DOT/FAA/AR-95/32

Office of Aviation Research
Washington, D.C. 20591

Light Shaping Diffusers for Improved Visual Inspection of Aircraft

April 1996

Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/AR-95/32	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LIGHT SHAPING DIFFUSERS FOR IMPROVED VISUAL INSPECTION OF AIRCRAFT		5. Report Date April 1996
		6. Performing Organization Code
7. Author(s) Richard N. Shagam		8. Performing Organization Report No.
9. Performing Organization Name and Address Sandia National Laboratories Aging Aircraft NDI Validation Center Albuquerque, New Mexico 87185		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFA-03-91-A-00018
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington D.C. 20591		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code AAR-430
15. Supplementary Notes FAA Technical Center Monitor: Dave Galella, AAR-430		

16. Abstract

This report is a study of flashlights used for visual inspection of aircraft. The report documents measurements of selected flashlight illumination devices and demonstrates that flashlights generally produce irregular beams that can mask defects from view. A significant, but relatively inexpensive, improvement to flashlights in the form of the Light Shaping Diffuser™ is demonstrated. This device dramatically improves the uniformity of flashlight illumination. The device has been tested by aircraft inspectors and is finding general acceptance within the inspection community for detailed inspection.

17. Key Words Aircraft Inspection, Flashlights, Illumination Aids, Illumination Measurements, Light Shaping Diffuser (LSD), Optical Inspection, Viewing Aids, Visual Inspection		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 35	22. Price

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This work was performed by the Aging Aircraft Nondestructive Inspection Validation Center (AANC) operated by Sandia National Laboratories, Albuquerque, NM, for the Federal Aviation Administration (FAA) Technical Center, Atlantic City International Airport, NJ, as authorized by Interagency Agreement DTFA-03-91-A-00018. The author extends his appreciation to Joe McDuffy of Ross Aviation, Albuquerque, NM; Jason Beechwood of Mesa Airlines, Farmington, NM; and Burl Nethercutt, Frank Sitterly, and Paul Davis of American Airlines, Tulsa, OK, and to their respective inspection and maintenance crews for participating in the field trials. Also, to the staff of the AANC and Sandia National Labs, including Ken Harmon for helping to set up the field trials, and to Mike Hinckley of the Photometrics Dept. for his assistance in making laboratory measurements. Thanks are also due to Rick Shie and Jeremy Lerner of Physical Optics Corporation for making Light Shaping Diffuser samples available. Also, acknowledgment is due to the Air Transport Association Nondestructive Testing (NDT) Forum for allowing the opportunity to distribute samples and surveys to the attendees.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The traditional tool in routine use for aircraft visual inspection is the hand-held flashlight. The aircraft inspector uses a flashlight both as a means to provide local lighting to an otherwise dimly illuminated or nonilluminated area of an aircraft structure and as a means of highlighting and directing his attention to a particular point on the structure, much like a pointer. The inspector will use his flashlight to illuminate a surface from a number of different angles in order to detect glints or shadows which may be indicators of structural problems. Glints may indicate cracks or scratches in a metallic component. Shadows, especially revealed with grazing incident illumination, may indicate wavy surfaces due to underlying corrosion. Many times the defects will be obvious, but sometimes the effect that the inspector is looking for is subtle.

There are many different styles and varieties of flashlights on the market today. Metal or plastic cases and reflectors, environmentally sealed, adjustable or fixed beam spread, switch activated or twist-on/twist-off, the battery size and number, and the type of bulb are just some of the various differences to be found in flashlights. Many share a common problem however, that of uneven illumination. A flashlight beam having a high peak illumination value may also contain areas of relatively brighter and dimmer intensities spread throughout the beam.

This report is a study of representative flashlights available to inspectors of commercial aircraft. The report documents light beam measurements from selected flashlights. Commercially available flashlights are shown to produce uneven illumination that could hamper an aircraft inspection.

The report also describes a major, but low cost, innovation to existing flashlights—the Light Shaping Diffuser (LSD), which significantly improves the quality of the illuminating beam. The LSD is an inexpensive optical component which reshapes the light from a flashlight, making it significantly more uniform than the "off-the-shelf" version.

Tests of the LSD at aircraft inspection facilities demonstrated that the LSD is a positive improvement to inspection flashlights. Ninety percent of inspectors that responded to a survey distributed during the 1994 Air Transport Association Nondestructive Testing Forum said the LSD-equipped flashlight was an improvement over their standard flashlight.

INTRODUCTION

Approximately 80 percent of the inspection of commercial aircraft is performed visually [1]. It is the visual inspector who first assesses that an inspection site is either in compliance with airworthiness standards, or must be repaired or inspected by more sophisticated methods. Despite the extreme importance of the inspector's task, the principal tools for visual inspection of airframes have been largely limited to those found in any hardware store, namely the hand-held flashlight and inspection mirror. While these tools are generally effective, there is significant room for improvement. In particular, the beam quality of common flashlights leaves much to be desired. Uneven illumination can lead to operator eyestrain and fatigue, leading to the possibility of an incomplete, deficient, or at the least, a slower, more tedious, and costly inspection.

According to definitions established by the Illuminating Engineering Society [2] a "detailed" visual inspection requires a minimum of 100 foot-candles (fc) of illumination, while a "difficult" inspection requires 200 to 500 fc. Up to luminance levels of about 300 footlamberts (fL), equivalent to an illuminance level of about 900 fc, it has been demonstrated that speed and accuracy of office workers improves with illumination levels [3]. Contrast of the target relative to the background is an important factor when considering illumination levels. Figure 1 shows how performance increases with relative target contrast, while figure 2 illustrates how the contrast of the target must increase with decreasing background luminance levels in order to achieve a particular level of performance. Clearly, if a target is not well illuminated, there is increased probability that it will not be detected.

If an inspector is to locate small defects with low contrast, then the background should be bright and evenly illuminated. If the light source projects considerable structure onto the target scene, then targets having low contrast will be lost among the projected structure. The light source should also be glare-free and should allow illumination of inspection sites from near-grazing incidence to normal incidence.

In terms of beam quality only, the best light source for an inspection application should be a bright, uniform beam. Such an illumination system could include a metal halide arc lamp for the source and a flexible fiber-optical bundle or a liquid-filled or flexible cast acrylic light guide. Uniformity of the beam would be generated by the scrambling associated with light being totally reflected internally from the walls of the conduit. Significant power to drive the lamp would be necessary due to coupling losses between the lamp and the conduit and internal to the conduit. This would have to come from an AC wall outlet. Hence, the brightness and uniformity come with a price, namely the size, weight, and the inconvenience of moving the light source around and about the work site—not to mention the trip hazard associated with running flexible power cords and light conduits around and about the confined spaces of an airframe or up on an access scaffold. Such sources, while commercially available, are also expensive, with even the bulbs costing in the several hundred dollar range and lifetimes of only tens of hours. This expense would preclude a facility from owning more than one unit to be shared by several inspectors. Thus, despite the advantages of brighter and more uniform beams from wall plug-powered illuminators, there is undoubtedly considerable resistance on the part of aircraft inspectors to use anything but the highly portable, battery-operated flashlight.

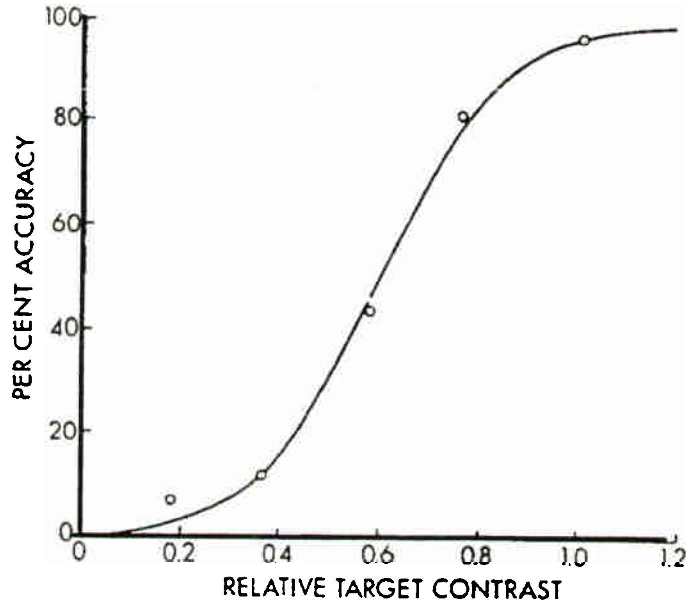

FIGURE 1. TARGET CONTRAST VERSUS PERCENT ACCURACY OF DETECTION [4]

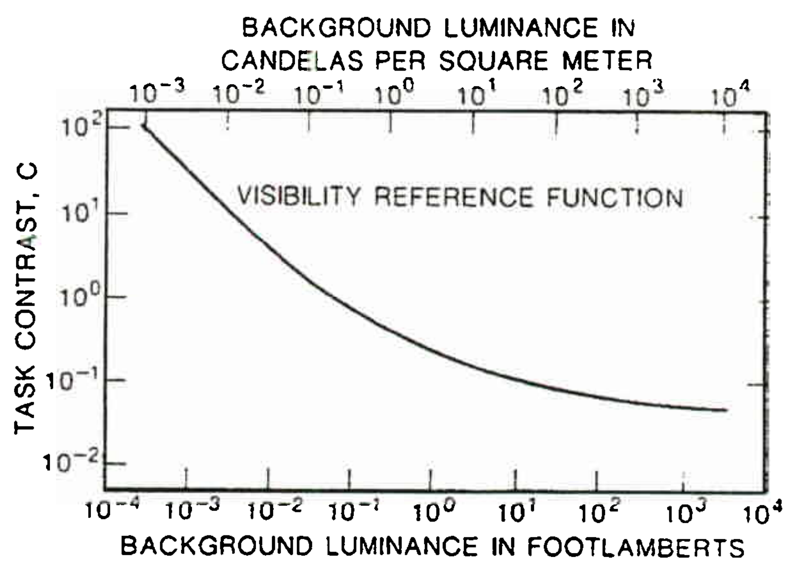

FIGURE 2. BACKGROUND LUMINANCE VERSUS REQUIRED TASK CONTRAST [4]

By using a uniform or homogenized beam as an illumination source, the inspector is more likely to concentrate on the surface, rather than the beam properties. The effective target contrast relative to the background scene remains high for the available illuminance. The inspector can fix his aim point, rather than dither the flashlight beam across the target. This results in a more rapid, accurate, and less fatiguing inspection.

This report presents measurements made on a number of flashlights available to aircraft inspectors and demonstrates that beam nonuniformity is a major deficiency of these devices. A simple accessory, the Light Shaping Diffuser, is presented as a means to generate a more uniform beam on stock flashlights. Field trials with aircraft inspectors demonstrate that this device can significantly improve flashlight illumination.

EVALUATION OF THE PERFORMANCE OF TYPICAL FLASHLIGHTS USED FOR AIRCRAFT VISUAL INSPECTIONS

There are many varieties of flashlights on the market—marked by different case styles, battery sizes, reflectors, and lens styles. Figure 3 illustrates some representative units on the market. All have a battery source for powering the flashlight, a switch for controlling the power, a bulb for generating the visible light, and a reflector for controlling the direction of the beam. The cases may be of various styles, and made from metal or high impact plastics.

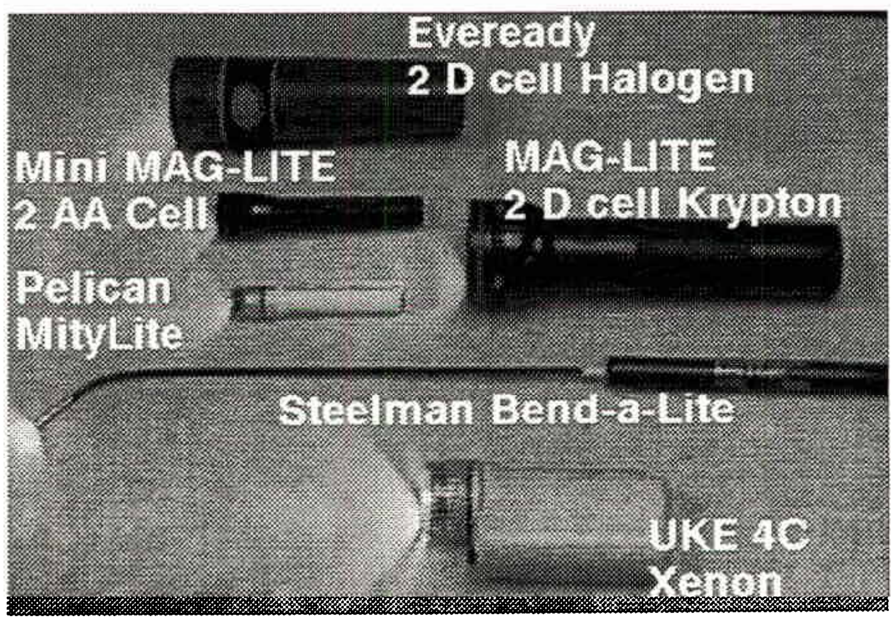

FIGURE 3. SOME REPRESENTATIVE BATTERY OPERATED ILLUMINATION DEVICES

Most inspectors appear to choose their flashlights based upon cost, portability, size, durability or repairability, but not necessarily for the quality of illumination. For example, an inspector will need an electrically nonconductive, explosion-proof flashlight for use in fuel cells. But explosion-proof flashlights are generally more inconvenient to operate because they are usually activated by twisting the lens cap, whereas other types will have a more convenient slide or push-button switch. Another consideration is durability—flashlights tend to get dropped, so they should be resistant to impact damage. However, illumination should be of prime consideration because it is that property that ultimately influences the accuracy with which small defects can be found. Table 1 shows some representative task lighting levels for assorted industrial activities. Depending upon the shape and size of the target and contrast relative to the background, illumination levels upwards of 200 to 1000 foot-candles (fc) are required for reliable detection of small defects [5].

TABLE 1. REPRESENTATIVE TASK LIGHTING LEVELS FOR NORMAL INDUSTRIAL ACTIVITIES [2]

Category	Illuminance Range (fc)	Contrast	Type of Activity
A	2-3-5	—	Public areas with dark surroundings (e.g., lobbies)
B	5-7.5-10	—	Simple orientation for short temporary visits (e.g., corridors, storage rooms)
C	10-15-20	—	Working spaces where visual tasks are only occasionally performed (e.g., waiting rooms, reception desks)
D	20-30-50	0.75-1.0	Performance of visual tasks of high contrast or large size (e.g., printed material, typed originals, ink handwriting, rough industrial work)
E	50-75-100	0.62-0.75	Performance of visual tasks of medium contrast or small size (e.g., medium pencil handwriting, poorly printed or reproduced material, medium industrial work)
F	100-150-200	0.50-0.62	Performance of visual tasks of low contrast and very small size over a prolonged period (e.g., hard pencil handwriting on poor quality paper, faded dittos, difficult industrial work)
G	200-300-500	0.40-0.50	Performance of visual tasks of low contrast and very small size over a prolonged period (e.g., fine industrial work, difficult inspection)
H	500-750-1000	0.30-0.40	Performance of very prolonged and exacting visual tasks (e.g., extra fine bench, machine or assembly work)
I	1000-1500-2000	<0.30	Performance of very special visual tasks of extremely low contrast and small size (e.g., surgical procedures, sewing academic gowns)

Flashlights are among the least sophisticated of optical illuminators. With only a simple reflector, bulb, and sometimes a lens element, the illumination they produce cannot be as uniform as that from a condenser-based optical projector. Flashlights are ultimately limited by the amount of illumination they can provide because of battery size and lifetime. From an illumination standpoint, an inspector would be better served to use a "wall plug" source of illumination, possibly combined with an optical cable for a delivery system, thereby taking advantage of unlimited wall plug power (figure 4). However, the presence of a power supply box and electrical or optical cable seriously limits the mobility of inspection personnel, as well as provides a serious trip hazard to all personnel in the vicinity. For these reasons, it is difficult to envision the battery operated flashlight being replaced by wall plug lighting.

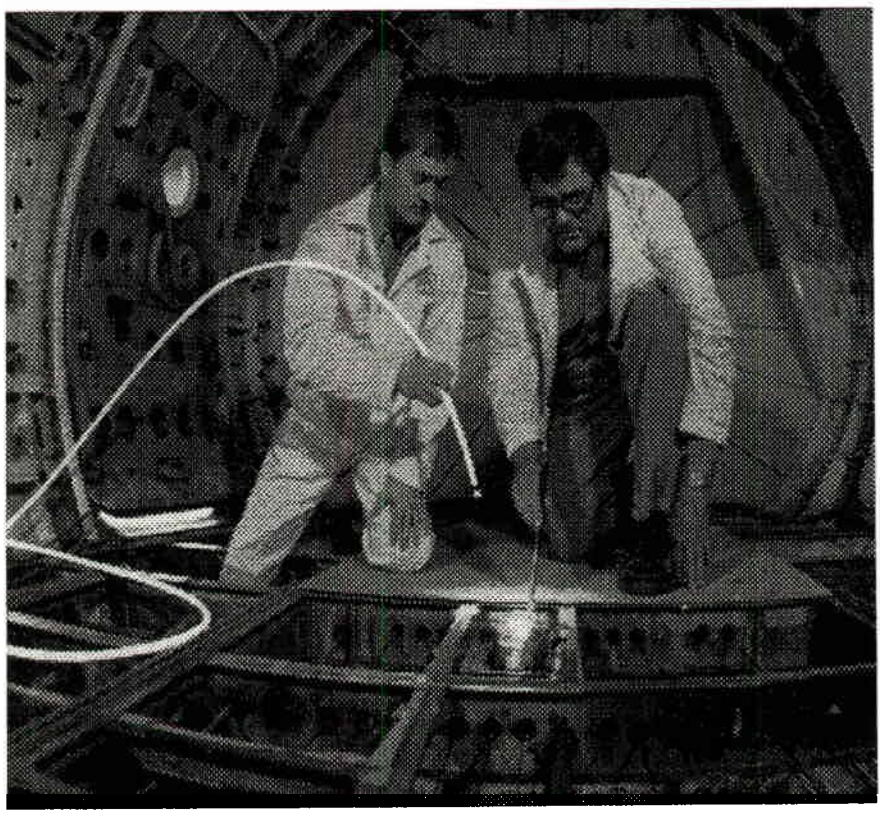

FIGURE 4. "LUMENYTE" FLEXIBLE FIBER OPTIC CABLE IN OPERATION

A common multiple C or D cell flashlight with fresh batteries used by the aviation industry illuminates a surface with a peak illumination level of about 500 fc when held 0.5 m from a surface [6]. However, variations in the useful area of a flashlight beam can be 70 percent or more below the peak beam illuminance, or levels approaching 150 fc. This can result in illumination levels in the beam which are below a minimum recommended level. An uneven beam will create the appearance of shadows on the surface and lower the inspector's accuracy and efficiency. Furthermore, during the course of an inspection, battery performance will drop off significantly, even within one or two hours of use, perhaps without the inspector's awareness of the decreased illumination. Therefore, with limited battery power available, it is important that every lumen from a flashlight be efficiently used.

A large number of flashlights on the market today are distinguished by their poor beam quality, as characterized by irregular shape and illuminance distribution. This is a result of the shape of the reflector and the shape of the filament in the bulb. Even in ideal circumstances, there is no reflector shape which can project a uniform beam from a coiled wire filament due to off-axis aberrations inherent in the optical system comprising the reflector and source. Contributing to the nonuniformity are defects in the manufacture of the reflector surface, shadows from the lead-in and filament support wires, as well as defects in the glass constituting the bulb envelope. In flashlights which have an adjustable beam spread, these variations can lead to dark spots or holes in the beam.

All of the variations in the projected beam contribute to a loss of scene contrast especially when an inspector is looking for targets which may be small in size or of low contrast to begin with. According to Murdoch [5], a decrease in contrast of 10 percent requires roughly an increase of 100 percent in illuminance for equal visibility for two otherwise identical inspection tasks. An inspector, who may be sweeping his flashlight around the inspection site, may direct his attention on the irregularities which make up the projected beam rather than to the irregularities of the inspected surface.

LABORATORY MEASUREMENTS.

In order to demonstrate the optical performance of commercial flashlights, representative flashlights were measured by standard photometric instrumentation. The measurements include average illuminance to compare relative brightness, illuminance versus time for comparison of performance life on a set of batteries, and beam nonuniformity to measure irregularities in illumination levels.

AVERAGE ILLUMINANCE. The average illuminance of a sampling of flashlights with fresh batteries was measured using a conventional photometer (Luxtron LX-102) at a distance of 20 inches (0.5 m) between source and detector. This distance represents a typical distance an inspector might hold a flashlight from an inspection surface. The measurement is an average because the photometer probe has a finite area (approximately 2 square inches) over which it is light sensitive. The results are given in table 2. Most of the flashlights measured have peak illuminances of at least 200 fc with fresh batteries.

ILLUMINANCE VERSUS TIME. Battery powered flashlights lose illuminance with time due to weakening batteries. Measurements were made of flashlight output versus time with a photometer and storage oscilloscope. Figure 5 illustrates the degradation of illuminance with continuous operating time for selected flashlights. Most of the flashlights tested lost 50 percent of their illuminance after only 2 hours of operation. Thus, a flashlight with an initial output that is acceptable for detailed inspection may quickly become marginal or unacceptable, possibly without the awareness of the operator.

TABLE 2. PROPERTIES OF SELECTED FLASHLIGHTS

Brand	Model No.	Number Battery Type	Peak Illuminance Raw Beam (fc)	Explosion Proof?	Peak to Average	Beam Dia. (in.)	Eff. Area (in^2)
Underwater Kinetics	UKE4C	4 C	2340	n	1.9	2.6	2.2
Pelican Super Sabrelite		3 C	1226	y			
MAG-LITE	3D016	3 D	1143	n	2.9	1.75	1.25
Eveready Halogen	251 WB-E	2 D	760	n	2.7	2.1	1.6
MAG-LITE	2D016	2 D	631	y	2.8	0.5	1.1
Pelican Super PeliLite	800	2 C	452	y			
Mini-MAG-LITE		2 AA	440	n	2.7	1.5	1.0
Bright Star	217	2 D	355	y			
Ray-O-Vac	N3	3 D	350	y			
Pelican Mity-Lite		2 AA	145	n	2.9	2.8	1.4
Lumenyte Optical Cable w/ "ELV" 150 W bulb based illuminator		(AC-powered)	1100		2.3	2.0	1.7

*Measurements made at a distance of 20 in. with fresh batteries.

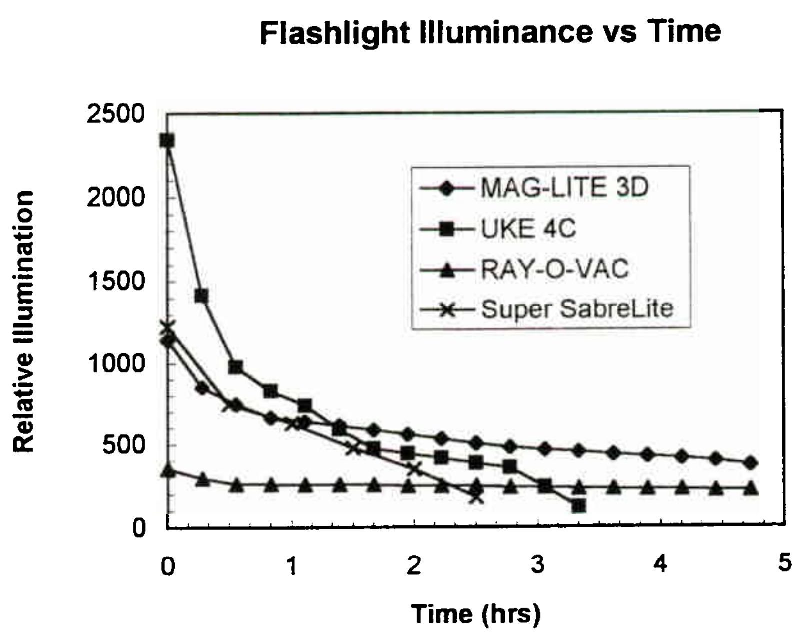

FIGURE 5. BATTERY LIFE OF SELECTED FLASHLIGHTS

One can argue about the supposed "bounceback" effect of batteries during intermittent operation; however, figure 6 shows that the recovery brightness of a flashlight that has been cycled on for 50 minutes and off for 10 minutes is not long-lived and has no appreciable effect on the time dependent illuminance. The discontinuity observed in figure 6 after six hours of operation is due to the subsequent measurements performed on a different day. This shows that the long term bounceback is not appreciable.

Of the flashlights measured, the Ray-O-Vac flashlight was the longest running, but also had the lowest overall illumination performance.

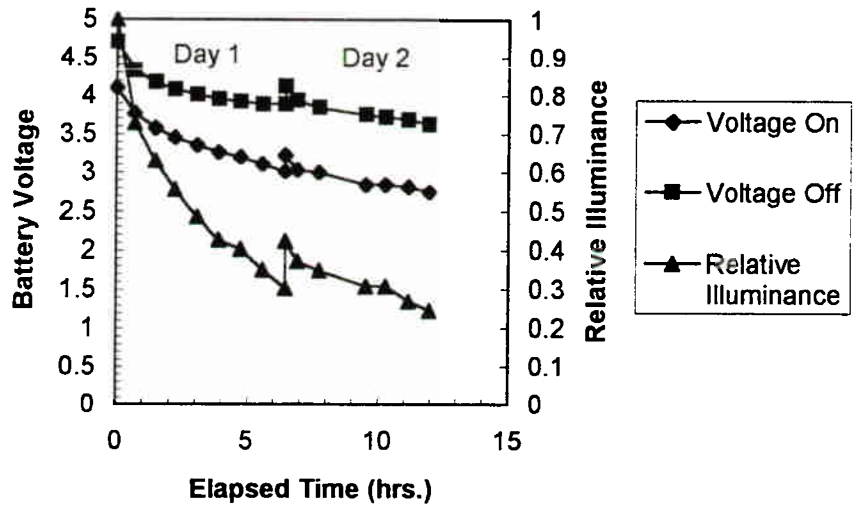

FIGURE 6. BATTERY LIFE OF A CYCLED MAG-LITE 3 D-CELL FLASHLIGHT. BATTERY WAS CYCLED 50 MINUTES ON 10 MINUTES OFF DUTY CYCLE. MEASUREMENTS MADE OVER TWO 6-HOUR PERIODS.

BEAM NONUNIFORMITY. The ideal illumination distribution would be a "flat top" profile in which the beam exhibits constant illuminance over the area of illumination. However, all illumination sources must obey the "$1/r^2$" law, meaning that there will be variations in illumination which should vary smoothly with the distance from the optical axis. However, in addition to gradual variations in illuminance, many sources exhibit irregularities due to nonuniform construction. Commercially available flashlights, for the most part, exhibit rather irregular beam profiles due to such factors as nonoptimal reflector or filament construction or alignment.

To quantify flashlight performance, video tools developed for laser beam analysis were used. Beam profiles were measured with the Beam View Analyzer (figure 7), a PC based video camera, frame grabber, and software analysis system developed by Big Sky Laser, Bozemann, MT. Flashlight beams were projected onto a white card from a distance of 0.5 m and imaged with the Big Sky video camera for a number of flashlights. Both contour and isometric plots of the irradiance profiles were recorded and are displayed in figures 8 through 12. All of the beams profiles show significant spatial variations in intensity.

Table 2 gives peak-to-average values of intensity and effective area of the flashlight beams as calculated by the Big Sky system analysis. Peak to average numbers approaching unity would mean a more uniform beam than higher values. The lowest values belong to the Lumenyte optical cable system and the Underwater Kinetics flashlight, while the most irregular are the MAG-LITE and the Pelican Mity-Lite flashlights.

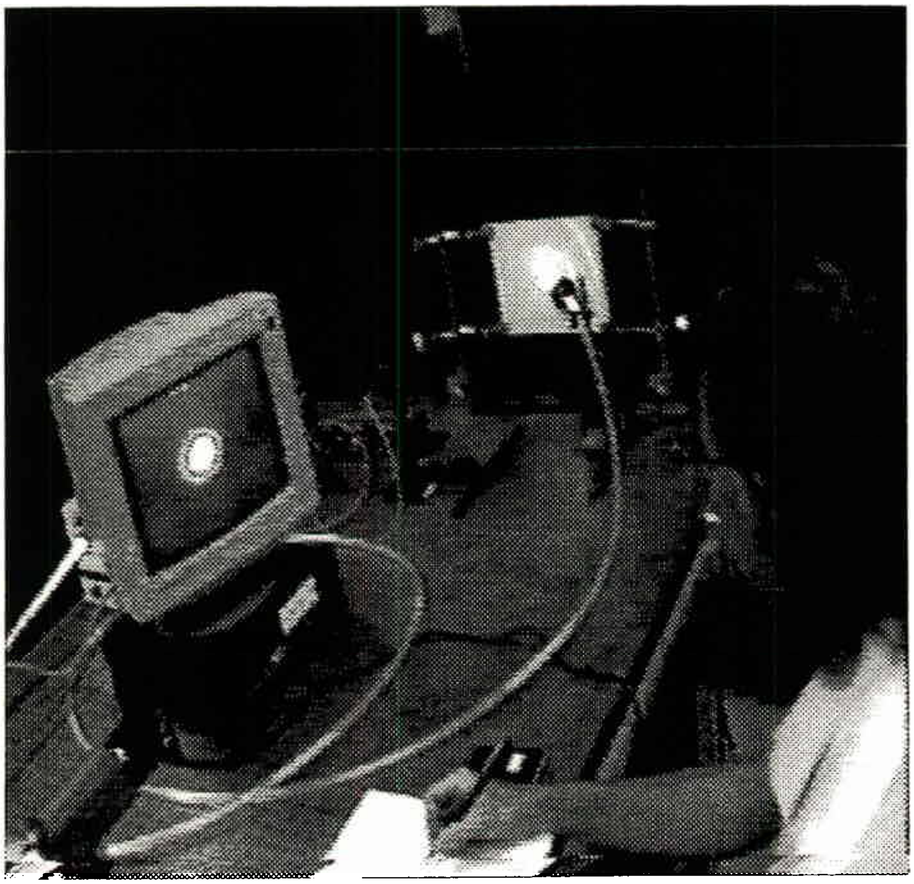

FIGURE 7. BEAM VIEW ANALYSIS SYSTEM

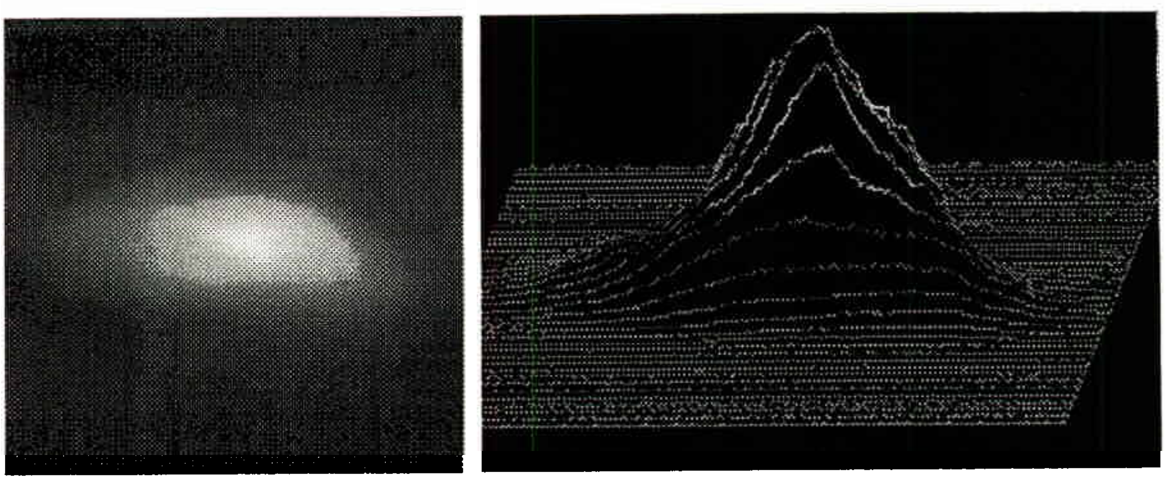

FIGURE 8. MINI-MAG-LITE ILLUMINANCE DISTRIBUTION

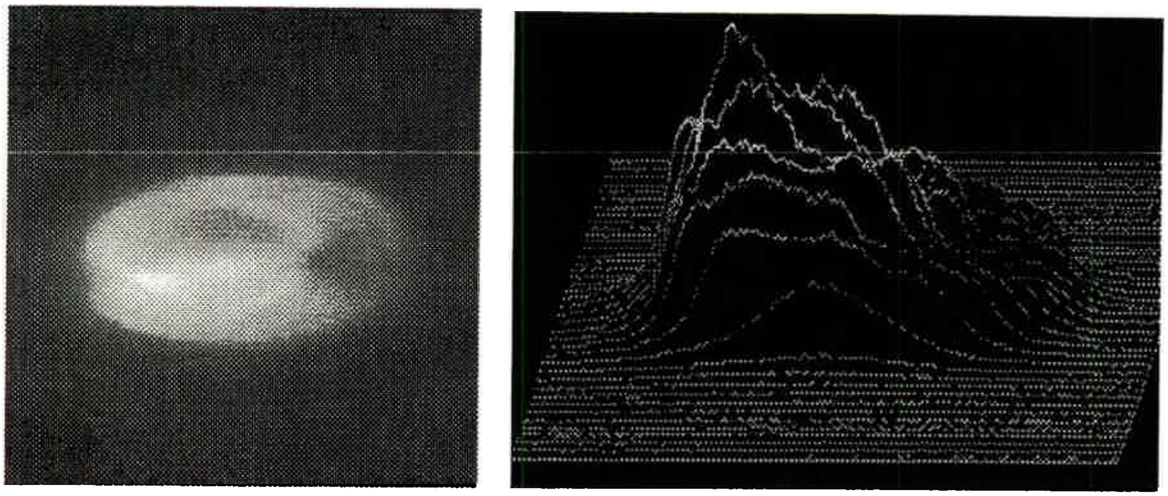

FIGURE 9. EVEREADY FLASHLIGHT ILLUMINANCE DISTRIBUTION

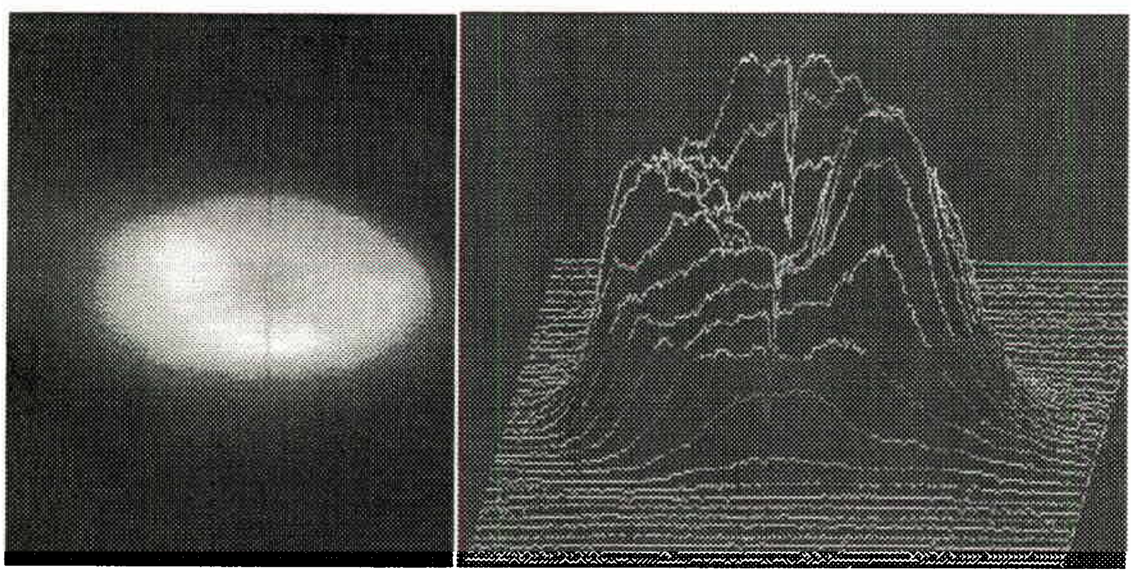

FIGURE 10. UKE4C FLASHLIGHT ILLUMINANCE DISTRIBUTION

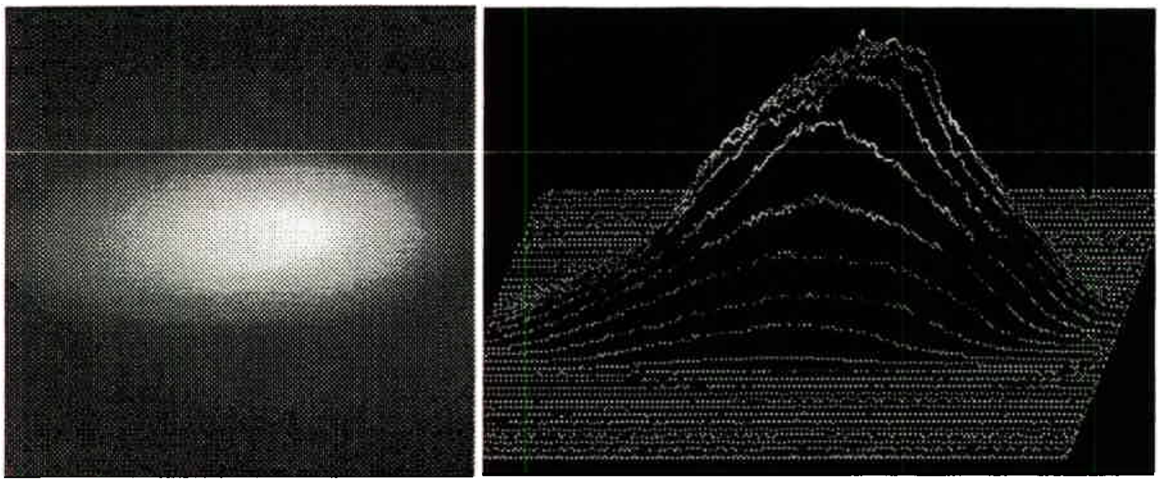

FIGURE 11. LUMENYTE CABLE ILLUMINANCE DISTRIBUTION

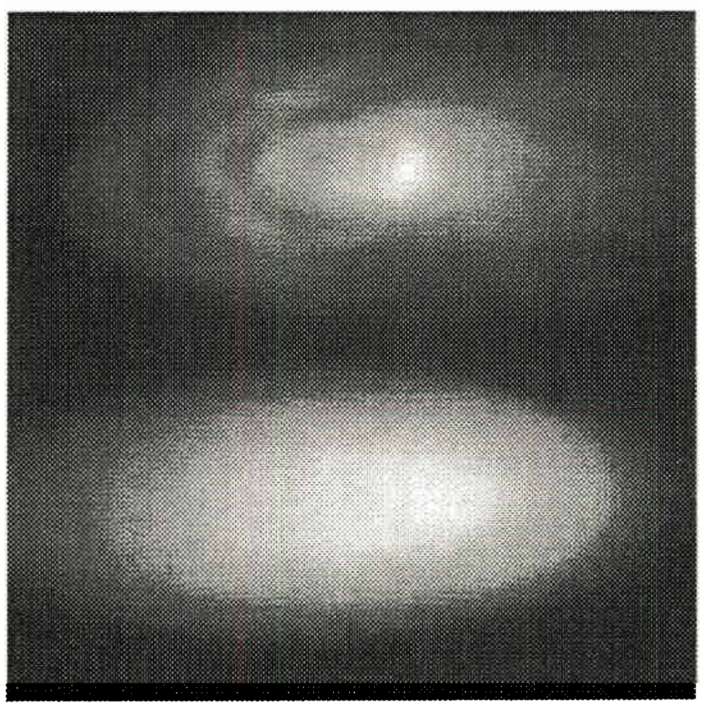

FIGURE 12. MAG-LITE (TOP) VERSUS LUMENYTE CABLE (BOTTOM)

The effective area is defined as the total luminous flux from the flashlight divided by the peak illuminance in the flashlight beam. The effective area is then a measure of the size of a beam having a flat top shape with an illuminance equal to the peak illuminance in the beam.

DISCUSSION

During the course of the measurements, it was difficult to capture the subtleties of the beam variations that the human eye can detect. Although the eye can only detect one to two dozen gray levels at any one time, as compared to a digital video camera which can capture 256 or more gray levels, the eye can process subtle changes in light owing to its tremendous ability to adaptively track local brightness levels. Thus, while the recorded beam patterns may appear smooth, in actuality, virtually all of the flashlights produced patterns with relatively high spatial frequency irregularities which cannot be effectively documented. However, the overall low spatial frequency variations can be recorded and demonstrate the wide variations in illumination levels presented to an inspector.

THE LIGHT SHAPING DIFFUSER AS AN ENHANCED VISUAL INSPECTION AID FOR FLASHLIGHT INSPECTION OF AIRCRAFT

A simple and increasingly low cost improvement adaptable to most flashlights on the market is the light shaping diffuser (LSD™) manufactured by Physical Optics Corporation, Torrance, CA. It is a filter which generates a more uniform beam than is normally possible from a flashlight. It substitutes for the clear lens element in an adjustable or fixed focus flashlight. The diffuser has the property that a pencil of light passing through it is scattered into a cone whose angle is a function of the effective roughness of the scattering surface. The surface is generated by a proprietary holographic replication process which randomizes the phase of the transmitted light. The replication can be added to any polycarbonate, acrylic, or glass substrate. The scattering properties are such that over 90 percent of the light is transmitted in the forward direction.

With the LSD, the projected spot from the flashlight is homogenized and made much more uniform than without the filter. While the filter cannot fill in holes in the beam which exceed the scattering angle of the filter, it smoothes out the beam to create a dramatic increase in beam quality. Glare and hot spots are virtually eliminated. With a smooth beam profile, the user is more likely to concentrate on the object he is illuminating—not a structured illumination pattern. The user does not have to scan the beam back and forth to make out details which may be masked by the beam structure. He should be able to complete an inspection more accurately, in less time, and with less fatigue than with the average flashlight beam.

LABORATORY MEASUREMENTS

As an illustration, several flashlight illuminance patterns with and without a light shaping diffuser were recorded. Figure 13 shows illuminance spot patterns from the MAG-LITE™, a commercially available flashlight from Industries, Ontario, CA, which is used widely in the aircraft inspection and maintenance industry, and figure 14 shows the same flashlight after a light shaping diffuser with a 5-degree scatter angle was installed. Both images were recorded with the flashlight 0.5 m from the surface at normal incidence. The diffuser has eliminated a significant hot spot from the beam. Figures 15 and 16 show a false gray scale representation of two similar cases. The images were recorded with a Beam View video camera and a computer-based system designed for the radiometric analysis of laser beams. All measurements were made with the flashlight illuminating the surface at an angle of 70 degrees from normal incidence. In all cases, the flashlight focus was adjusted for a minimum spot size. Contours of equal intensity are shown as horizontal and vertical profiles through the center of the beam. A curve which represents the best fit Gaussian profile to the beam profile is also plotted. Note how the beam uniformity is dramatically improved with the diffuser. Figure 15 shows significant departure from the Gaussian curve, while figure 16 very nearly matches the Gaussian curve.

Figures 17 and 18 show the effect of beam homogeneity on scene illumination. In both figures, the identical flashlight was set to the same beam spread and pointed at a USAF 1951 resolution target. A video camera recorded the scene. In both cases the lens aperture was set to maximize the peak scene signal. The flashlight with the diffuser clearly produces a superior image.

The LSD is available in various scatter angles. Figure 19 is a plot of the peak transmission of a LSD equipped flashlight for a variety of scatter angles. The data is normalized to the peak illuminance of the undiffused flashlight. Note that while an LSD with a wide-scatter cone will more uniformly homogenize a beam, the intensity will drop dramatically. This effect is most effectively demonstrated in figure 20, which graphs the beam profile of a defocused MAG-LITE versus various diffuser scatter angles for a fixed input beam, represented by the background image superimposed on the graph. It was empirically determined that a MAG-LITE works best with a 5-degree scatter cone in order to accommodate beam spread adjustments with the focusing reflector, but at a price of about 40 percent of the peak illumination of a non-LSD equipped flashlight. A 2- or 3-degree diffuser will raise the peak brightness to a level of about 70 percent, but at an expense of less overall uniformity. Other brands of fixed focus flashlights could probably benefit with narrower scatter angles, while broader scatter angles would benefit those applications requiring greater coverage, but at the expense of decreased peak illumination.

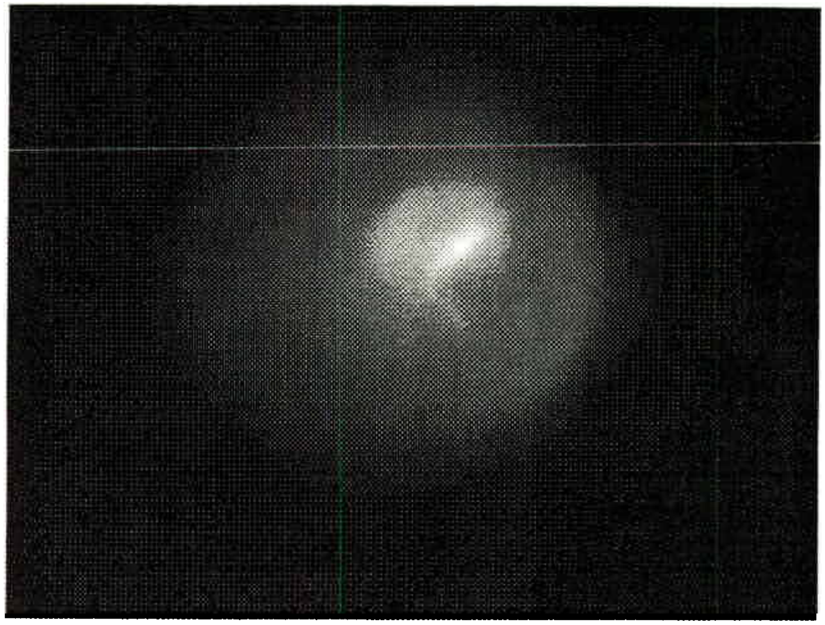

FIGURE 13. REPRESENTATIVE UNDIFFUSED MAG-LITE® ILLUMINATION PATTERN AT NORMAL INCIDENCE

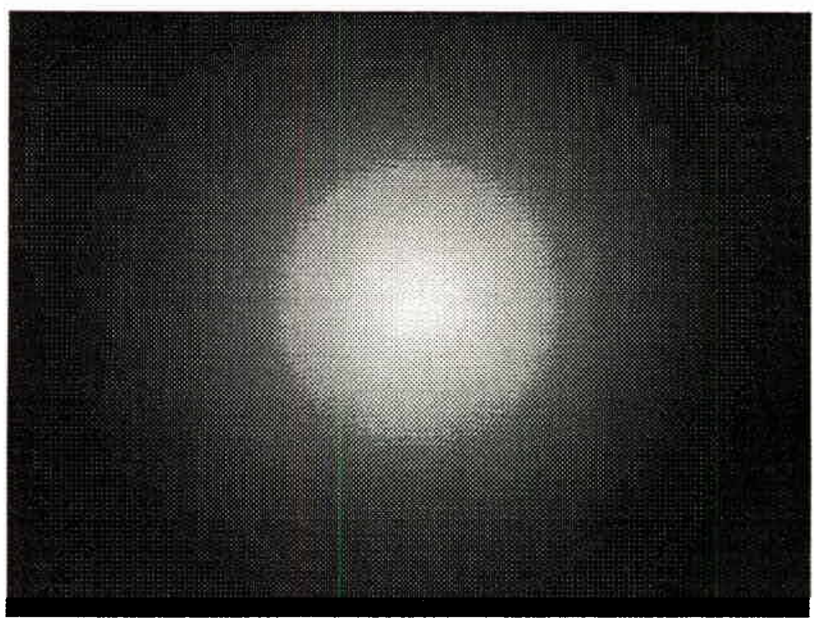

FIGURE 14. MAG-LITE WITH 5-DEGREE LSD, NORMAL ANGLE OF INCIDENCE. FLASHLIGHT IS SAME AS IN FIGURE 13.

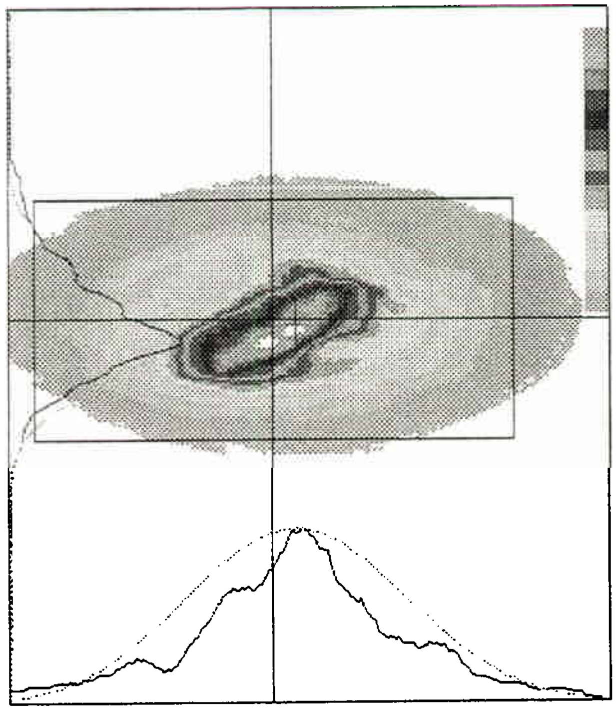

FIGURE 15. A BEAM INTENSITY PLOT OF A 3 D-CELL MAG-LITE WITHOUT DIFFUSER. ANGLE OF INCIDENCE IS 70 DEGREES FROM NORMAL.

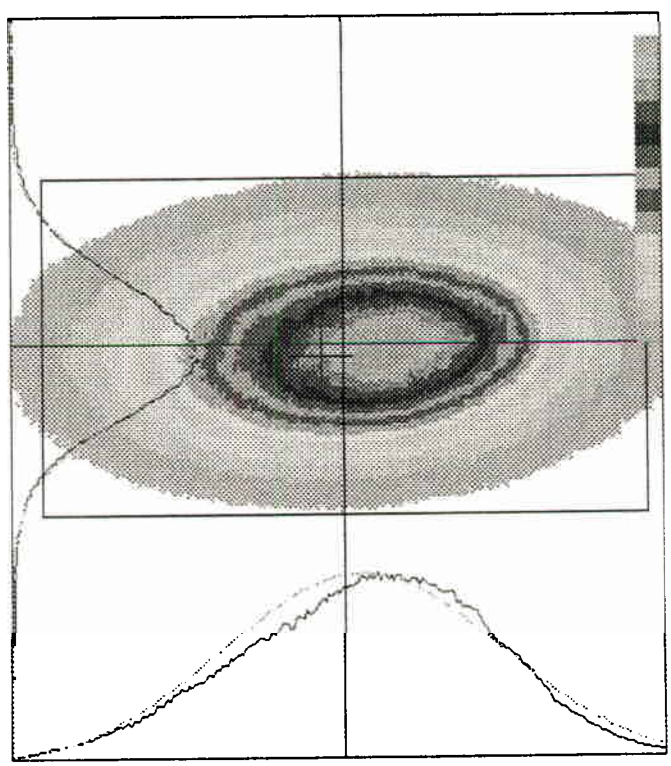

FIGURE 16. SAME FLASHLIGHT AS IN FIGURE 15 WITH A 5-DEGREE DIFFUSER. ANGLE OF INCIDENCE IS 70 DEGREES FROM NORMAL.

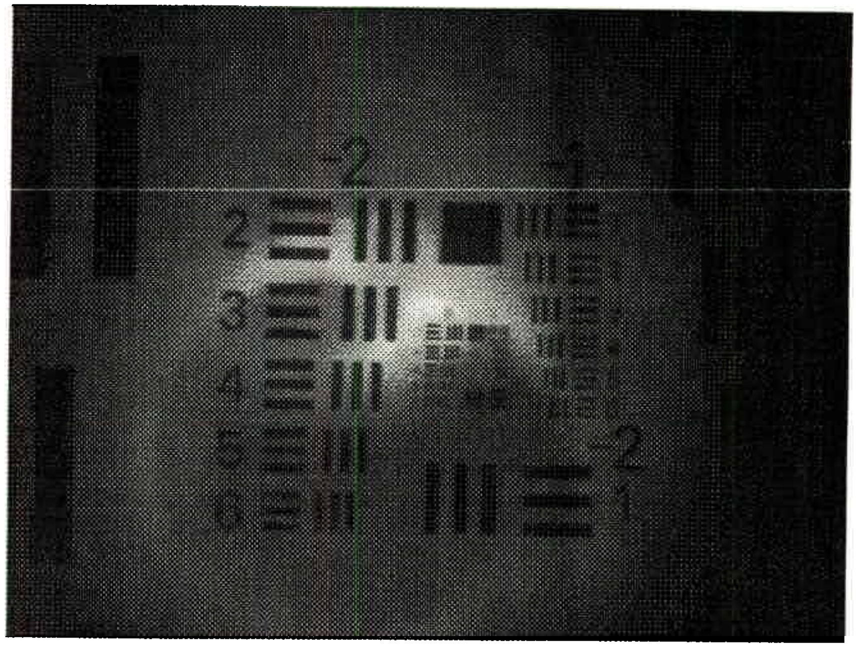

FIGURE 17. USAF 1951 RESOLUTION TARGET ILLUMINATED WITH UNDIFFUSED MAG-LITE FLASHLIGHT. FLASHLIGHT HAS BEEN DEFOCUSED.

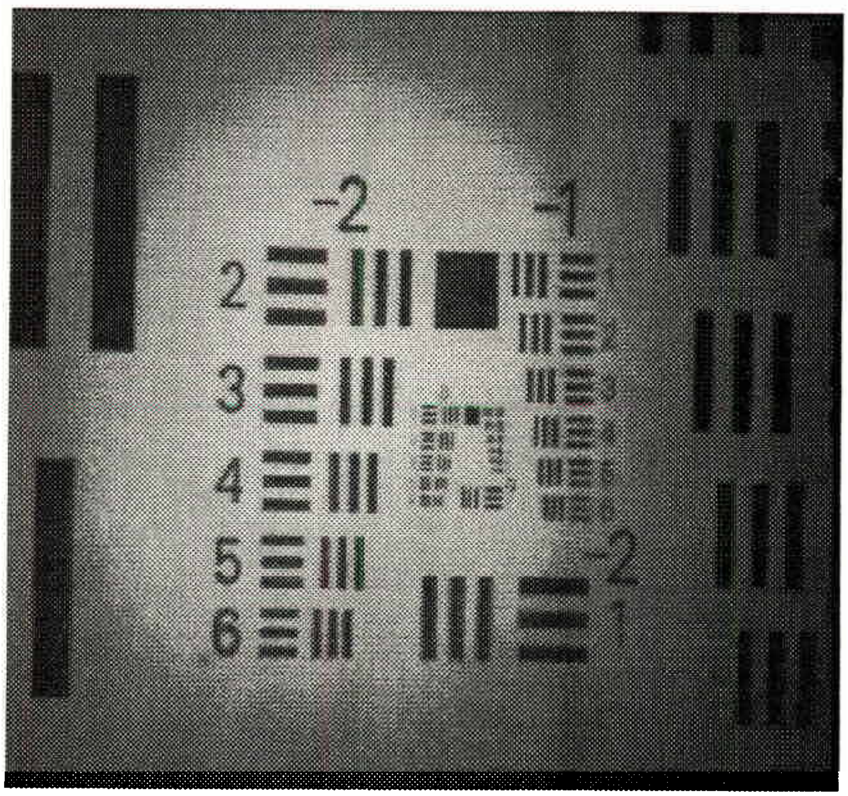

FIGURE 18. USAF 1951 RESOLUTION TARGET ILLUMINATED WITH LSD-EQUIPPED MAG-LITE FLASHLIGHT. FOCUS ADJUSTMENT IS SAME AS FIGURE 17.

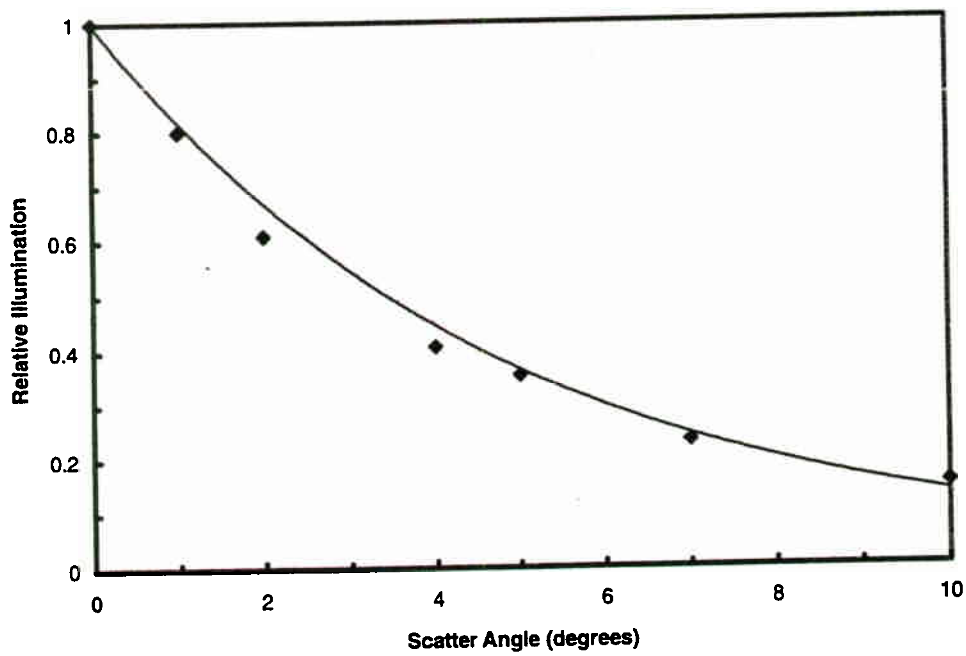

FIGURE 19. RELATIVE PEAK ILLUMINATION VERSUS LSD DIFFUSER ANGLE RELATIVE TO A MAG-LITE

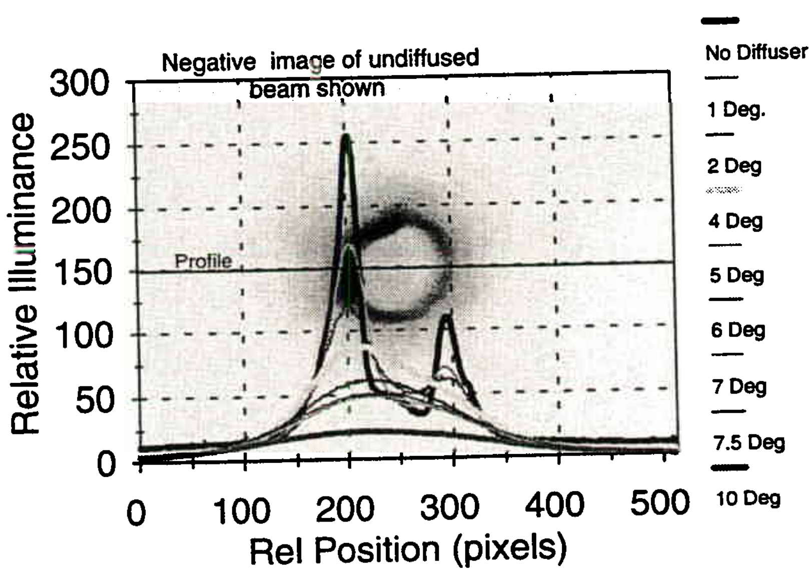

FIGURE 20. BEAM SPREAD PROFILE VERSUS DIFFUSER ANGLE. BEAM IS DEFOCUSED APPROXIMATELY THE SAME AMOUNT AS IN FIGURES 17 AND 18.

FIELD TRIALS.

While the figures demonstrate the improvement in beam quality using the LSD, nothing is quite as convincing as actual field tests. With the cooperation of several area airlines, flashlights were loaned to inspectors at two regional commuter aircraft maintenance facilities, Ross Aviation, Albuquerque, NM, and Mesa Airlines, Farmington, NM, and to inspectors at the American Airlines Maintenance and Engineering Center in Tulsa, OK, a major airline facility. Also, through the auspices of the Air Transport Association Nondestructive Testing Forum, LSDs were distributed to aircraft inspectors, who tested them for a period of several weeks.

REGIONAL COMMUTER FACILITY TRIALS. At the regional facilities, each inspector was given two otherwise identical 3 D-cell MAG-LITE flashlights which are widely available commercially and used by many aircraft maintenance personnel. One flashlight was unmodified, while the other was modified with a 5-degree LSD in place of the stock cover lens. The inspectors were allowed to use the flashlights for a period of one to three weeks. The inspectors were not told what the differences in flashlights were, but were told to use whichever of the two flashlights they preferred. At the end of the trial, each inspector was asked to answer a questionnaire, identifying his likes and dislikes about each flashlight and ranking the flashlights that he used. To assess the relative usage of the two flashlights, battery voltages were measured before and after the trial period.

All of the inspectors interviewed said they preferred the flashlight with the more uniform beam for close inspection work (viewing distances less than 20 inches). At least one inspector initially preferred the unmodified flashlight because the beam was brighter but then switched to the flashlight with the LSD because of the more uniform beam. Some inspectors even thought that the uniform beam was actually brighter, which was not the case.

A number of inspectors at a facility where most maintenance is done at night, preferred the flashlights without the LSD when performing general exterior walk around inspections on the ramp. This was due to the increased brightness of the unmodified flashlight and the requirement to look at surfaces 20 or more feet away from the inspector's position. At this range, the LSD equipped flashlight proved to be unsatisfactory. Some inspectors suggested that the LSD be made easily removable, as with a clip-on accessory for use when the greater illuminance was necessary. From this suggestion, a design concept was generated as shown in figure 21. This accessory slides over the end of the flashlight but is attached to the flashlight with a strap so that it cannot be misplaced.

All of the inspectors appreciated the improved quality of the beam using the LSD for close inspection work. Some inspectors were even unwilling to part with the LSD-modified flashlights at the end of the trial period—a worthwhile endorsement. Measurements of the battery voltages before and after the test period indicated that most inspectors used the LSD-modified flashlights at least six times more than the unmodified flashlights.

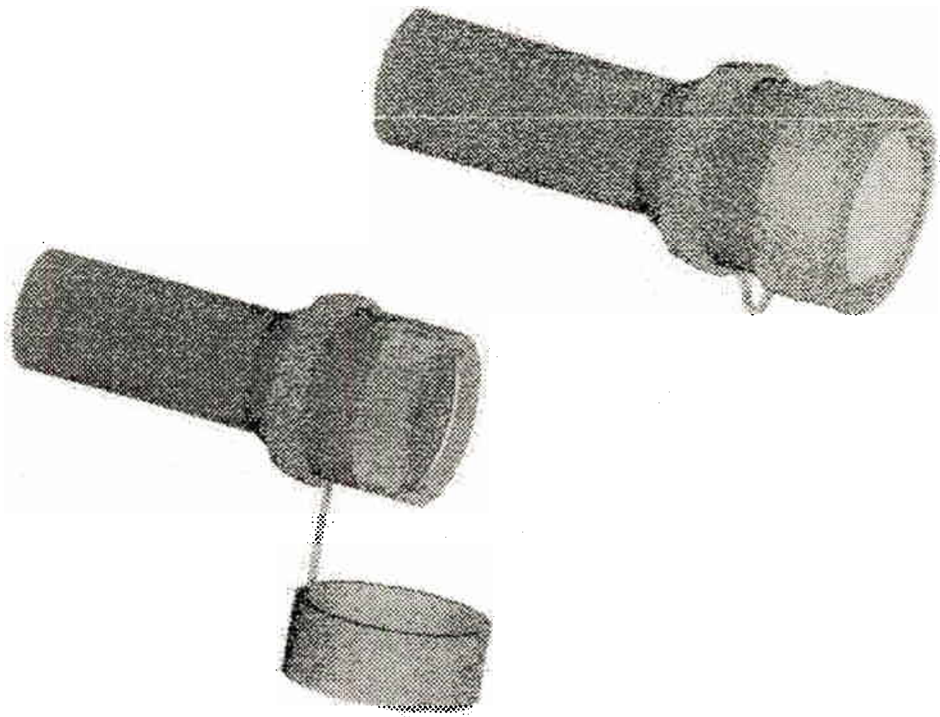

FIGURE 21. CLIP-ON LSD CONCEPT. "ON" (TOP RIGHT) AND "OFF" MODES SHOWN.

<u>MAJOR AIRLINE TRIALS</u>. At the major airline facility, inspectors were given only one 3 D-cell MAG-LITE brand flashlight and asked to compare the performance to their own flashlight. Both qualified visual inspectors and NDT inspectors were included in this part of the study. Unfortunately, this didn't prove to be as definitive as had been hoped, as the inspectors that were surveyed regularly use 2 or 3 C-cell sized MAG-LITE flashlights, which weigh substantially less than the D-cell size. Consequently it was found that the inspectors were inclined to prefer their own flashlights on the basis of size and weight alone. However, the bulbs and reflectors are physically identical between models, so it is reasonable to make an optical performance comparison.

Most of the participants noticed and liked the superior uniform beam provided by the 5-degree diffusers as compared to their own flashlights. However, several visual inspectors said that they would prefer the smaller spot of their own flashlights, while the NDT inspectors did not care about beam size. The NDT inspectors generally use flashlights for area illumination while they perform tests like eddy current or ultrasonic inspections. The visual inspectors prefer a more tightly focused beam, because they use a flashlight as a pointer with which they scan across the surface while following the spot with their eyes. Too large of a spot left them with too much area to scan at any one time.

Also, the visual inspectors may have noticed that shadows generated by the LSD-equipped flashlight were more diffuse than those generated by a stock flashlight. This is a reasonable concern, given that the LSD-equipped flashlight illuminates a surface with a moderate area diffuse source. Unlike a point source illuminator, a finite-sized diffuse source will cast both an umbra and a penumbra, which diffuses the shadow somewhat. Several inspectors felt that this interfered with their ability to see small cracks and other out-of-plane surface effects, but this may have also have been their reaction to viewing a larger spot than they are used to coupled with the lack of hot spots that they have been used to with their regular flashlights. Both of these concerns could possibly have been alleviated by using a diffuser angle narrower than 5 degrees, although the overall beam uniformity may be compromised with a narrower scatter angle.

WIDESPREAD INDUSTRY TRIALS. An opportunity was presented at the Air Transport Association Nondestructive Testing (ATA-NDT) Forum held in Albuquerque, New Mexico, November 1994. At this session, which was attended by over 350 airline inspection representatives, airline manufacturers, and other support organizations, 182 LSD survey packets were distributed to interested aviation representatives, including representatives from major air carriers, commuters, and foreign carriers. The packets contained a sample 3-degree LSD sized to fit in a C- or D-cell MAG-LITE, an informational article about the LSD, and a questionnaire (see appendix). The recipients were asked to forward the LSD packets to line inspectors within their organizations who used MAG-LITE flashlights for evaluation.

Of the 52 responses received within the following 8-week period, 90 percent were positive about the improved beam uniformity from an LSD-equipped flashlight, while 88 percent said that they would use the LSD if commercially available. On average, respondents rated LSD-equipped flashlights as having at least a one point improvement (on a 1 to 5 scale) over their unmodified flashlights, while perceiving no substantial difference in brightness between the two flashlights. Results of the survey are tabulated in table 3. The survey form and individual comments are given in the appendix.

While most comments were positive, several respondents expressed concern about resistance of the LSD to chemicals such as aircraft hydraulic fluid and degreasers, and several others were concerned about the cost of the component (given at $10 U.S. each). The price of the LSD is a sharp function of volume manufacturing costs and is expected to drop substantially in large volumes. While compatibility with solvents is a function of the substrate on which the LSD is manufactured—the LSD technology can be applied to a wide range of transparent substrates. Both of these issues will be addressed by the LSD supplier.

TABLE 3. RESULTS OF ATA-NDT FORUM SURVEY

Survey Question Rank (Score)	Poor 1	Fair 2	Good 3	Excellent 4	Superior 5	Mode	Mode diff. (LSD-Reg)	Avg.	Avg. Diff. (LSD-Reg)
4. LSD Close Inspection	0	1	8	20	23	5	2	4.25	1.27
5. Reg. Flashlight Close Inspection	0	16	24	9	3	3		2.98	
6. LSD Intermediate Inspection	0	4	13	25	10	4	1	3.79	0.87
7. Reg. Flashlight Interim. Inspect.	2	14	22	8	3	3		2.92	
8a. LSD Close Inspection	0	2	10	21	19	4	1	4.10	1.15
8b. Reg. Flashlight Close Inspect.	1	11	31	8	1	3		2.94	
9a LSD Brightness	0	8	17	18	9	4	1	3.54	0.15
9b. Reg. Flashlight Brightness	1	5	23	19	4	3		3.38	
10a LSD Beam Uniformity	0	1	6	13	32	5	3	4.46	1.92
10b Reg. Flashlight Uniformity	4	22	21	4	1	2		2.54	
11a LSD Fine Detail	0	1	8	23	20	4	1	4.19	1.2
11b Reg. Flashlight Fine Detail	0	9	32	11	0	3		3.04	

12. Did the LSD improve the flashlight beam over what you usually use	yes	47	90%
13. If the LSD were on the market, would you use it?	yes	46	88%
Total surveys distributed		182	
No. of surveys returned		52	29%

CONCLUSIONS

The representative sampling of flashlights evaluated demonstrates that, while most flashlights provide sufficient initial illumination according to accepted standards, little attention has been paid by flashlight manufacturers to the quality of illumination that is required for detailed visual inspection.

The Light Shaping Diffuser (LSD) is an effective means for converting a poorly uniform light beam into a smooth beam. A uniform beam may improve the quality of an inspection by reducing inspector eyestrain and fatigue. Ninety percent of inspectors responding to a survey distributed during the 1994 Air Transport Association Nondestructive Testing Forum said the LSD-equipped flashlight was an improvement over their standard flashlight.

The peak illuminance level from an LSD-equipped flashlight is lower than without the LSD by an amount which depends upon the scattering angle. However, the advantage of the uniform beam far outweighs the reduced illumination because the overall quality of the light is improved.

REFERENCES

1. Goranson, U.F. and Rogers, J.T., 'Elements of Damage Tolerance Verification," 12th Symposium of International Commercial Aeronautical Fatigue, Toulouse, France, May 1983.

2. Illuminating Engineering Society (1987). IES lighting handbook, application volume. New York: Illuminating Engineering Society.

3. Smith, S.W. and M.S. Rea: 'Performance of Office-Type Tasks under Different Types and Levels of Illumination," IERI Report, October 1976.

4. Illuminating Engineering Society (1981). IES lighting handbook, reference volume. New York: Illuminating Engineering Society.

5. Murdoch, Joseph B., Illumination Engineering—From Edison's Lamp to the Laser, Macmillan, NY, NY, 1985.

6. Reynolds, J.L., Gramopadhye, A., and Drury, C.G. (1992). Design of the aircraft inspection/maintenance visual environment. Unpublished final report (Contract No. DTFA01-92-R-08651). Federal Aviation Administration, Office of Aviation Medicine, Washington, D.C.

APPENDIX—LIGHT SHAPING DIFFUSER SURVEY, QUESTIONS, AND COMMENTS

Sandia National Laboratories

Albuquerque, New Mexico 87185-0615

Aging Aircraft Program

Questionnaire for *Flashlight/Light Shaping Diffuser* Study

Thank you for participating in this survey on Light Shaping Diffusers in inspection flashlights. Please replace your C- or D-cell MAG-LITE® (or equivalent) flashlight lens with the Light Shaping Diffuser provided. Install the shiny face out.

If you don't use a model of flashlight that will fit this diffuser, please pass this package along to someone who does. Use the flashlight for two weeks and answer the following questions.

Please Respond by December 15, 1994

Use the postage-free reply envelope provided

1. In what model flashlight did you install the Light Shaping Diffuser (LSD)? (Check all that apply)

   ☐ 2 C-cell ☐ 3 C-cell ☐ 4 C-cell Brand: ☐ MAG-LITE

   ☐ 2 D-cell ☐ 3 D-cell ☐ 4 D-cell ☐ Other____________________

2. What color bead is in your lamp filament?____________________
3. Please indicate any other identifying marks on the bulb base________________

Please answer the following questions by marking the corresponding number on the following scale.

[(1) Poor (2) Fair (3) Good (4) Excellent (5) Superior]

4. How would you rate the Light Shaping Diffuser equipped flashlight for "close" inspections (surface less than 1 foot from flashlight)?	1	2	3	4	5
5. Rate your non-LSD-equipped flashlight for "close" inspection?	1	2	3	4	5
6. Rate the LSD equipped flashlight for "intermediate" inspections (surface 1 to 6 ft. from flashlight)?	1	2	3	4	5
7. Rate your non-LSD-equipped flashlight for "intermediate" inspection?	1	2	3	4	5
8. Rank how well each flashlight helped you do your inspection tasks					
(a) LSD-equipped flashlight	1	2	3	4	5
(b) Your own unmodified flashlight	1	2	3	4	5
9. Rank the relative brightness of each flashlight					
(a) LSD-equipped flashlight	1	2	3	4	5
(b) Your own unmodified flashlight	1	2	3	4	5
10. Rank the relative uniformity (eveness) of the light beam from each flashlight					
(a) LSD-equipped flashlight	1	2	3	4	5
(b) Your own unmodified flashlight	1	2	3	4	5
11. How well could you see fine detail in your inspections with each flashlight?					
(a) LSD-equipped flashlight	1	2	3	4	5
(b) Your own unmodified flashlight	1	2	3	4	5

12. Did the LSD improve the flashlight beam over what you usually use? ☐ Yes ☐ No
13. If this LSD-device were on the market, would you use it in your inspection activities? ☐ Yes ☐ No

In your work, what properties of a flashlight do you consider important? Rank on a 1 to 5 relative scale, where 1 is least, and 5 is most important.

14. Ruggedness	1	2	3	4	5
15. Beam uniformity (eveness of beam)	1	2	3	4	5
16. Size	1	2	3	4	5
17. Weight	1	2	3	4	5
18. Brightness	1	2	3	4	5
19. Adjustable beam size	1	2	3	4	5

Exceptional Service in the National Interest

20. Are there other features you feel are important in a flashlight? (Describe)

____

____

____

____

____

21. Please state any problems/concerns that you may have with the LSD-equipped flashlight.

____

____

____

____

____

____

____

If you have any additional comments, they would be appreciated.

____

____

____

____

____

____

____

____

Your Name (optional)_______________________________

Your Telephone (optional)___________________________

Your Job title (please provide)_______________________

Airline/Maintenance Facility/Company__________________

Address____

City/State/Zip____________________________________

Thank you for your participation. The Light Shaping Diffuser is yours to keep.

ATASURV1.DOC No.________

Comments received from survey respondents to questions. The comments are listed in random order and are quoted verbatim. (Responses of "None", etc. omitted).

Question 20: "Are there other features you feel are important in a flashlight? (Describe)".

"A flash of colour on case to make more noticeable to ensure torch not left in aircraft structure"

"Brightness or intensity are the most important features. You never have too much light"

"I feel that the proposed cost of the LSD lens would prohibit its use. I have had my MAG-Charger for approximately five years and have replaced the lens at least 5 times because of breakage"

"Durability"

"Sky fluid (hyd fluid(caster base damages lens. If this LSD can be resistance to skydrol fluid damage (sic)"

"Have to be skydrol fluid resistance, if not the flashlight are slippy. Lens fogging and some time melt to spot (soft) (sic)"

"polarizer for flashlights, fluorescent bulb"

"SKYDROL Resistance are must"

"Bulbs that last longer"

"switch durability, corrosion resistant"

"Battery life, bulb life"

"needs to be adjustable for both close and intermediate inspections. needs to be as bright as possible, using small power source. Needs to be durable"

"Light bulb quality-grip-parts availability"

"good reflector variable switch good grip fuel proof rechargeable"

"Control Brightness & control beam size"

"Reliability"

"Reflectors made out of aluminum instead of plastic.-Plastic reflectors tend to crack easily"

"I wish bulbs were available with higher wattage (use nickel cadmium batteries and a bulb with about a 1.5A draw (5-6 watts) for short duration intensified inspection)"

"Beam uniformity as this lens gives; but for distance a clear lens of course works best."

"Availability of parts for repair"

"Compact, Hanger clip, Adjustable Focus"

"Safety (Shielded), Spotlight combined with fluorescent lamp."

"Compact Hanger clip, adjustable focus"
"Sustain 20 foot drop from top of aircraft to non-skid/cement deck. One annoying facet of most flashlights is design—lay a cylindrical object on top of aircraft, add pitching/rolling aircraft carrier—watch flashlight roll overboard!"

Responses to Question 21: "Please state any problems/concerns that you may have had with the LSD-equipped flashlight."

"The lens does not give enough variety to use in close & distant inspection uses. Very good light diffusion from one foot or closer."

"The LSD reduced the brightness or intensity of the light. The further away you are from an item being inspected, the dimmer the LSD appeared. In other words, the LSD lens used a lot of light energy, and the further away from a object the light got dimmer more rapidly

"Light intensity diminishes too much for use at distances 6 ft and beyond/however beam uniformity for close inspections is superior than non LSD equipped lamps."

"Not as bright as regular lens"

"I'd like to use the lens. However, the price as shown on your price list (11/1/94) combined with the 10 pc min. order make it unlikely that I will."

"light intensity at distance greater than 6 ft."

"no, only when use over 10 ft light lost about 20% of brightness"

"No, but brightness was drop down on far inspection."

"LSD material too soft"

"Loss of Peak Beam Brightness"

"Loss of beam intensity"

"Poorer light intensity over 1 ft distances"

"At more than 3-5 ft. away, the beam is weaker than normal and difficult to work with. with close-up work, the beam is very effective. I don not feel the advantages outweigh the price, especially for versatility."

"Price and how well lens will hold up to abuse!"

"Impact resistance and effects of harsh chemicals"

"When inspecting airplanes the flashlight is exposed to various chemicals; hydraulic fluids, that may damage the lens. Plastic diffuser lenses could easily be damaged by these fluids."

"Beam intensity at distance beyond 6 ft."

Responses to Question 22: "If you have any additional comment, they would be appreciated."

"The LSD would be great for reading. I tested many different ways to be fair, but each time I came to the same conclusion, as previously noted above."

"The LSD is a definite improvement in terms of visual aids; however more emphasis should be placed on developing flashlights with an improved bulb/reflector/lens combination which will provide the Brightness & Beam uniformity required for carrying out AI"

"I would like to know if the LSD is SKYDROL or fuel resistant"

"The LSD was much easier to use when used in conjunction with a mirror, especially when holding the light close to the eye and reflecting back in a mirror. With the LSD it seemed less likely to get the light back in your eye instead of where you want it. "

"This is and outstanding device. Before I installed the LSD in my flashlight the wide angle feature was almost useless"

"This LSD was test in our pacific sta. (Tokyo) NRT Japan. For 1 week test due request to return in 2 weeks. Overall feedback from insp. are excellent. They wish to try out wide LSD angle for their walk around inspection"

"This test was feedback from Pacific Sta. TPE Taiwan Inspector. Inspection working on engine inspection. At far end inspection the LSD still provide a uniform beam only the brightness goes down. They like to try out the wide angle LSD"

"Wants wide beam more uniform"

"This are feed back return from Pacific sta. HKG Hong Kong insp. They use for cabin lighting wire inspection and general inspection inside cabin on B-747-400 access system. They did not encounter any brightness loss due all lights cond. are w/ 4-6 ft areas"

"expensive"

"The LSD eliminated the dark spots in the center of the beam"

"reflector should be clear"

"the LSD is perfect for close quarters inspection on aircraft. This survey was filled out by L Giacoman after giving the LSD to 4 different quality control inspectors for the evaluation of the product."

"I am 100% satisfied with your product. The eveness of the beam is remarkable when compared to a conventional non-LSD lens. However, I believe that a "glass" model of an LSD lens which incorporates the same characteristics of plastic. LSD lenses would be a plus "

"Try to lower the cost below the stated $10.00 per unit. Make them available for mini-mag lights and Head lamp by Justrite No. 1904 (2.250" Dia.)."

"Quality flashlights other than MAG LIGHT are not available."

"Congratulations, excellent development"