests for ophthalmic lenses are appropriate for the ground glass product of precision grinding and polishing, but not for the moulded plastics transparencies currently in use in the space program. In considering the optical quality of helmets and visors, it is apparent that the following basic considerations underlie the choice of specifications:

(1) The specifications should be realistically attainable by the production techniques available.

(2) The specifications should relate to human visual performance.

(3) The specifications should contain provision for wear-and-tear factors so that a service life of the transparency may be established which ensures that optical quality degradation does not cause unacceptable effects upon the wearer's visual performance.

On the basis of the findings of our previous study, we recommend that future specifications be set to include the better 50% of transparencies currently in use. As stated in the earlier study-report, overall optical quality may be assessed by the means of sample modulation transfer curves taken at various points on the transparency. The means and standard deviations of these values at selected spatial frequencies (20, 60 and 100 lines per millimeter) were shown to be useful objective measurements, agreeing with assessments of quality made from the visual performance attained by highly trained subjects through the same areas of the transparencies.

In using optical measuring instruments and specially designed clamps in the testing of the plastics transparencies, it readily became apparent that the ophthalmic portions are liable to suffer significant quality degradation in use. The mechanical scratching of the surfaces from contact with relatively hard objects of equipment, or even a dust-covered glove, make it necessary to develop hard protective coatings for operational use

The use of modulation transfer function testing, vertex focometer testing, projection testing, hazemetering and scratchmetering were selected as being the best measures of optical performance decrement from surface damage. These tests were applied to a group of transparencies. It is unfortunate that helmet/visor systems used in flight or in flight training could not be made available for such a thorough optical evaluation.

It was determined, however, that of these tests, only modulation transfer function (MTF) measurement and macro and microscopic scratchmetering were of adequate sensitivity.

Photographic scratchmetering was performed as follows: A high intensity projection lamp was masked by a curved slit corresponding to the radius of curvature of the edge of a sample Apollo visor. With a visor in the proper position, the projection lamp trans-illuminated the central portion of the transparency surface. Scratching of the surface of the visor became dramatically apparent when so illuminated. Figures 3 and 4 show two sample visors, one lightly scratched and the other heavily scratched, respectively. All of the scratches had resulted from normal handling of these transparencies. Similar photographic techniques were used on two sample helmets as well. Figure 5 is a used training helmet while Figure 6 is of a new, non-used, helmet.

Photometric measures of surface reflections were made at four sites on a sample visor before and after scratching the sample sites with an 0-grade steel wool pad or an 8" bastard file. The four areas' average light diffusion, measured with a Pritchard Spectrophotometer, was 0.24 foot lamberts before scratching. The diffusely reflected light values for the four sample sites after scratching were.

Area #1	Area #2	Area #3	Area #4
Steel Wool Pad		8" Bastard File	
Light Scratching	Heavy Scratching	Light Scratching	Heavy Scratching
0.7 fL	0.8 fL	2.4 fL	2.8 fL

Figures 7 through 11 show an MTF instrument calibration curve and sample MTF curves of the four sample sites mentioned above. MTF curves before and after scratching are indicated in the graphs by solid or dashed lines, respectively. From these graphs the degradation in image quality as a result of various degrees of scratching can be seen readily.

NOT REPRODUCIBLE

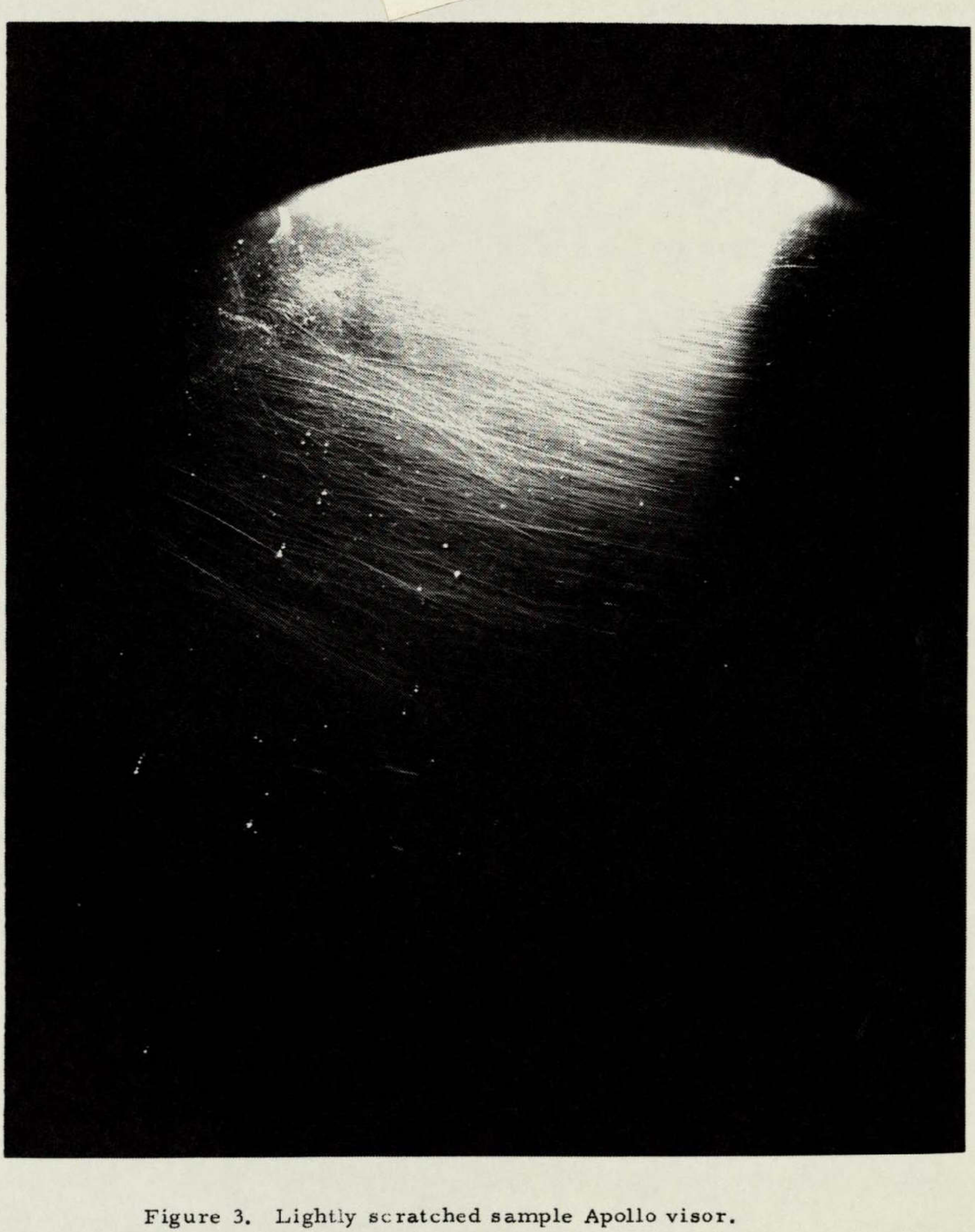


Figure 3. Lightly scratched sample Apollo visor.

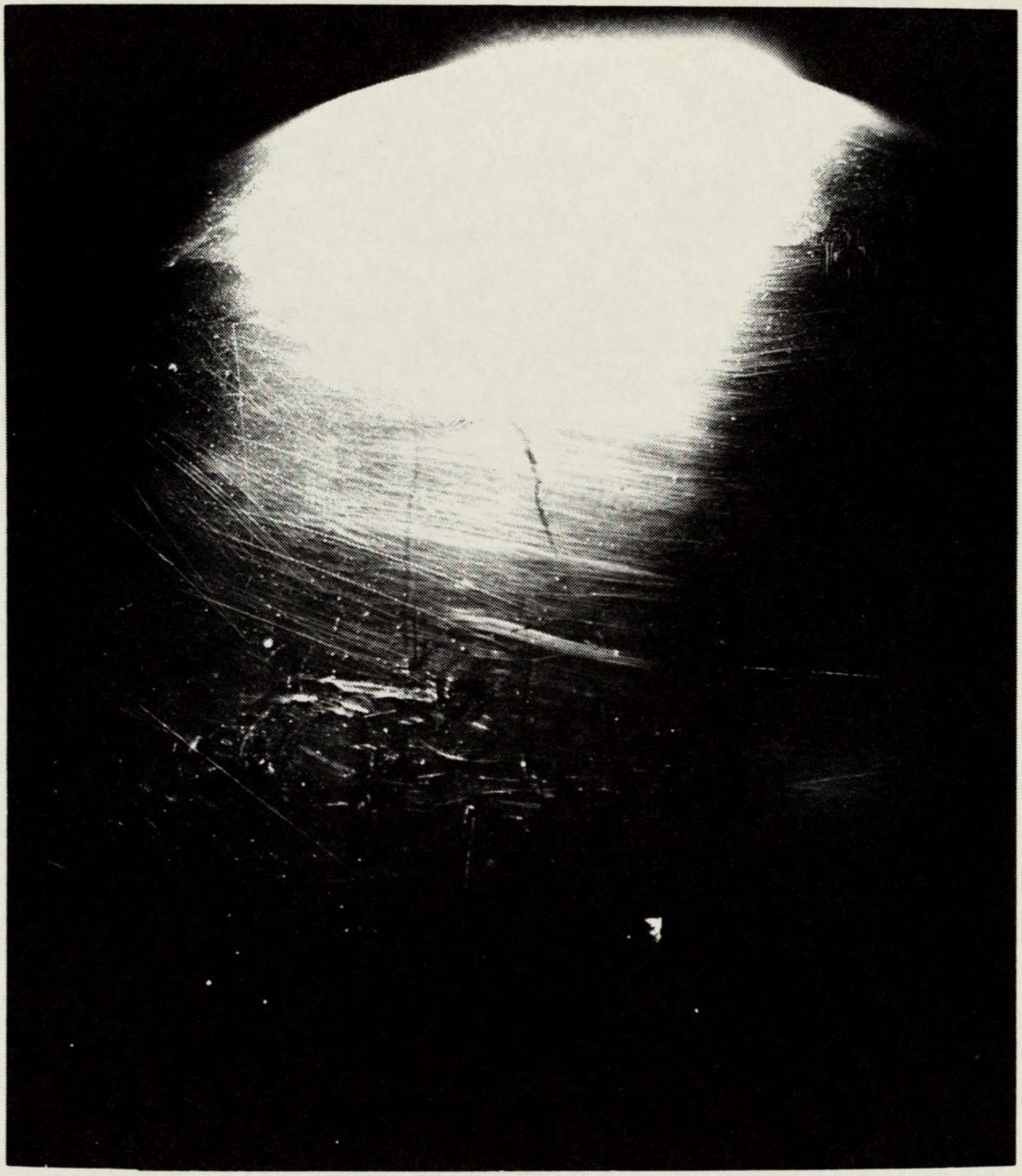


Figure 4. Heavily scratched sample Apollo visor.

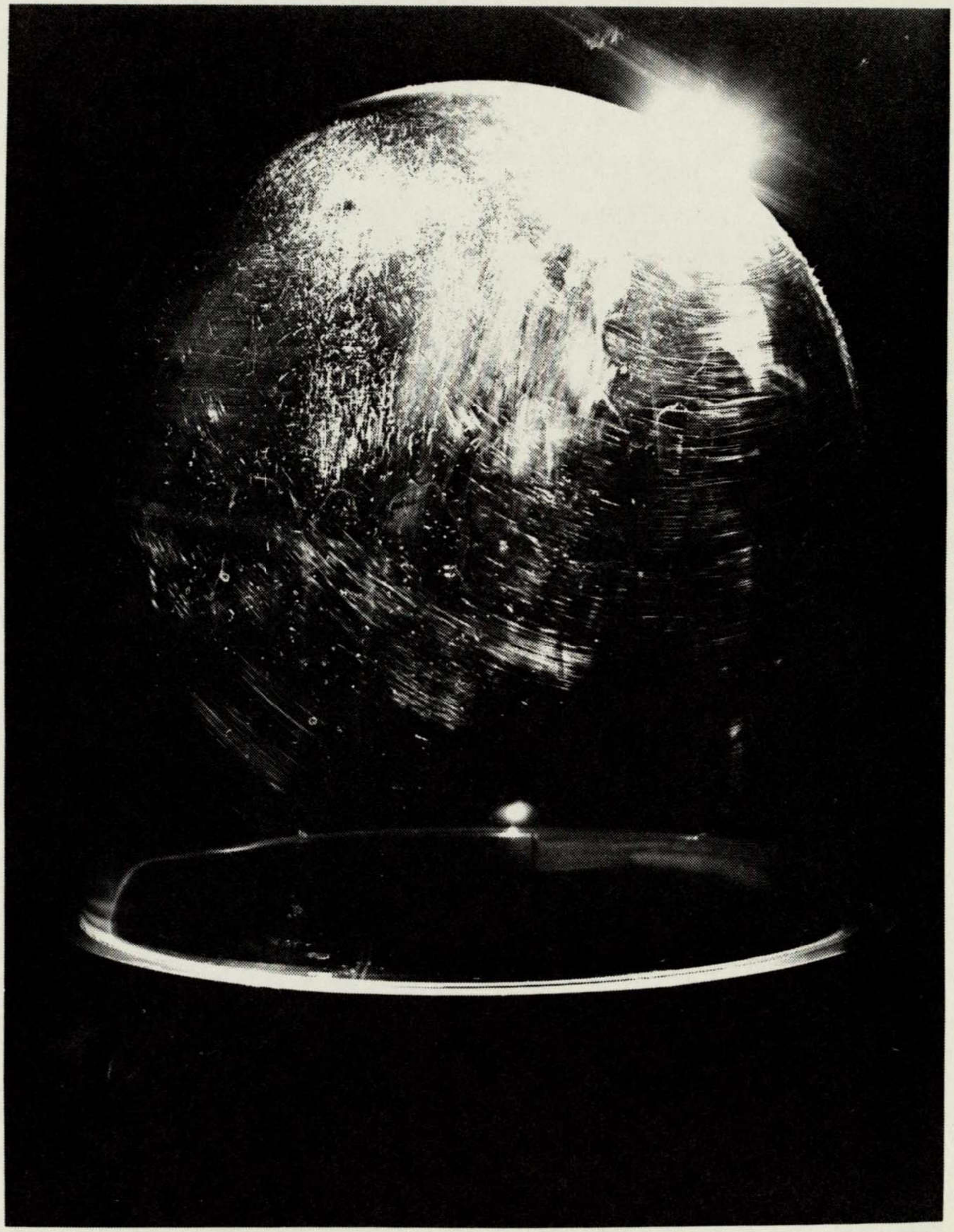


Figure 5. Heavily scratched, used Apollo helmet (training only)

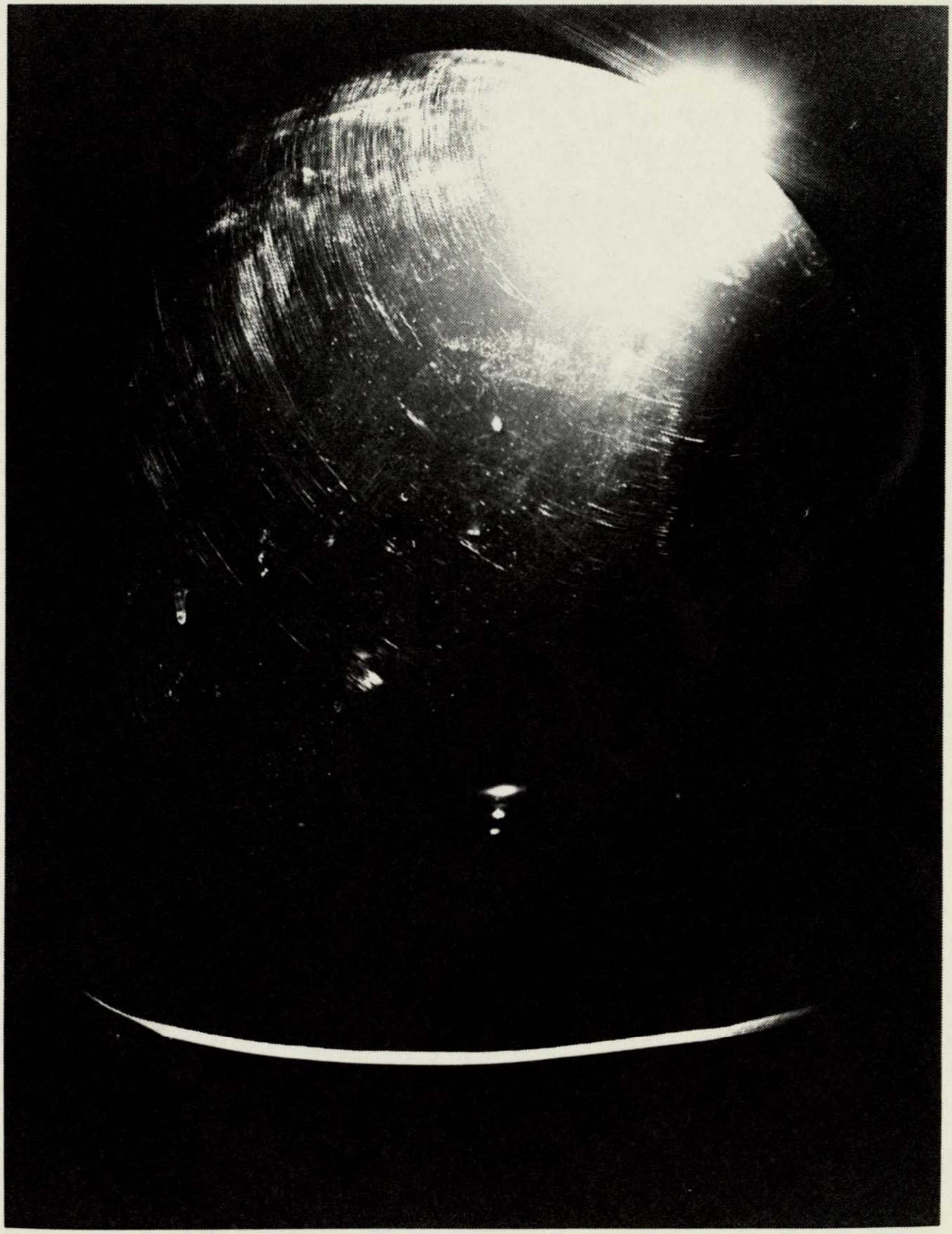


Figure 6. Non-used, new sample Apollo helmet.

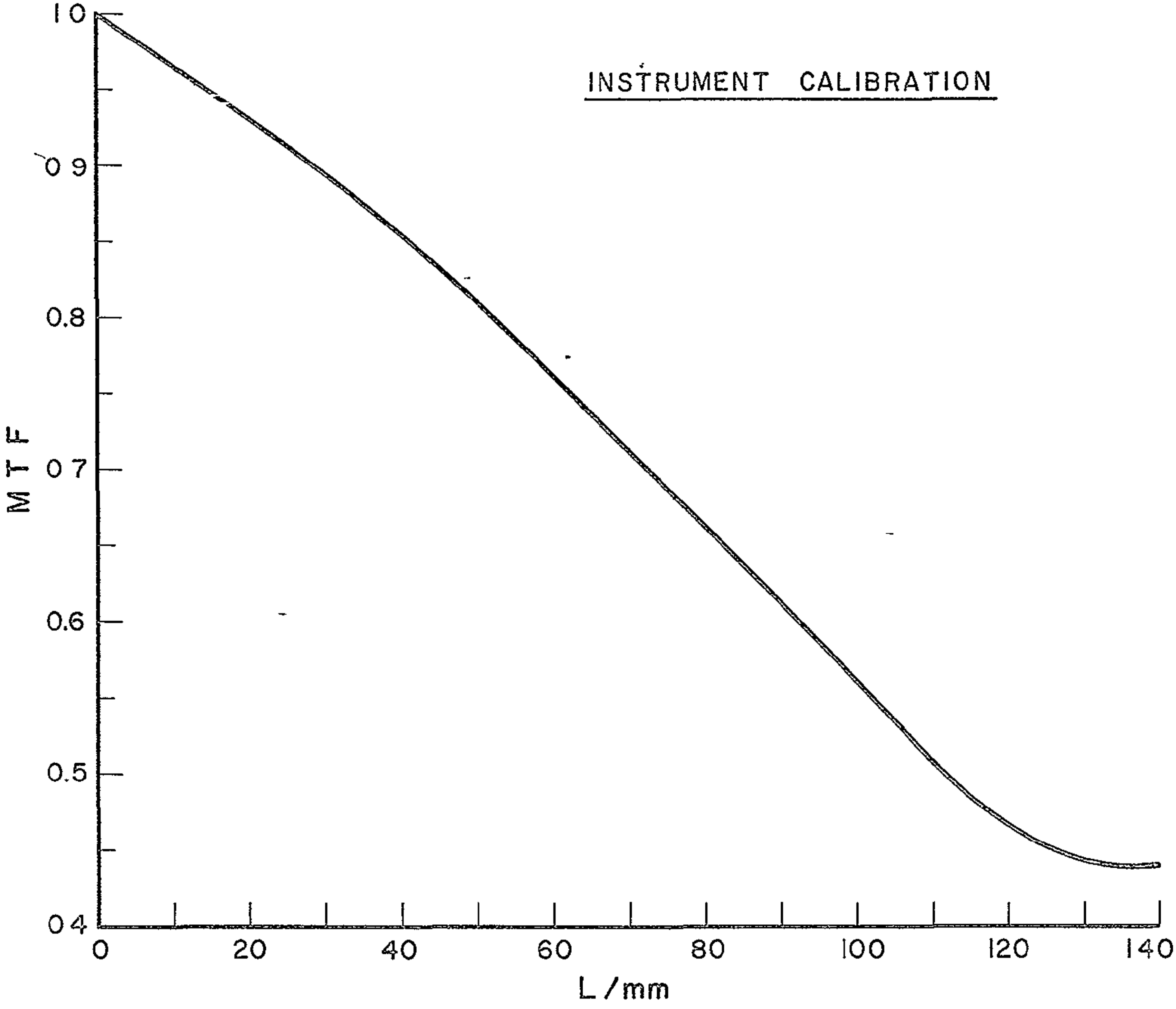


Figure 7. MTF Instrument calibration curve - no sample transparency.

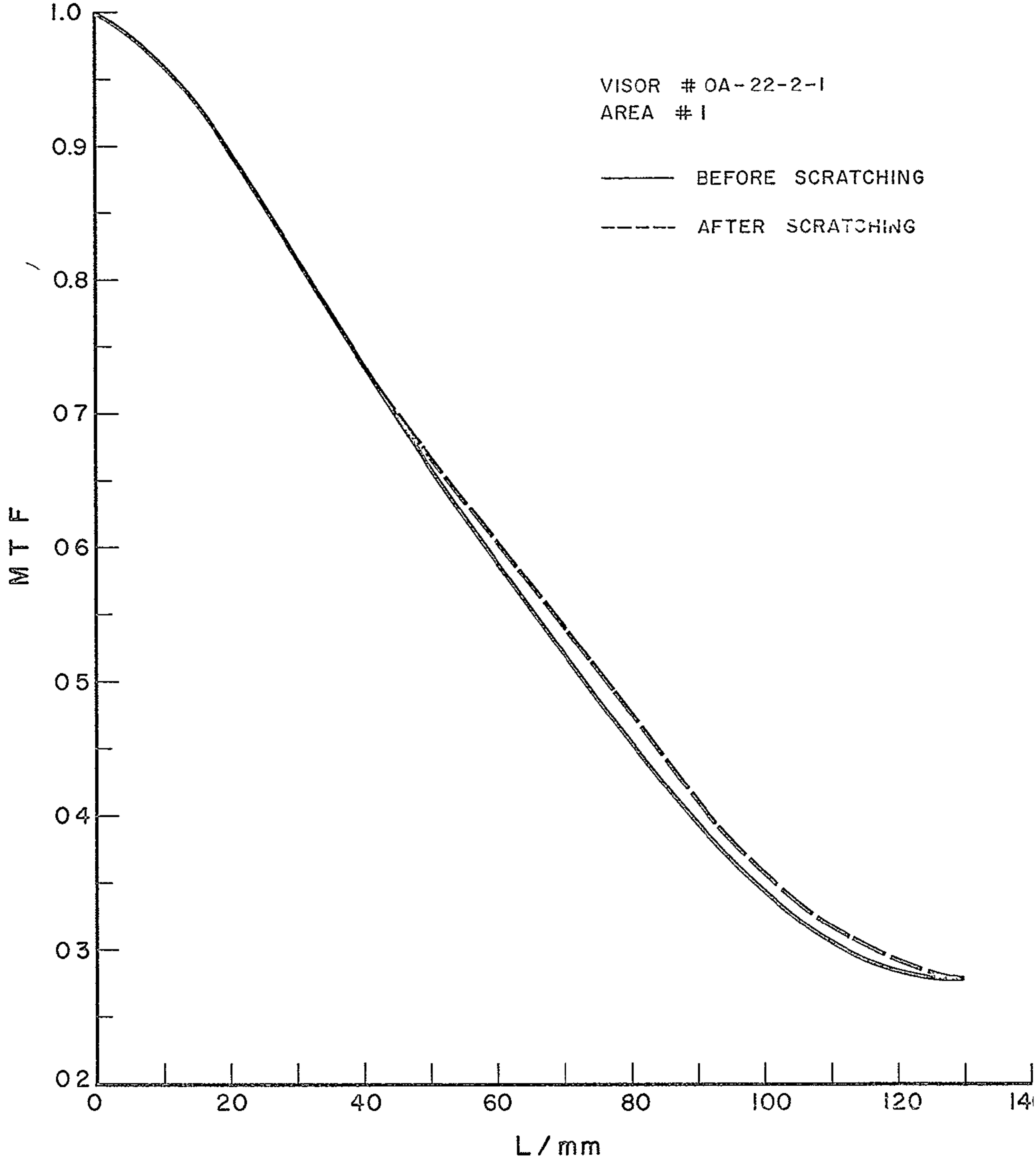


Figure 8. MTF of Apollo visor before and after light abrasion with 0-grade steel wool pad

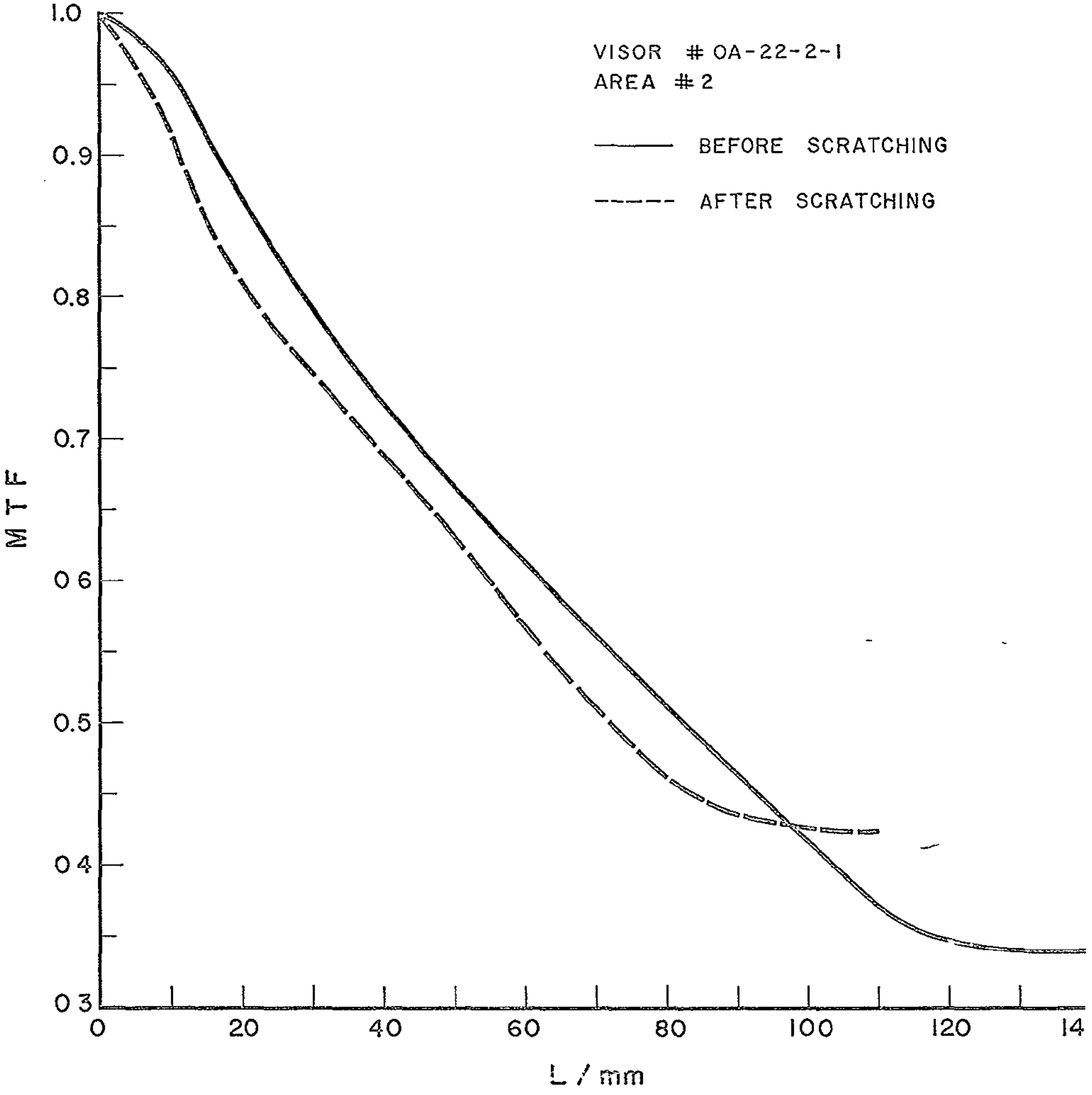


Figure 9. MTF of Apollo visor before and after heavy abrasion with 0-grade steel wool pad

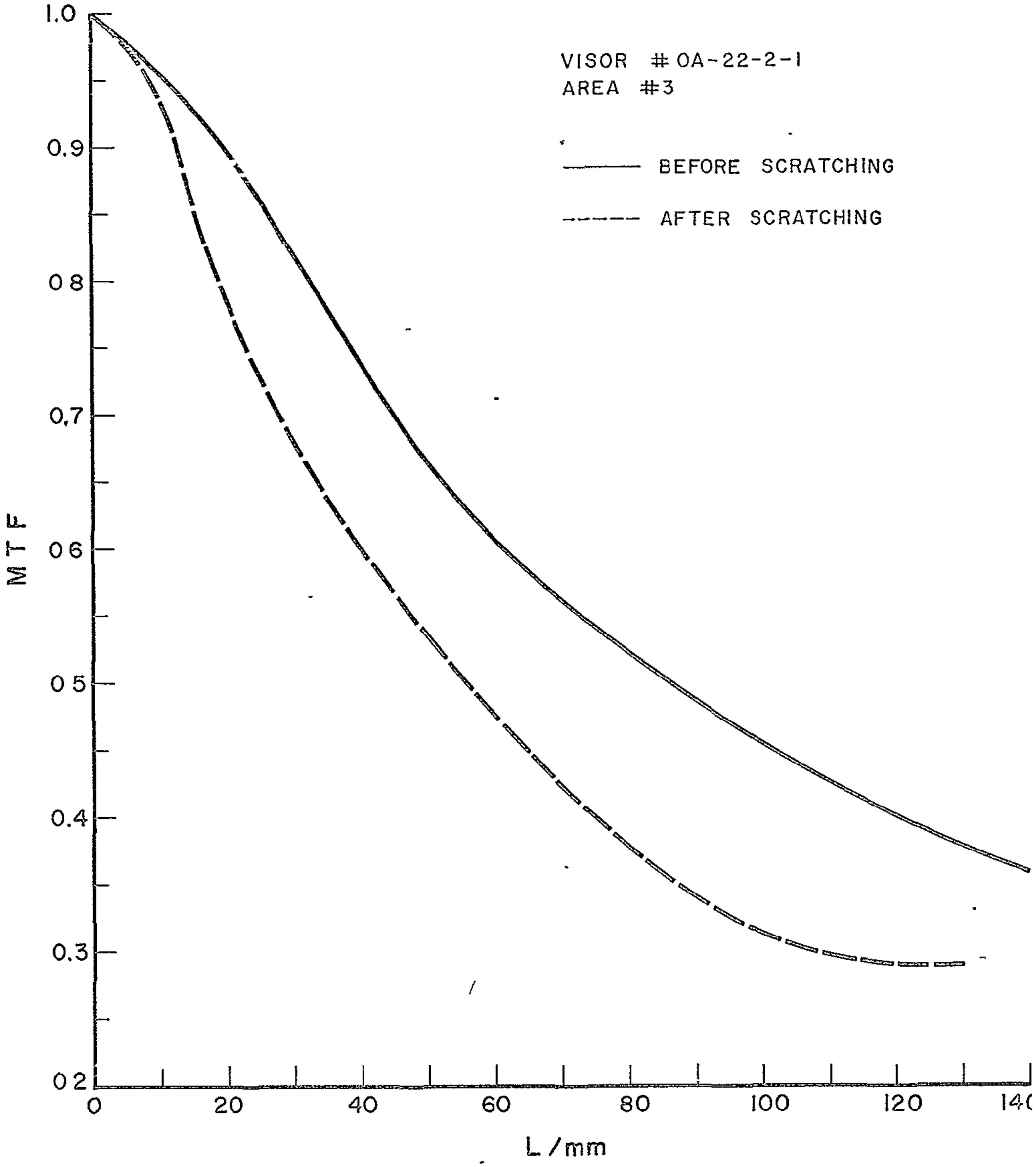


Figure 10. MTF of Apollo visor before and after light abrasion with an 8" bastard file

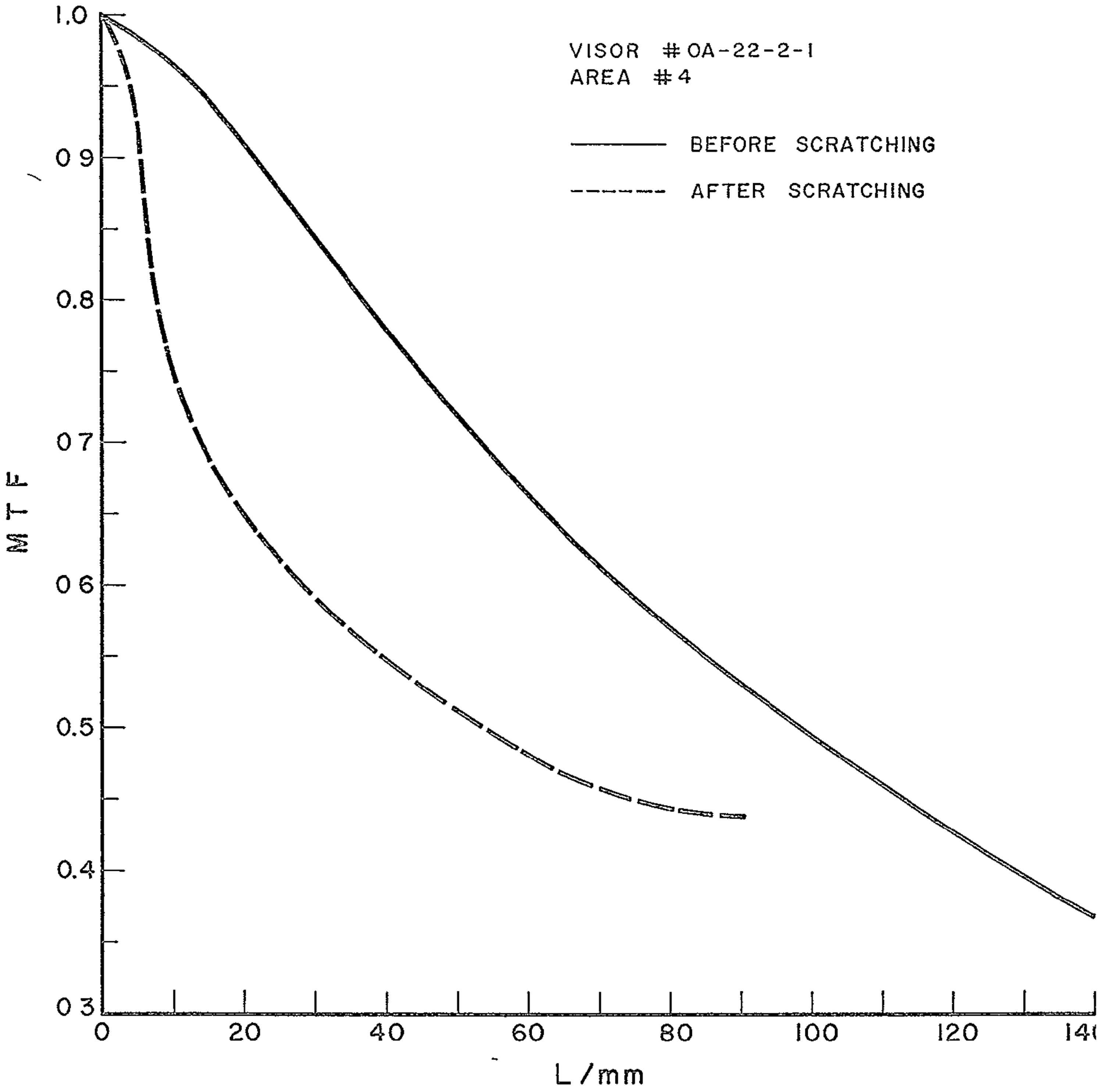


Figure 11. MTF of Apollo visor before and after heavy abrasion with an 8" bastard file

It is apparent that current helmet-visor systems are liable to significant optical degradation from scratching. From experience in attempting to measure the visual factors related to helmet and visor transparency, it is apparent that special techniques are required in order to assess surface scratching It is felt that a technique of transillumination similar to the one described above is a useful approach to surface scratch evaluation.

Minor scratching, which might be totally unnoticeable in diffuse illumination, would produce a veiling light in strongly directional lighting of the type common in space. The superimposition of illuminated scratches can have significant obscuring and desensitizing effects in a relatively dark adapted eye viewing a low contrast visual field. Scratches and local unevennesses in the visor's gold coats will cause more infrared and visible light to be passed, and illuminated scratches will be seen out-of-focus and superimposed upon the visual field.

3.2 Infrared Absorption of Helmets and Visors

Infrared absorption measurements have been made on various helmets and visors, without the final metallic coating. The results were obtained using a combination of a tungsten light source, a collimating lens, the transparency to be measured, a focussing lens, an infrared-grating monochrometer, a Barnes thermopile and a Keithley electrometer.

The results of certain selected measurements are presented in Figures 12-13. These results are representative of similar measurements made on components supplied by the contract monitor.

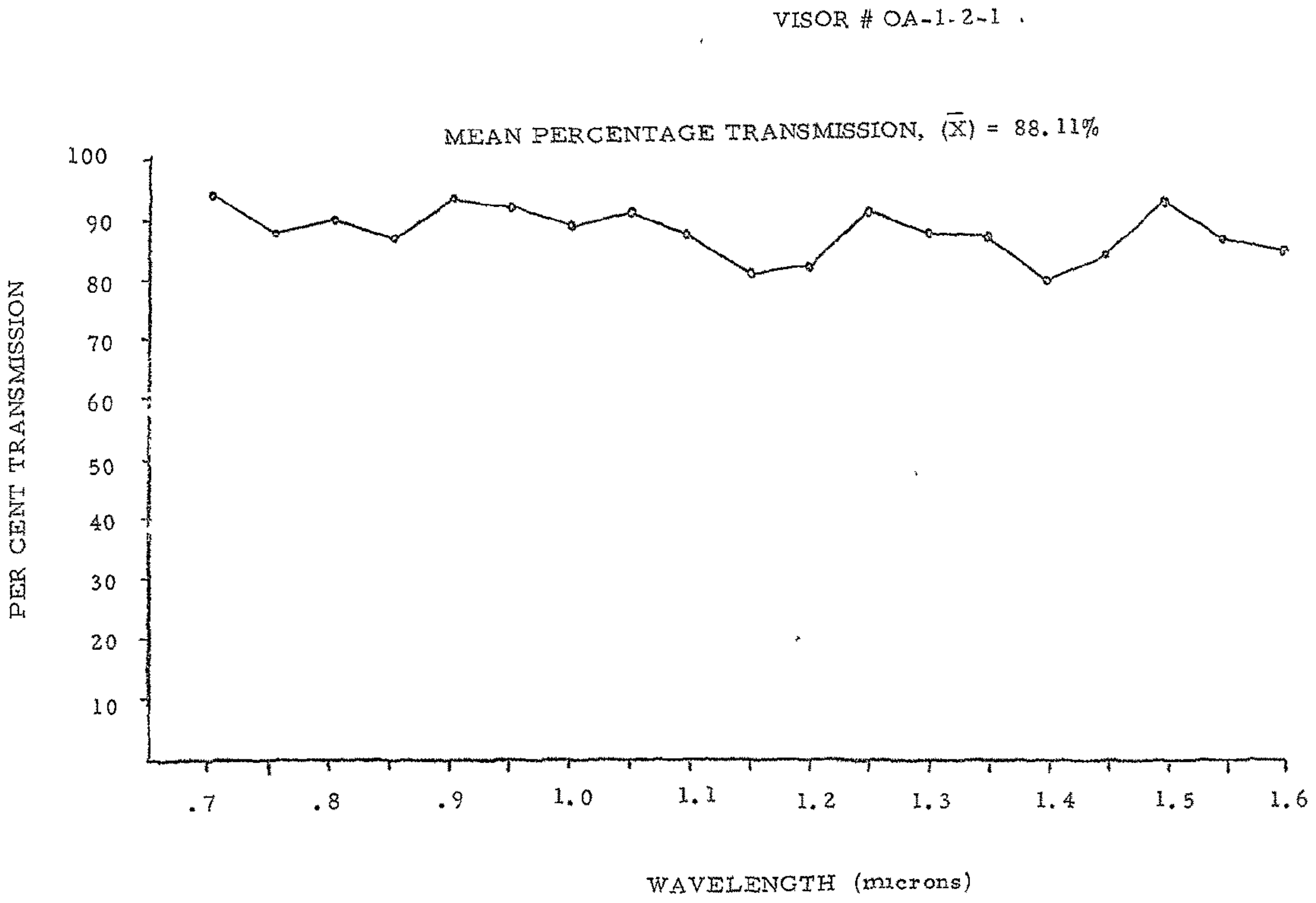


Figure 12. IR transmission of a non-tinted visor

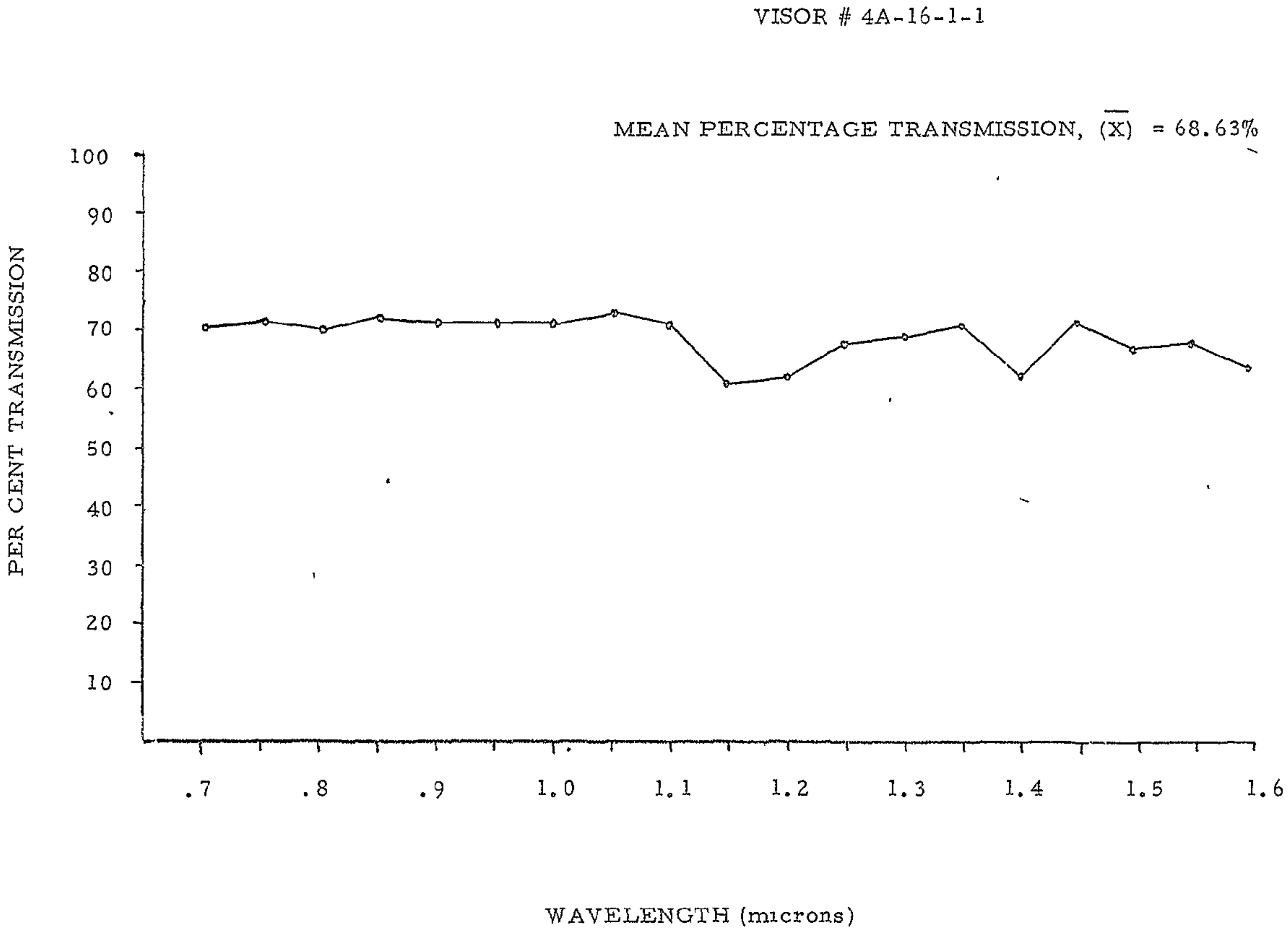


Figure 13. IR transmission of a non-tinted visor

In designing safe filtering for the protection of the astronaut, ultraviolet absorption is satisfactorily accomplished by the thickness of material used in the transparencies. Additional absorption in the visible and infrared portions of the spectrum, however, is provided by means of neutral density filtering contributed by a reflective gold coat on the visor.

The results of this study indicate the expected requirement for filtering in the infrared portion of the spectrum, in addition to that provided by the material of the transparencies themselves. However, the current use of a gold coating causes severe reflection problems, and it would therefore be desirable for the density of this coating to be reduced, without creating a hazard of chorioretinal burns from solar radiation. This may be done, taking into account the results of the study performed by Technology Incorporated and presented in Section 1 of this report, by introducing forms of radiation absorption.

3.3 Ultraviolet Absorption Measurements in Transparency Materials

The ultraviolet densitometer constructed under Contract NAS 9-6865 has been employed to make optical density measurements on various optical transparencies, in response to the requirements of the Neurophysiology Laboratory, NASA, MSC. The spectral range covered is 240 to 320 nm. Transmittances of the order of 10^{-6} have been measured with satisfactory repeatability. The ultraviolet densitometer will be found to be fully described in an earlier report.(28)

Components and complete systems subjected to analysis in this way during the course of the reporting period were·

(1) spectacle crown lenses

(2) .astronaut helmets

(3) astronaut visors

(4) astronaut wrap-around goggles

(5) spacecraft windows, heat shields and samples of proposed temporary coatings for quartz components, and

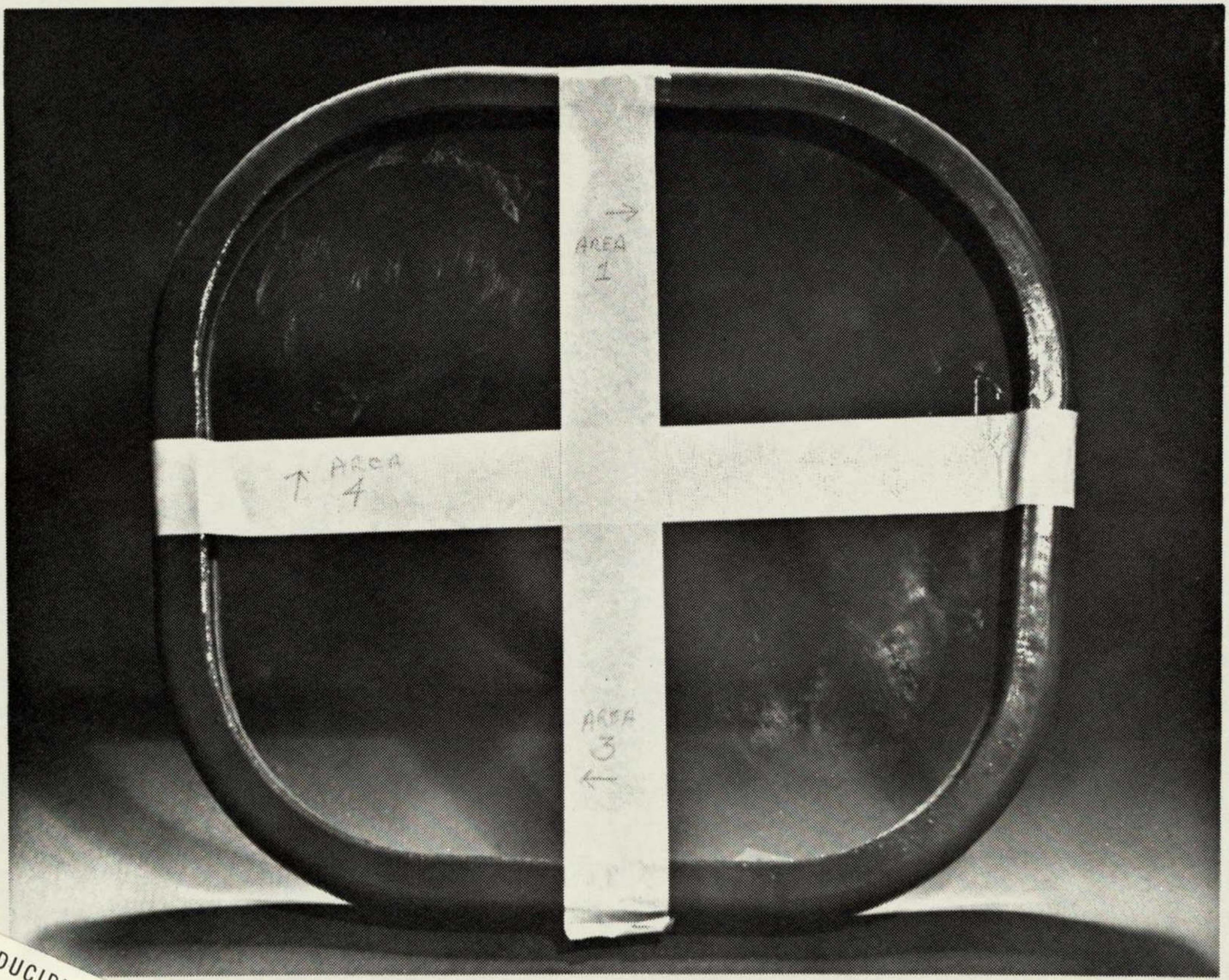
(6) Lexan samples

The quartz spacecraft window was divided into four segments using tape and labeled 1 through 4, respectively, as shown in Figure 14. A detector reading was recorded for each as it was placed in the measuring beam. The transmittance was computed and recorded for each tested area. Areas 2, 3, and 4 were then coated as indicated on the chart and transmittance was again recorded. The data as recorded on the chart indicates the results.

A piece of ordinary household wrapping material (Handi-wrap) was tested in the same manner and the results were recorded.

A pair of flight certified eyeglasses were tested and the transmittance determined to be less than 10^{-4}. Due to a failure in one optical chopper we were unable to operate the device in the dual beam mode, and therefore the test range was limited to 10^{4} units of optical density.

Calibration of the equipment was confirmed before and after the tests by



Quartz spacecraft window coated with U-V absorbing films for testing on U-V densitometer.

placing known ND filters in the beam and comparing measured transmittance to manufacturer's specification. Accuracy was better than 10% for all wavelengths tested.

Each light path of the double beam densitometer is equipped with electronic light choppers of the tuning-fork variety. With use, these components have been found to reduce their chopping gaps to an extent which interferes with the passage of focussed beams. During the course of the year, these components have been removed for examination (by the manufacturer) and repair.

The following pages contain sample results of ultraviolet and visible spectrum transmission curves which have been supplied to NASA, MSC on a fast-response bases (Figures 15-18, Table II).

3.4 Modulation Transfer Function Determinations

During the course of Contract NAS 9-6865, the Life Sciences developed the application of the modulation transfer function (MTF) to the assessment of the visual and optical properties of ophthalmic transparences.

During the reporting period, a series of such measurements has been made on ophthalmic components, at the request of the Contract Monitor

The results of these measurements have been supplied to the Contract Monitor, and selected examples of these findings have been presented in earlier progress reports.

2 ⊕

TABLE II

SPACE WINDOW

Area 1 - UNCOATED

Area 2 - Coated with Pad Lubricant

Area 3 - Coated with ST-51F 324-01

Area 4 - Coated with ST-53F-382-01
* All Areas Uncoated

Area 1	i	f	T_x
2200Å	$9.4x50x10^{-3}$	$8.0x50x10^{-3}$	.85
2500Å	$9.2x50x10^{-3}$	$8.4x50x10^{-3}$	.91
2700Å	$10.8x50x10^{-3}$	$9.8x50x10^{-3}$	.91
2800Å	$11.0x50x10^{-3}$	$10.0x50x10^{-3}$	.91
3100Å	$11.2x50x10^{-3}$	$10.6x50x10^{-3}$	.95
Area 2*			
2200Å	$9.4x50x10^{-3}$	$8.5x50x10^{-3}$	.90
2500Å	$9.2x50x10^{-3}$	$8.3x50x10^{-3}$	.90
2700Å	$10.8x50x10^{-3}$	$10.0x50x10^{-3}$	.93
2800Å	$11.0x50x10^{-3}$	$9.8x50x10^{-3}$	.89
3100Å	$11.2x50x10^{-3}$	$10.6x50x10^{-3}$	.95
Area 3*			
2200Å	$9.4x50x10^{-3}$	$8.6x50x10^{-3}$	.91
2500Å	$9.2x50x10^{-3}$	$8.3x50x10^{-3}$	.90
2700Å	$10.8x50x10^{-3}$	$10.2x50x10^{-3}$	.94
2800Å	$11.0x50x10^{-3}$	$9.5x50x10^{-3}$	.86
3100Å	$11.2x50x10^{-3}$	$10.7x50x10^{-3}$	.96

SPACE WINDOW (continued)

	i	f	T_x
Area 4*			
2200Å	$9.4x50x10^{-3}$	$8.3x50x10^{-3}$	.88
2500Å	$9.2x50x10^{-3}$	$8.2x50x10^{-3}$	.89
2700Å	$10.8x50x10^{-3}$	$10.0x50x10^{-3}$	.93
2800Å	$11.0x50x10^{-3}$	$9.6x50x10^{-3}$	.87
3100Å	$11.2x50x10^{-3}$	$10.6x50x10^{-3}$	.95
Area 2			
2200Å	$10.4x50x10^{-3}$	$4.4x50x10^{-3}$	.42
2500Å	$11.5x50x10^{-3}$	$4.9x50x10^{-3}$	.42
2700Å	$10.1x50x10^{-3}$	$4.7x50x10^{-3}$	.47
2800Å	$14.2x50x10^{-3}$	$8.0x50x10^{-3}$	.56
3100Å	$11.8x50x10^{-3}$	$6.2x50x10^{-3}$	.53
Area 3			
2200Å	$10.4x50x10^{-3}$	$6.6x50x10^{-3}$	.63
2500Å	$11.5x50x10^{-3}$	$7.7x50x10^{-3}$	.67
2700Å	$10.1x50x10^{-3}$	$7.2x50x10^{-3}$	.71
2800Å	$14.2x50x10^{-3}$	$10.7x50x10^{-3}$	.75
3100Å	$11.8x50x10^{-3}$	$8.0x50x10^{-3}$	.68
Area 4			
2200Å	$10.4x50x10^{-3}$	$1.9x50x10^{-3}$	.18
2500Å	$11.5x50x10^{-3}$	$2.9x50x10^{-3}$	.25
2700Å	$10.1x50x10^{-3}$	$2.4x50x10^{-3}$	.24
2800Å	$14.2x50x10^{-3}$	$4.0x50x10^{-3}$	.28
3100Å	$11.8x50x10^{-3}$	$2.7x50x10^{-3}$	.23

SPACE WINDOW (continued)

HANDI-WRAP

	i	f	T_x
2200Å	$10.3 \times 50 \times 10^{-3}$	$4.9 \times 50 \times 10^{-3}$	.48
2500Å	$14.4 \times 50 \times 10^{-3}$	$9.4 \times 50 \times 10^{-3}$	.65
2700Å	$11.1 \times 50 \times 10^{-3}$	$6.7 \times 50 \times 10^{-3}$	.60
2800Å	$11.2 \times 50 \times 10^{-3}$	$6.9 \times 50 \times 10^{-3}$	.62
3100Å	$10.9 \times 50 \times 10^{-3}$	$7.5 \times 50 \times 10^{-3}$	.69

$T_x = \frac{f}{i}$

f = instrument + sample

i = instrument alone

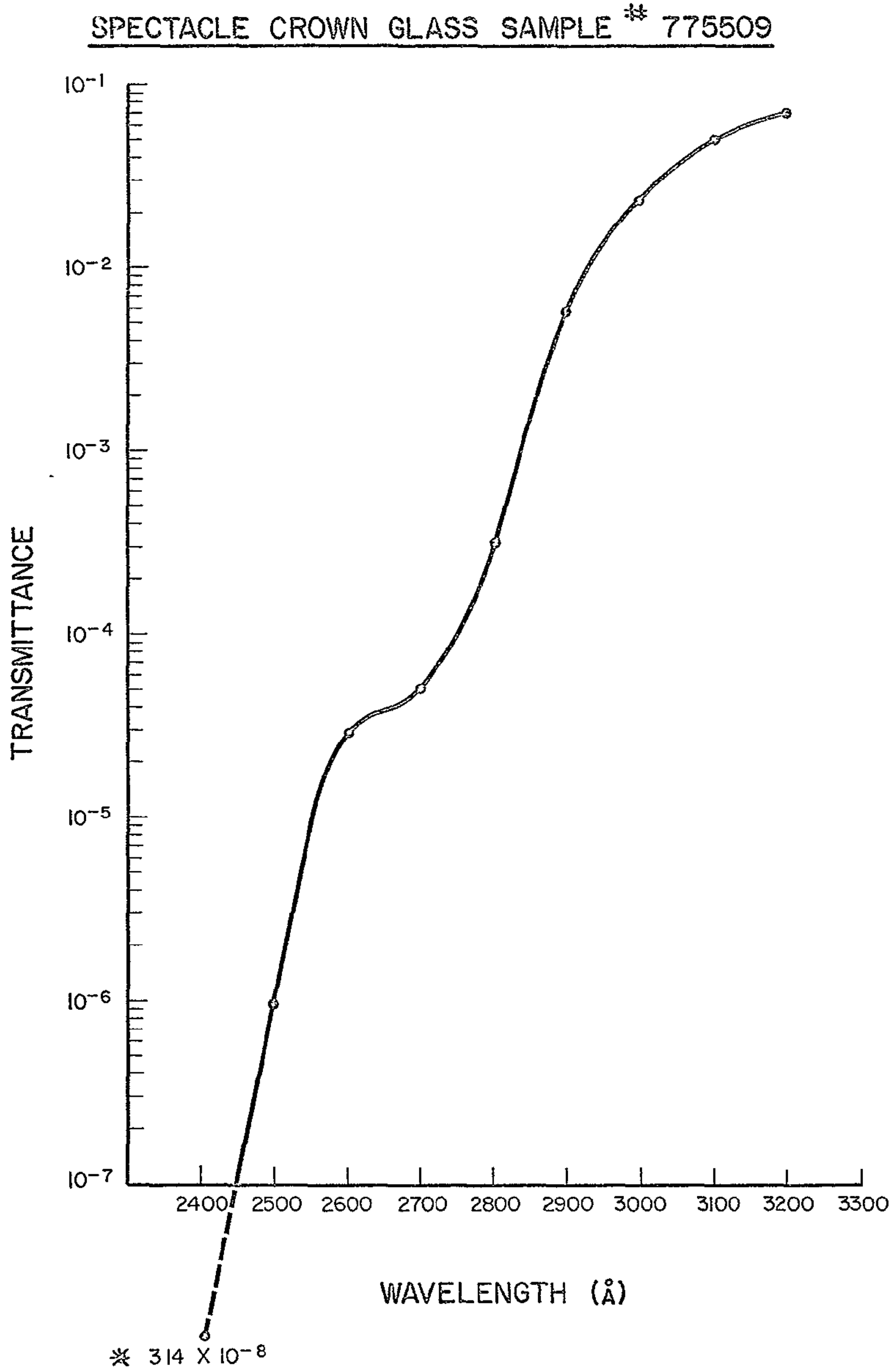

SPECTACLE CROWN GLASS SAMPLE # 775509

Figure 15. UV transmission of specific crown glass

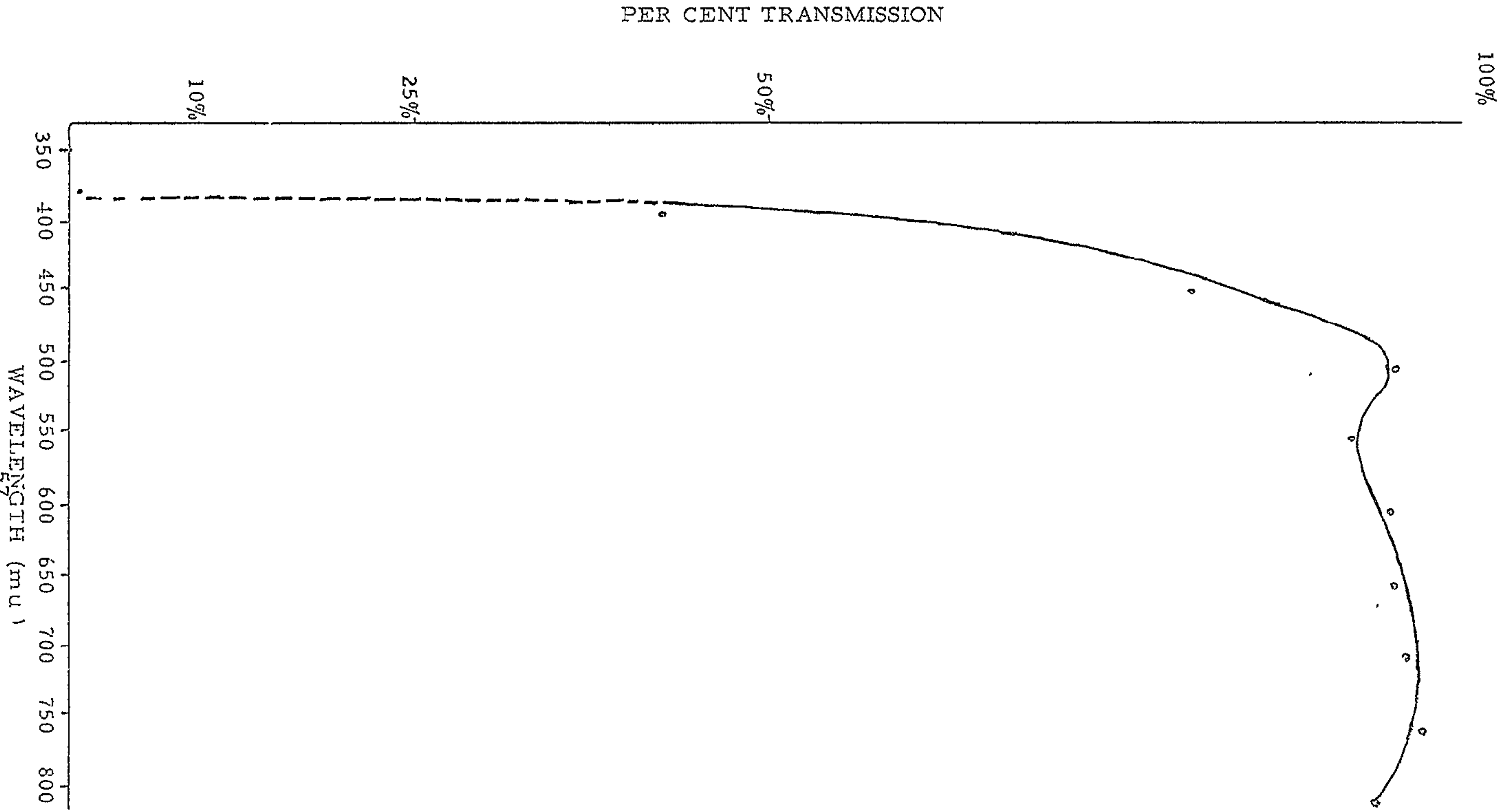


Figure 16. Visible and UV transmission of right lens (center) of clear wraparound astronaut goggles

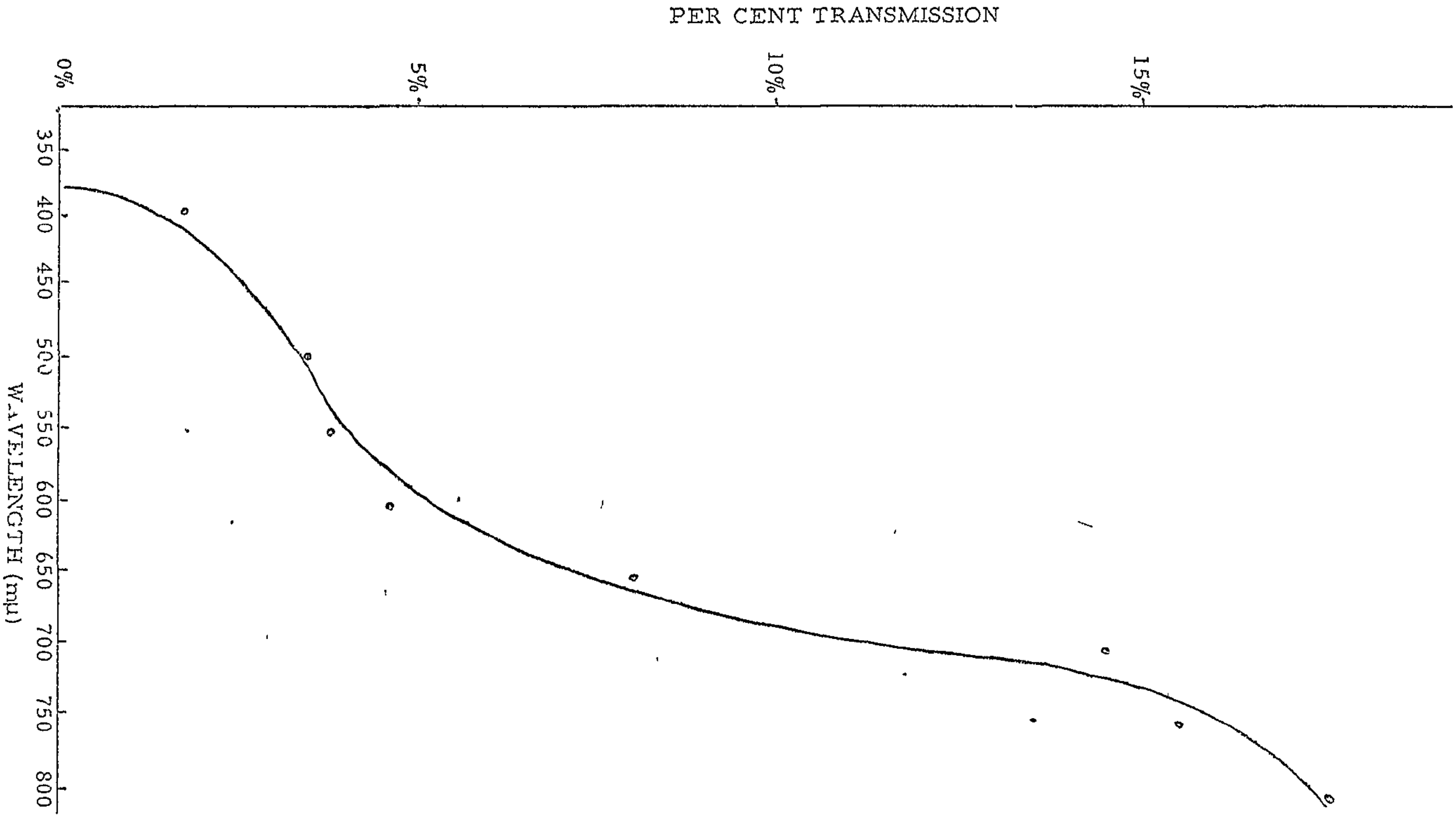


Figure 17. Visible and UV transmission of right lens (center) of tinted wraparound astronaut goggles

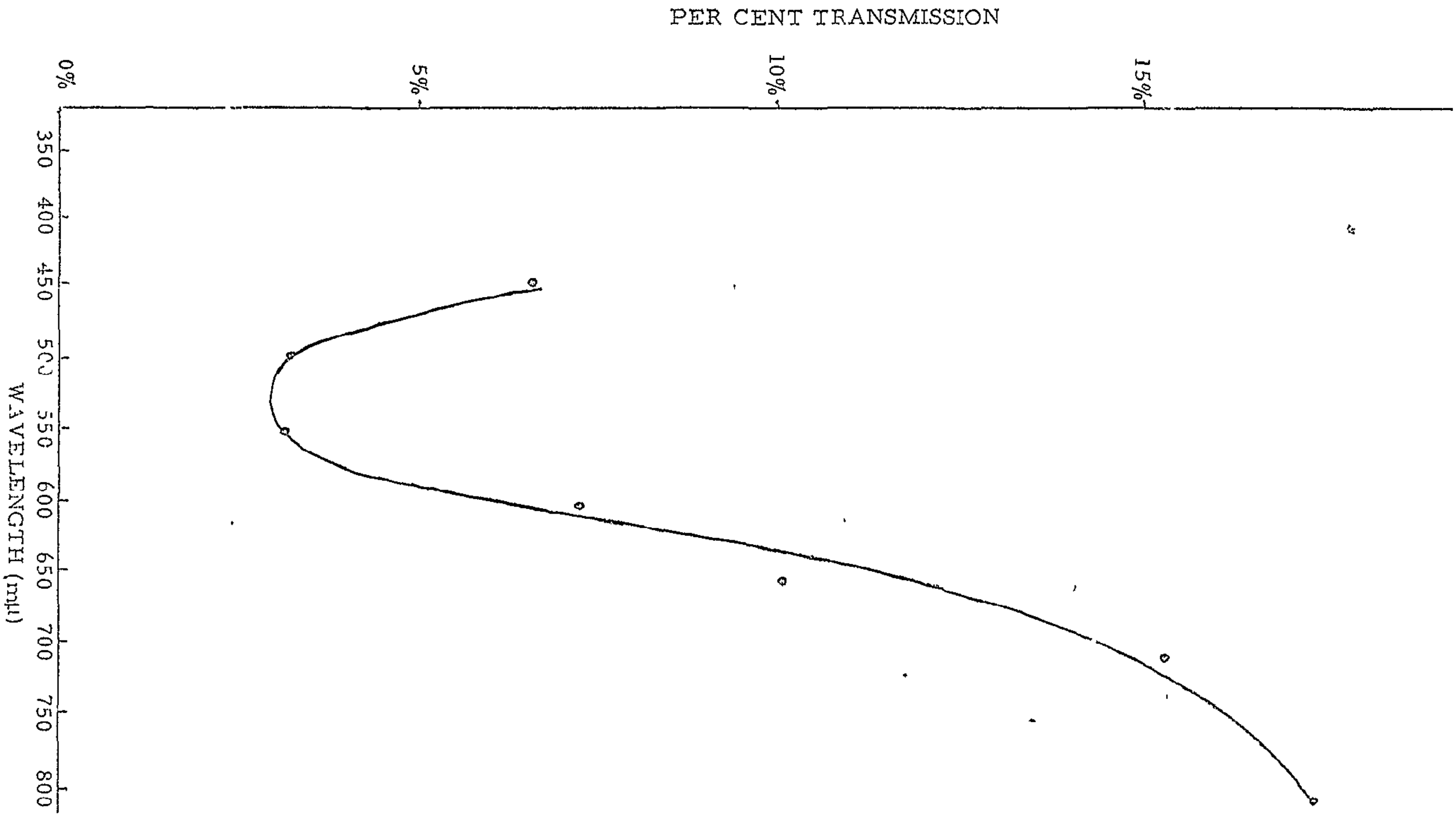


Figure 18. Visible and UV transmission of right lens (periphery) of tinted wraparound astronaut goggles

3.5 Glare and Reflection in the Helmet/Visor System

Astronauts operating on the lunar surface have commented on troublesome facial reflections from the helmet and visor systems. The helmets and visors themselves act as concave mirrors at each interface. The protective gold coatings on the outer and inner visors increase the reflectivity of one surface of each of these components enormously.

Figure 19 illustrates the boundary conditions for reflection in concave mirrors for an object

(1) outside the radius of curvature of the mirror,

(2) at the center of curvature,

(3) between the center of curvature and the focal point of the mirror,

(4) at the focal point, and

(5) within the mirror's focal length.

It will be noticed that the real, inverted image moves away from the mirror as the object approaches the system's focal point. The image is at optical infinity when the object is at the mirror's focal point. Objects situated within the system's focal point are imaged in a magnified, virtual and errect fashion. Images of objects outside of the radius of curvature are minified, objects within the radius of curvature are magnified.

This reduced geometrical optical scheme illustrates the way in which features of the astronaut's face are imaged. All such images may act as in-focus or out of focus veiling-glare images at the retina.

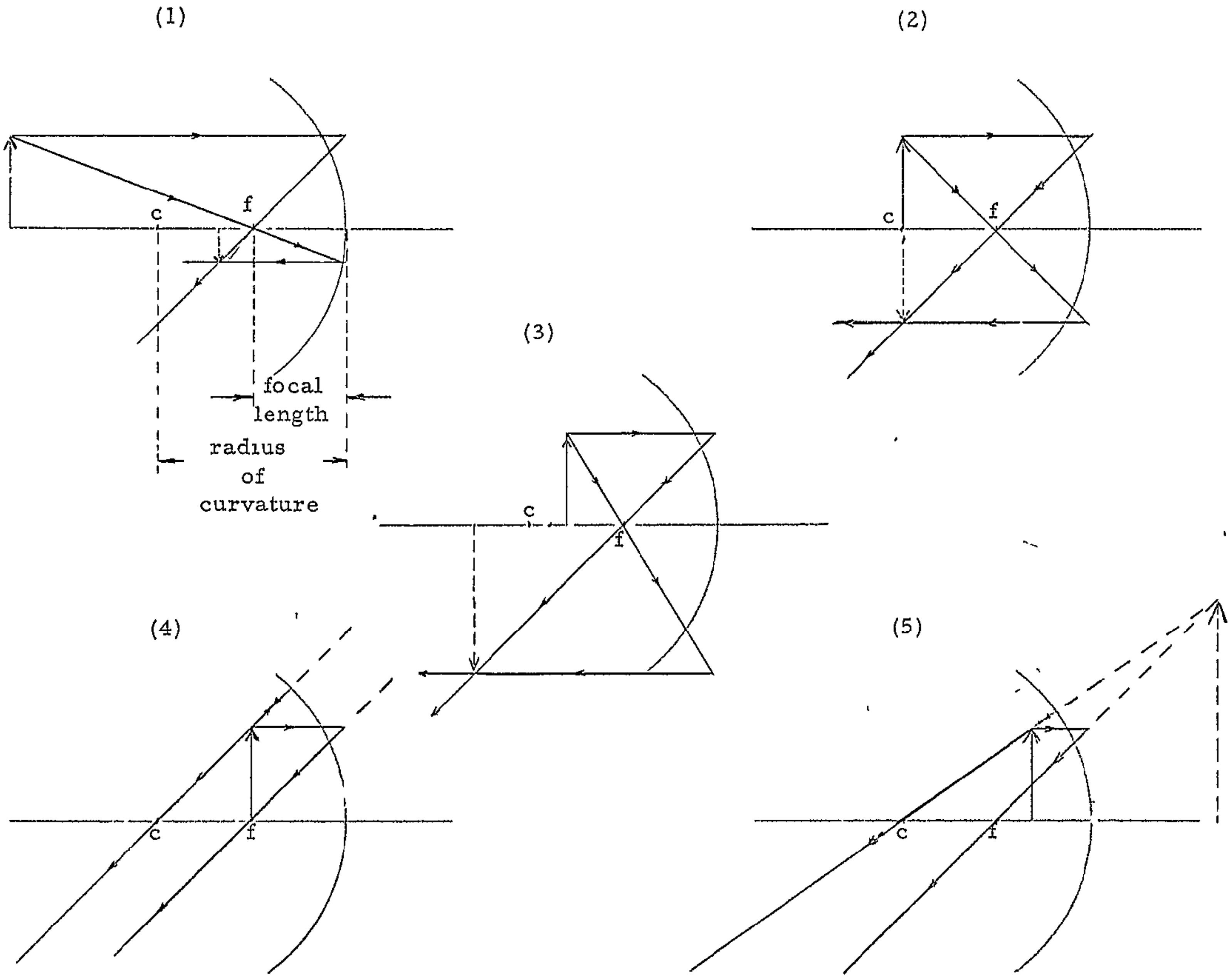


Figure 19. Boundary conditions of visor reflections

This reduced geometrical optical scheme illustrates the way in which features of the astronaut's face are imaged. All such images may act as in-focus or out of focus veiling glare images at the retina.

The general equation applying to reflection for a convex mirror in air is,

$$L' = L + F$$

or

$$L' = L - 2R, \text{ where}$$

L = vergence of light in the object space

L' = vergence of light in the image space

R = curvature of the mirror

F = power in diopters

and $$L = \frac{1}{\zeta}, \quad L' = \frac{1}{\zeta'}, \text{ and } R = \frac{1}{r},$$

ζ, ζ' and r being the object distance, image distance and radius of curvature respectively (measured from the pole of the mirror in meters)

3.6 Determination of the Approximate Luminances of Facial Reflections on the Lunar Surface

Let.

E_1	solar illuminance at lunar surface. -	*12,729 ft cd(29)
E_f	solar illuminance at astronaut's face	
T_h	transmittance of helmet/visor system. -	*0.1(30)
R_f	reflectance of face	*0.35(31)

L_f luminance of astronaut's face

L_i luminance of image of face

R_h reflectance of helmet visor system - $^{*}0.36^{(32)}$

C conversion factor, meter candles to foot candles

W effective solid angle into which light is reflected from the astronaut's face

*approximate values

$$L_f = E_l\, T_h\, R_f\, C\, W^{-1}$$

$= [12,729 \text{ ft cd}]\,[0.1]\,[0.35]\,[10.766]\,\frac{1}{\pi}\ \text{cd m}^{-2}$, assuming lambertian reflection

$= 1526 \text{ cd m}^{-2}$

$L_i = L_f \times R_h$ (assuming a plane reflecting surface)

$= 1526 \times 0.36$

$= 550 \text{ cd m}^{-2}$

Computations show that this luminance level is similar to that of lunar terrain of average reflection factor 0.1.

Glare studies have been performed in which facial reflections were superimposed upon various vision targets. It has been shown that acuity may be totally unaffected or reduced to 20/200 or less, according to the part of the facial image superimposed upon the target.

4. ANALYSIS OF VISUAL PROBLEMS IN SPACEFLIGHT

This program is concerned with the identification and analysis of visual problems in spaceflight and the recommendation of procedures for their elimination.

The following pages contain an analysis of likely sources of the flashing lights which have been perceived by the astronauts on moonflights.

4.1 Introduction

Apollo crew members have reported being aware of discrete flashes and streaks of light during periods of darkness in spaceflight. These unusual light perceptions were visible with the eyelids open or closed and occurred with a frequency no greater than 1-2 per minute in Apollo flights 11, 12 and 14, but more frequently in Apollo 13.

The origin of these phenomena is not known, and therefore, their significance has not been ascertained. The physics, physiological optics and neurophysiology of the visual system suggest several possible explanations. Some explanations suggest benign sources which constitute no danger to the astronaut, while other possible causes are potentially injurious. It is desirable that the origin of these phenomena be identified.

Table III summarizes reported sightings of entoptic light flashes on missions Apollo 11 through 14.

4.2 Possible Sources of Entopic Lights in Space

The likely sources of these phenomena may be conveniently divided into

TABLE III

Summary of reports of entoptic light flashes on missions Apollo 11 through 14. This composite is made up of the remarks recorded by Fazio, Jelley and Charman,(38) plus information made available by NASA, MSC, Houston, Texas.

Flight	Astronaut	Observations
Apollo 11	Edwin Aldrin	All incoming light blocked by shades, spacecraft revolving, pinpoint-like flash that dissipated rapidly, single flash, white, frequently streak, occasional double flash, random location, saw them at will, static electricity not the cause, never recalled seeing them with eyes closed.
	Neil Armstrong	Saw approximately 100 flashes, rate about one per minute.
Apollo 12	Charles Conrad	Observed flashes with eyes closed, approximately 10 per cent of flashes were streaks and double points, streaks appeared horizontal, all streaks appeared in the upper field of view.
Apollo 13	General comments	Each crewman saw light flashes, but only while in the dark and with the eyes closed All observations were made in the command module, both in and under the couches. None of the flashes were obtrusive The crewman had to be relaxed before he noticed them. They observed many more dots than streaks, and the colour was always white.
	James Lovell	Frequency of flashes about once every two minutes.
	Jack Swigert	Counted only two flashes in one half hour.
	Fred Haise	First evening counted 10 flashes in a 5-min period, time intervals varied from 7 s to 1·5 min, all but one flash were dots that looked like "roman candles", in this set there was one streak that passed from

TABLE III (continued).

Flight	Astronaut	Observations
Apollo 13 (continued)	Fred Haise (continued)	left to right, the second night 12 to 15 flashes observed before falling asleep (time interval not defined)
Apollo 14	Allan Shepard E.R. Mitchell	Flashes observed in darkened cabin with eyes open or closed.
	Stuart A Roosa	Flashes observed within one minute of illuminating the eyes with a flashlight.

two groups:

A. Those originating from stimuli having an origin outside the body.

B. Those of an internal nature

4.2.1 Stimuli having an origin outside the body

A. The near-visible and visible electromagnetic radiations

Visible light is composed of electromagnetic radiations within the wavelength band of approximately 400-700 nm. It consists of radiation which may penetrate the optical media of the eye and supply quantal bleaching energies to molecules of visual pigments, stored in the outer segments of the retinal receptors. The stimulus effectiveness of a radiation is dependent upon ocular transmission and visual pigment absorption characteristics.

Infrared radiation (IR) is significant because its absorption may produce surface and chorioretinal burns. The visual pigments are almost completely transparent to the infrared wavelengths up to 1400 nm which are significantly transmitted by the ocular media. Therefore, visual effects are not expected except as a temporary secondary effect of thermal damage.

Ultraviolet radiation (UV) may constitute "visible light" when allowed to reach, and be absorbed by, the receptoral photopigments in the retina. However, the normal eye absorbs UV in the ocular media, preventing it from reaching the retina.

Visible, IR and UV radiations are significantly absorbed and diffused by the closed lids. Consequently, stimulation of the retina by these radiations would be significantly altered by closing the eye lids.

Visible light could conceivably be released by high-energy particles of ionizing radiation penetrating to the vitreous or retina. Cherenkov radiation consists of energy released when a particle enters a medium in which its velocity is greater than the velocity of light in that material. The coherent visible light is released in a cone about an axis which lies along the path of the particle. The half angle (ϕ) of the cone is given by: $\cos \phi = \frac{B1}{B}$ where B1 is the speed of light in the medium and B is the speed of the particle in the medium.(33) There is no ocular optical focussing mechanism which would focus fluorescent intra-ocular sources sharply on the retina, and it must therefore be assumed that the released light must impinge upon the receptors, providing the adequate stimulus for visual detection.

B. Nerve stimulation by radiation bombardment

Stimulation of the visual pathway at any level will give rise to a visual perception presumably identical to the retinal light stimulus configuration which the neural response has by chance mimicked. We may assume that point-of-light sensations may be evoked by unit stimulation in the retina or in the visual pathway between the retina and the highest perceptual centers in the occipital lobes of the cerebral cortex. Receptor cells or receptor sites on cells, however, form the most likely sites for such stimuli to be effective.

It may also be possible for the visual perception of a streak of light to be the result of the sequential stimulation of a whole row of neural units. In this case one would expect no sense of movement, because of the high velocity of a stimulating particle. The direction of travel through the retina would presumably influence the form and orientation of the shapes perceived. There do exist, however, complex form and movement sensitive units at various levels in the visual pathway, which are visual-form-specific in the information which they normally carry.(34) Were one of these latter units to be stimulated, it must be assumed that the perception of some line, bar or border might reach the level of conscious awareness. The stimulation of complex neural units might explain entoptic lights evoked by radiation or "physiological" stimuli with fewer quantal energy absorption events than are commonly considered to be required (5-14 simultaneous absorptions in different receptors[35]). While the term stimulation is commonly employed to signify the application of sufficient energy to a neural unit to cause it to respond, it may also include temporary stimulation concomitant with an injury current in a nerve cell. Such a response, familiar to the single-cell electrophysiologist, frequently signals the impending functional and biological death of the unit.

If repeated cosmic bombardments are causing a significant amount of cellular death, then the super-sensitive dark adapted visual system may prove a detecting tool superior to histopathological examination.

Observation of frequency, duration and visual appearance may indicate the level of the visual pathway involved as the site, or sites, of primary stimulation. In this connection, it should be remembered that the cortex within its bony case is as vulnerable to penetrating particles as is the retina.

Lipetz[36] has proposed that radiations outside the normal visual spectrum may cause the stereoisomerization of visual pigment molecules contained within receptor outer segments. Any such change, which produces an adequate neural response, becomes a visual event regardless of the fact that the initiating radiation lies outside of the accepted visible spectrum.

Dawson and Wiederwohl(37) found no evidence for X-ray bleaching of receptor photopigment in investigations on the eye of the limulus crab, but they were able to show adaptive changes including a hypersensitivity to visible light stimulation.

The perception of visual phosphenes from X-ray stimulation of the retina appears to occur with little or no cell damage. The reverse, however, appears to be the case when nerve tissue is irradiated with the higher energy level particles associated with primary and secondary cosmic radiations.

Lipetz(36) has concluded from his reviews of the literature that β particles from radium cause phosphenes by vitreous fluorescence, and γ particles by action upon the photopigment molecules.

Fazio, Jelly and Charman(38) have recently considered the reports of the observances of the crew members of Apollo 11, 12, and 13 missions. From the fact that most sightings were made under conditions of darkness, they concluded that the source lies in primary cosmic radiation. Two suggested stimulus situations were:

(1) Cherenkov radiation generated within the optical media of the eye, and

(2) the excitation of receptors or other retinal cells by ionizing radiation.

Since the flight of Apollo 14, the observation of entoptic light flashes in partially light adapted eyes has re-opened the question of the phenomenon's origin. It might be expected that the quantities of light emitted by the Cherenkov effect and capable of causing low level response from a dark adapted eye would not be likely to be perceptible to the less light-sensitive light adapted eye.

The absolute quantal threshold for 60% probability of detection is 5-14 (effectively summated) absorptions.(39) If we round off to 10, and compare this with the photopic eye's maximum sensitivity during dark adaptation (which is the order of 2 to 3 log units less), we arrive at a figure of the order of 10^3 to 10^4 quanta for photopic threshold. However, the light adapted eye is functionally different, having smaller units for retinal spatial integration, as well as an increasing directional sensitivity. The foregoing facts illustrate that significantly higher Cherenkov light yields would be required for light perception in the light adapted eye. Such yields would seem to be adequate for correspondingly more intense and noticeable perception in the dark adapted eye.

It is apparent, at this time, that further research is required to answer the question whether Cherenkov radiation can satisfactorily explain the perception of light flashes soon after the eyes have been exposed to the desensitizing effects of light adaptation from a flashlight. The observations to date seem to indicate an external stimulus source, and consequently the term "entopic" is probably inappropriate.

4.2 2 Sources of a purely internal nature

The dark adapted retina produces a perception, not of blackness, but of moving scintillating lights. This "eigenlicht" or "dark-light" of the eye is assumed to result from the relatively random firing of neural units of the visual system, and may represent receptoral activity due to photochemical thermal decomposition or spontaneous neural activity. Such mechanical factors as arterial pulsation or tissue traction from muscular tissues may contribute to stimulation or to the synchronization of these noise perceptions These factors may differ in their significance between the normal and the weightless states.

The recent observation of flashes after light adapting the eye with the light from a flashlight would seem to eliminate sources of an internal nature from consideration.. A full photometric and physiological analysis will, however, be required before the validity of this test may be confirmed.

It would be advantageous to know something about the appearance of the dark-light of the visual system in the physiological state of weightlessness. The dark image of the visual system, if not responsible for the perceptual phenomena reported in space, is in fact the background against which it is viewed in the dark adapted eye.

5. DIRECT SUPPORT TO THE NEUROPHYSIOLOGY LABORATORY, NASA, MSC, HOUSTON

5.1 Introduction

During the past year the Houston group of Technology Incorporated's Life Sciences Division, Vision/Neurophysiology Section, has been involved in work on a large number of problems in the areas of vision, audition, and neurophysiology. The wide variety of subjects to be covered in this section suggests that each area be covered as a separate entity rather than treating the effort as a unified whole.

5.2 Motorized Howard-Dolman Device

The construction of the motorized Howard-Dolman device, begun under Contract NAS 9-6865, has been completed during this year. A complete description of this system appears in the manual associated with the device. Briefly, the instrument consists of a stimulus box with a stationary rod, a motor driven stage supporting a movable rod, two fluorescent lights and brackets, and control electronics and a power supply. In addition to the stimulus box there is a subject's control box with a one dimensional joystick control, and an experimenter's box with a digital voltmeter and check-out switches.

The subject's task is the same as that with the conventional string-operated model. The two pegs must be aligned so that they appear to be equidistant from the subject. With the motorized system, peg speed and direction are determined by the displacement and direction of the joystick controller.

Longitudinal separation between the pegs is read in millimeters on the digital display.

At present, 21 clinical subjects have been tested on the device. Their tests have been conducted in the course of standard visual examinations performed by the Contract Monitor. Summary results, presented in Table IV, show no uniform instrumental bias, and the overall standard deviation is similar to those values reported in the literature.(40)

In the course of the design of the instrument we undertook the task of defining meaningful statistics to be used in the analysis of the raw scores. The subject responds to the stereopsis angle perceived between the pegs, not to the absolute longitudinal distance between them. The equation relating peg displacement and stereopsis angle is

$$\alpha = (\mathrm{Tan}^{-1} \frac{P}{D-X}) - (\mathrm{Tan}^{-1} \frac{P}{D})$$

where

α is the stereopsis angle

P is the inter-pupillary distance

D is the distance from the eyes to the fixed peg

X is the longitudinal distance between the fixed and movable pegs. The sign convention normally used assigns + to the condition of movable peg closer to the subject than the fixed peg.

Since the equation is non-linear, it is evident that if α is normally distributed,

TABLE IV

Mean and standard deviation for all settings
by 21 subjects (10 settings each).

	SECONDS OF ARC	MILLIMETERS
MEAN	-.496	-1.337
STANDARD DEVIATION	6.690	18.447
N	210.	210.

X will not be normally distributed. In order to use standard statistical tests in this situation, it is necessary to convert the subject's setting errors (in millimeters) into stereopsis angle (in arc seconds). A program was written for a Wang 700B Calculator to perform the conversion and to generate the summary statistics in both arc seconds and millimeters. A sample printout is shown in Figure 20. The program uses a converging series technique which ensures an error in the angle calculation of less than 3.6×10^{-10} arc seconds. This approach avoids the finite errors introduced in the approximation technique usually used in the conversion of distances to stereopsis angles on the Howard-Dolman device.

The Motorized Howard-Dolman device and its associated data reduction program should provide a very stable measurement system for determining minimum stereopsis angles. The device is simple and sufficiently rugged for both clinical and laboratory use.

5.3 Haze Measurements

In addition to the helmet and visor haze measurements mentioned elsewhere in this report, five sets of haze measurements have been made on coated and uncoated samples of Lexan provided by the Crew Systems Division, NASA, MSC The measurements were made in support of an effort by that division to determine the compatibility of a new anti-fog compound with helmet materials for Apollo 15. Each sample (6 to 8 in each set) was measured at three different places with a Gardner pivotable sphere hazemeter. Measured haze and transmittance were reported for each

Figure 20. Sample data of automated Howard-Dolman apparatus

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                SETTING                   SUBJECT NO.A  13
    mm       sec         mm       sec     P.D. 65mm
1 -69.1   -24.64    2  68.3    24.91
3  78.1    28.53    4  -9.9    -3.56
5 -50.2   -17.96    6  79.8    29.16
7  42.3    15.36    8   3.4     1.22
9 -29.7   -10.66   10  78.9    28.83


                                                 mm                 arc  sec.
                                          MEAN    SIGMA          MEAN      SIGMA
                                         19.19   57.494          7.121     20.829
                                         Converted to
                                         arc seconds:
                                           6.944   20.938
```

testing position on each sample.

5.4 Apollo Transcript Production

All references to vision and visual perception have been extracted from the Apollo Air-Ground Communication Transcripts for Apollo Flights 13 and 14. These excerpts have been typed and delivered to the Contract Monitor. Review of the excerpts from Flights 12 through 14 indicates that no unanticipated effect has been encountered, with the exception of the perception of light flashes on the lunar missions. The vast majority of the comments refer to observation of surface details of the Earth and Moon, and, during lunar surface operation, to descriptions of gross and fine surface details. The excerpts provide a primary source for anecdotal data on man's visual experience in space.

5.5 Light Flash

Light flashes reported by the crews of Apollos 11, 12, 13, and 14 have raised considerable comment and interest in the past year. Consequently, a portion of our effort has been directed toward assisting some of the NASA scientists involved in the interpretation of these reports, and in the development of a Detailed Test Objective for Apollo 15. We have recommended that spectacle frames developed by Omnitech, Inc. be modified to serve as the face mounting support for the "Apollo Light Flash Moving Emulsion Device" to be flown on Apollo 15 and on subsequent missions. The recommendation was accepted, and assistance was provided in placing the spectacles into the MSC quality control system.

In addition, we have begun the task of evaluating the reliability of flight crew reports of which eye received the light flash. Earlier work, by a number of investigators, suggests that it should be difficult to identify correctly the stimulated eye. In order to verify this hypothesis a number of laboratory tests have been conducted involving the use of small light emitting diodes as the flash simulators. Generally, binocular fixation of a simple field or an array of the diodes has been arranged and the diodes on one side of the field pulsed for 200μ seconds or less. Due to the geometry of the viewing situations, the light from a given diode can reach only one eye. Results of subject reports so far have been inconclusive. Research is currently under way in an attempt to resolve the confusion and, by doing so, to answer the question.

5.6 Photometric Calculation

The Space Environment Simulation group of the Environmental Medicine Division is interested in determining the fatigue effects from the high lunar illuminance and contrast, and the nature of any changes in performance due to this fatigue. At their request, we have calculated illumination levels for a visor-up simulation which would correspond to the visor-down configuration on the lunar surface. Our recommendation was that the illumination be 1272 lm ft^{-2}. After examination of available light and power sources, it was determined that it was impractical to illuminate a significant portion of the chamber at those levels. In spite of this recommendation, work is proceeding to provide some high-level illumination in the simulation chamber for the fatigue tests. We have been requested to support the work with photometric measurements in the chamber following completion of the installation.

5.7 Auditory Research

One area of concern to the Neurophysiology Laboratory is the early detection of symptoms leading to loss of consciousness during $+G_z$ acceleration. For a number of years, loss of peripheral vision has been taken as such an indicator. It is well known that the sense of hearing is more resistant to the effects of anoxia than is vision. For example, under sustained linear $+G_z$ acceleration, auditory sensitivity is maintained at acceleration levels sufficient to cause visual blackout. (41, 42) It is no doubt partly for this reason that audition has been studied far less extensively than vision under conditions of anoxic stress. Thus, it is not known whether higher level auditory perception (as opposed to simple sensitivity) is affected in humans by a temporary reduced blood supply to the brain. Some recent work at Albany Medical College, however, points to the possibility of the eventual development of an auditory perceptual task of considerable sensitivity for the detection of anoxia. (43, 44, 45)

A 1000 Hz sine-wave signal with abrupt onset and decay must be presented for a minimum of approximately 10 msec to evoke a tonal sensation in a normal subject. A signal of shorter duration is heard as a click. It has been discovered, however, that persons with a vertebral-basilar artery insufficiency have tone thresholds dramatically higher than those of normal subjects, and signal duration must often be extended to 200 msec or more before acquiring a tonal quality. The vertebral-basilar system primarily supplies the brain stem, including auditory nerve centers. It is significant that this elevated threshold is not accompanied by a decrease in sensitivity, and that the phenomenon is at least partially reversible, since corrective surgery reduces temporal thresholds by more than 50%.

The characteristics of this phenomenon suggest that it may be of considerable value in the monitoring of subjects for early signs of cerebral decrement due to anoxia. For example, a simple auditory perception test could become a popular alternative to the vision tests routinely used in acceleration studies.

Investigations of a preliminary nature were undertaken to develop the optimal psychophysical techniques for the monitoring of tone thresholds, and to determine whether a threshold shift would reliably accompany a mild anoxic state.

A pure-tone generator was used in conjunction with logic circuitry in order to present a monaural, repetitive 1200 Hz signal at durations continuously variable from 5 to 35 msec. While several experimental procedures were tried, it appears that the method of adjustment is the most efficient means of determining a tone threshold. With a signal presented every 1.5 sec, the subject adjusted its duration to the minimum at which it retained a predominantly tonal quality. After a few practice sessions, subjects were able to make judgments rapidly and with low variability (standard deviations were 1 msec or less).

Attempts to demonstrate threshold shifts under conditions of mild anoxia produced suggestive, but inconclusive, results. No reliable shift occurred after breathing a mixture of 15% O_2 and 85% N_2 for 5 minutes prior to testing. This result may have been due to difficulties encountered with the breathing apparatus employed. While breathing a 12% O_2, 88% N_2 mixture, however, two subjects showed a significant threshold elevation, although the third did not. The subject showing the greatest shift also reported a dimming of the visual field, while the other two subjects reported no visual changes. No blood samples were drawn so that the actual decrease in blood oxygen level during these experiments is unknown.

It is clearly necessary to obtain more extensive and closely controlled data before the value of this test as a monitoring technique can be ascertained. It is felt that the preliminary data obtained to date do show sufficient promise to warrant a further effort, possibly by using lower body negative pressure to produce cerebral ischemia or by further reducing the O_2 level in the inspired air. Further tests of the tonal perception time may be attempted in the MSC man-rated centrifuge.

5.8 Neurophysiology

Our efforts in neurophysiology have been directed primarily toward identifying, specifying, and preparing to order the equipment required to establish well-equipped sleep and auditory laboratories at the NASA, MSC, Houston. Recommendations for equipment and techniques of data collection and reduction have been made and assistance has been supplied in the design of equipment interfaces for the final laboratory system.

6. REFERENCES

1. Mainster, M A., T. J. White, J. H. Tips and P. W. Wilson. "Retinal temperature increases produced by intense light sources" J. Opt. Soc. Am., 60, 264-270, 1970.

2. Gast, P. R., Handbook of Geophysics, Ed. C. F. Campen, Jr., et. al., MacMillan Co., New York, 1960, pp 14-32.

3. White, T. J , M. A. Mainster, P. W. Wilson and J. H. Tips, "Chorioretinal temperature increases from solar observation" Bull. Math. Biophysics, 33, 1-17, 1970.

4. Thetford, A , Techniques of photo stimulation in biology, Ed. B. H Crawford, G. W Granger, and R. A. Weale, North-Holland, Amsterdam, 1968, p. 89, et seq.

5. Wallach, H., and E. B. Karsh. "Why the modification of stereoscopic depth-perception is so rapid", Am. J. of Psychology, 76, 413-420, 1963.

6. Gregory, R. L., Eye and brain. The psychology of seeing, McGraw-Hill, New York, 1966.

7. Held, R. "Exposure-history as a factor in maintaining stability of perception and coordination", J. of Nervous and Mental Disease, 132, 26-32, 1961.

8. Harris, C. S. "Perceptual adaptation to inverted, reversed, and displaced vision", Psychological Review, 72, 419-444, 1965.

9. Kamiya, J., *Functions of varied experience*, Ed. D. W. Fiske, S. R. Maddi, Dorsey Press, Homewood, Ill., 1961.

10. Webb, W. B., *Sleep: An experimental approach*, MacMillan, New York, 1968.

11. Berger, R. J., "Oculomotor control: A possible function of REM sleep", Psychological Review, *76*, 144-164, 1969.

12. Clark, B., *Visual capabilities in the space environment*, Ed. C. A. Baker, Pergamon, New York, 1965.

13. Pitts, D G., "Visual illusions and aircraft accidents", School of Aerospace Medicine TR-67-28, Brooks Air Force Base, Texas, 1967.

14. White, W. J., *Visual capabilities in the space environment*, Ed. C. A Baker, Pergamon, New York, 1965.

15. Pigg, L. D., and W. N. Kama, "The effect of transient weightlessness on visual acuity", WADC Technical Report 61-184, Wright Air Development Center, Wright-Patterson AFB, Ohio, 1961.

16. Duntley, S. Q., R. W. Austin, J. L. Harris, and J. H. Taylor, "Experiments on visual acuity and the visibility of markings on the ground in long-duration earth-orbital space flight", Final Report, Contract NAS 9-5095, Scripps Institution of Oceanography, Visibility Laboratory, 1968.

17. Graybiel, A. and R. S. Kellog, Second symposium on the role of the vestibular organs in the exploration of space, Ed. A. Graybiel, NASA SP-115, Washington, D. C., 1966.

18. Peters, R. A. "Dynamics of the vestibular system and their relation to motion perception, spatial disorientation, and illusions", NASA CR-1309, Washington, D. C., 1969.

19. Howe, J. A. M. and R. L. Gregory, "Visual perception in simulated space conditions", J. of the British Interplanetary Society, 21, 209-221, 1968.

20. Gregory, R. L , The neuropsychology of spatially oriented behavior, Ed. S. J. Freedman, Dorsey Press, Homewood, Ill., 1968.

21. Gibson, J. J., The perception of the visual world, Riverside Press, Boston, 1950.

22. Talbot, J A., "Illusions", The MATS Flyer, 10, 18-27, 1963.

23. Apollo 12 Mission Report, National Aeronautics and Space Administration, Houston, Texas, MSC-01855, March, 1970.

24. Gibson, J. J., "The perception of visual surfaces", Am. J. of Psychology, 62, 367-384, 1950.

25. Apollo 11 Mission Report, National Aeronautics and Space Administration, Houston, Texas, MSC-00171, November, 1969.

25a. Apollo 14 Voice Transcripts, NASA, Manned Spacecraft Center, February, 1971.

26. Brown, J. L. and C. G. Mueller, Vision and visual perception, Ed. C. H. Graham, Wiley, New York, 1966.

27. Ward, B., et al, "Research on visual problems in spaceflight", Final Report, NASA Contract NAS 9-6865, Technology Incorporated, San Antonio, Texas, May, 1970.

28. Ibid.

29. Personal communication from Dr. R. Fitch, NASA, MSC, Houston, Texas.

30. Ibid.

31. Bioastronautics Data Book, Ed. P. Webb, National Aeronautics and Space Administration, Washington, D. C., NASA SP-3006, 1966, p. 122.

32. Personal communication from Dr. R. Fitch, NASA, MSC, Houston, Texas.

33. Taylor, E. F., and J. A. Wheeler, Spacetime Physics, W. H. Freeman and Co., 1966, p. 91.

34. Granit, R., The Eye, Vol. 2, Ed. H. Davson, Academic Press, London, 1962, pp. 621 et seq..

35. Pirenne, M. H., ibid, pp. 141, et. seq..

36. Lipetz, L. E., "The X-ray and radium phosphenes", Brit. J. Ophthal., 39, 577-598, 1955.

37. Dawson, W. W., and H. Wiederwohl, "Functional alteration of visual receptor units and retinal pigments by X-Irradiation", Radiation Research, 24, 292-304, 1965

38. Fazio, G.G., J.V. Jelley and W N. Charman, "Generation of Cherenkov light flashes by cosmic radiation within the eyes of the Apollo Astronauts", Nature, 228, 260-264, 1970.

39. Hecht, S., S. Shlaer and M.H. Pirenne, "Energy at the Threshold of Vision", Science, 93, 585-587, 1941.

40. Graham, C.H , et al, Vision and Visual Perception, Wiley, New York, 1966, p. 526.

41 Fraser, T.M., "Human response to sustained acceleration", NASA SP-103, 1966.

42 Roth, E.M., W.G. Teichner, and R.L Craig, Compendium of human responses to the aerospace environment, Ed. E.M. Roth, NASA CR-1205 (II), 1968.

43. Creel, W., P.C. Boomsliter and S.R. Powers, "Sensations of tone as perceptual forms", Psychological Review, 77, 534-545, 1970.

44. Creel, W., S.R. Powers and P.C. Boomsliter, "Tonal sensation as a criterion of vertebral artery insufficiency", Archives of Surgery, 98, 309-312, 1969.

45. Boomsliter, P.C., W. Creel, and S R. Powers, "Time requirements for the tonal function", Journal of the Acoustical Society of America, 36, 1958-1959, 1964.