Demonstration and Assessment of a Sulfur Lamp Retrofit Lighting System at Hill Air Force Base, Utah

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Dedication

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Summary

In late 1997 and early 1998, a partnership between government and industry combined efforts to replace the lighting in a hangar at Hill Air Force Base (HAFB) in Utah with new sulfur lamp (S-lamp) systems as part of a project to test and evaluate the technology. S-lamps use microwave energy to produce a plasma that emits a high level of visible light across a broad color spectrum, and they promise efficiency savings compared to conventional high intensity discharge lamps in comparable applications. Fusion Lighting, Inc., which developed the technology with assistance from the US Department of Energy (DOE), initially introduced the product as the Solar 1000™ lamp in 1994 and replaced this version in the fall of 1997 with an improved model, the Light Drive™ 1000.

The test space is located in a 284,000 square foot area in a building that houses maintenance and rebuilding activity for F-16 and C-130 aircraft at the base. Part of the area has a low ceiling, requiring hollow light guides, developed by 3M Corporation, to distribute the high intensity light with adequate uniformity. The remainder of the area has a high enough ceiling to permit the use of more traditional high-bay luminaires adapted for S-lamps by Cooper Lighting. In all, 288 Light Drive™ 1000 lamps have been installed, 50 in each of four high-bay areas, and 88 in the low-bay area at the ends of 44 tubular light guides, each 104 feet long.

With DOE program direction and financial support, Pacific Northwest National Laboratory (PNNL)[1] undertook to assess the efficiency and performance of the system. Both before and after installation, PNNL collected data characterizing lighting level and color, as well as electric energy consumption and power quality characteristics, for a section of the low-bay area and a section of one of the four high-bay areas. Because the lighting that was replaced by the S-lamps was antiquated, PNNL also developed a conceptual scheme for lighting the areas with conventional modern metal halide low-bay and high-bay downlight luminaires for purposes of comparison. Finally, the lab administered pre- and post-installation surveys of building occupant responses to gain insights into worker satisfaction and possible impacts on productivity.

The following findings resulted from the assessment:

- S-lamps produced lighting levels that were approximately 39 percent to 47 percent higher in the low-bay area, and 130 percent to 160 percent higher in the high-bay area, compared to the conventional high-intensity discharge systems they replaced.

- The S-lamp high-bay luminaires generally exceeded the 75 foot-candle lighting level target by 25 percent, while the light guides in the low-bay area fell short of the same target by approximately 19 percent.

- Characterized in terms of the CIE Uniform Chromaticity Scale, the new and old systems produced similar coloring on surfaces. S-lamps appear to provide greater uniformity in the high-bay area.

- Energy consumption increased by 63 percent in the high-bay area with the installation of the S-lamps. This was due to the inadequate lighting in place beforehand, the requirement to use preëxisting fixture locations that were closer than optimally-spaced, and the addition of 16 more S-lamps to illuminate side and storage areas not previously lighted. Had all of the pre-retrofit lamps been working and the 16 additional side lights not been installed, the high-bay energy consumption would have increased by only 26 percent and still provided at least twice the light level. In the low-bay area, energy consumption decreased by 42 percent, where the light guides replaced inefficient fixtures.

- Compared to an appropriately designed lighting system to achieve comparable lighting levels with metal halide lamps, the S-lamps in the low-bay area would consume 17 percent less energy, and the ones in the high-bay

[1] Pacific Northwest National Laboratory (PNNL) is operated for the U.S. Department of Energy by Battelle Memorial Institute

would consume 37 percent less. The difference in savings is due primarily to losses in the light guide arrangement needed to compensate for the lower ceiling in the low-bay area.

- As measured at individual lighting circuits, the S-lamps' power factor, total harmonic distortion (THD) and crest factor were approximately 99 percent, 2.7 percent and 1.4 respectively. These figures are similar to pre-installation values, except for THD, which was between 7 percent and 16 percent beforehand. Metal halide lamps typically have THD values around 19 percent.

- Workers in the building reported being able to read samples of small type on the occupant survey more easily after the S-lamp installation than before. Compared to pre-installation conditions, fewer workers perceived flicker from overhead lights as a problem, while more were bothered somewhat by reflections on computer screens, possibly due to the increased light levels from the S-lamps. Because defective fixtures were replaced in the low-bay area after the the post-installation survey was administered, the responses do not fully reflect the performance of the lighting now in place. The later replacements probably enhanced the ability of workers to read small type and increased the reflections on computer screens compared to what was reported.

Table of Contents

Demonstration and Assessment of a Sulfur Lamp Retrofit Lighting System at Hill Air Force Base, Utah

Introduction

This report presents the results of an assessment of a large commercial application of sulfur lamps, or S-lamps, developed by Fusion Lighting, Inc. with support from the US Department of Energy (DOE). Demonstrated as a prototype for the first time in 1994, the S-lamp embodies a new, microwave-powered, electrodeless technology that promises improved energy efficiency and color rendition compared to most available lighting sources.

In late 1997 and early 1998, CES/Way International, Inc. installed Fusion Lighting's Light Drive™ 1000 lamps to replace conventional lighting at Hill Air Force Base (HAFB) just south of Ogden Utah. CES/Way financed the acquisition and installation of the new system under the terms of an energy saving performance contract with the Air Force, and Utah Power provided incentives under their demand side management program. In conjunction with the new lamps, Cooper Lighting furnished specially designed downlight fixtures for part of the installation, and 3M Corporation supplied a light guide system using a proprietary prismatic film. In order to provide quantifiable information for those considering installing the technology, DOE undertook, through the efforts of Pacific Northwest National Laboratory (PNNL), to obtain data characterizing the lighting quantity and quality of the retrofit and existing system including energy use, power quality, light levels, color rendering and human responses.

The report begins with a brief summary of the history of sulfur lamp technology and highlights the features of the first commercial product, the Light Drive™ 1000. It then discusses the technology and associated light guide technology and the previous applications of the S-lamp. The remainder of the report is devoted to the analysis of two types of application at the base. One involves geometry and task requirements associated with light industrial applications, so the outcomes will be broadly applicable to other similar installations. The other is a high-bay application, and the information and design details will be relevant to that segment of the market place.

Background

Sulfur Lamp Development

Using microwave energy to produce sulfur plasma that emits a high level of visible light was first introduced in 1992 (Dolan, Ury, and Wood 1992). Prior to this time microwave discharges were used to produce ultraviolet (UV) light for industrial applications but had not been applied to producing visible light. The research prior to 1992 had not indicated that output of the visible spectrum would occur with the sulfur. Other researchers had explored the use of sulfur in electrodeless discharges and found efficiencies in the 11 - 13 percent range. However, the current sulfur source developed by Fusion Lighting has an efficiency of around 50 percent. In this application, spheres are filled with noble gas and a small dose of sulfur at less than one atmosphere. When bombarded with the microwaves from the Fusion microwave system the sphere exhibits between 2 and 5 atmospheres of sulfur vapor that forms the plasma medium that produces visible light by molecular radiation.

Research toward understanding the mechanisms and phenomenon of producing a broad-spectrum visible light with microwave energy has progressed rapidly. Initially, the efficiency of producing light by this method was questioned because of the low efficiencies of the existing magnetrons and the associated equipment for producing the microwave energy. Demonstration installations have been made with high power (>3 kW microwave power) at the Smithsonian National Air and Space Museum (NASM), the USDOE Forrestal Building, and the Sacramento (California) Municipal Utility District.

In the NASM application, three 90-ft long light guides replaced the 94 conventional fixtures in the "Space Hall." Each guide used a single 3 kW S-lamp system consuming 5900 watts. These light guide systems in the NASM emitted approximately 120,000 lumens per guide. The results in the museum were very positive resulting in an increase in light levels by a factor of three while reducing energy use by 25 percent and unwanted UV by a half. The installation at the Forrestal Building used a single 240-ft light guide which was powered by two 3kW S-lamps, one located at each end of the guide. This system consumed approximately 11,800 watts and produced approximately 185,000 lumen output. This replaced the 240 conventional fixtures each using a 175 watt source previously used to light the entrance and roadway outside the building. The installation reduced energy consumption by two-thirds and increased light levels by four. At the Sacramento Municipal Utility District, S-lamps were mounted on pedestals with mirrors designed to project the light on the ceiling, thereby illuminating a large reception area.

Development of the technology has progressed rapidly and is continuing to be refined. Application of the S-lamp system to different types of spaces is a logical step in development and commercialization. Possible applications include sports lighting, large retail stores, shopping malls, manufacturing facilities, assembly lines, subways and tunnels, and aircraft hangers.

Recently, a smaller wattage and potentially more applicable sulfur lamp has been produced and is available for use. This lamp, the Light Drive™ 1000, produces nearly 150,000 lumens with a system input wattage of 1350. The Light Drive™ 1000 uses an argon gas fill with small amounts of sulfur that are sealed in a glass bulb approximately 38 mm in diameter. The bulb is mechanically rotated in a wire mesh screen that forms a microwave cavity. The bulb is excited by microwave energy, producing a plasma that emits high intensity visible light. The current demonstrated whole system efficacies are approximately 110 lumens per watt. The S-lamp whole system efficacy accounts for the losses in the microwave generator and the associated electronic components. To compare the Light Drive™ 1000 to the metal halide and high-pressure sodium lamps, the whole system efficacy must be used because of the difficulty in measuring power delivered directly to an electrodeless lamp.

The predicted life of the S-lamp is based on the electronic components and not the lamp bulb itself. The life of the current technology microwave magnetron is projected at approximately 15,000 hours, while the life of the bulb is estimated to be considerably longer. The other components in the system that may fail include the ballast, transformer, and the motor that rotates the bulb. The bulb being electrodeless results in very low lamp lumen depreciation.

Light Guide Development

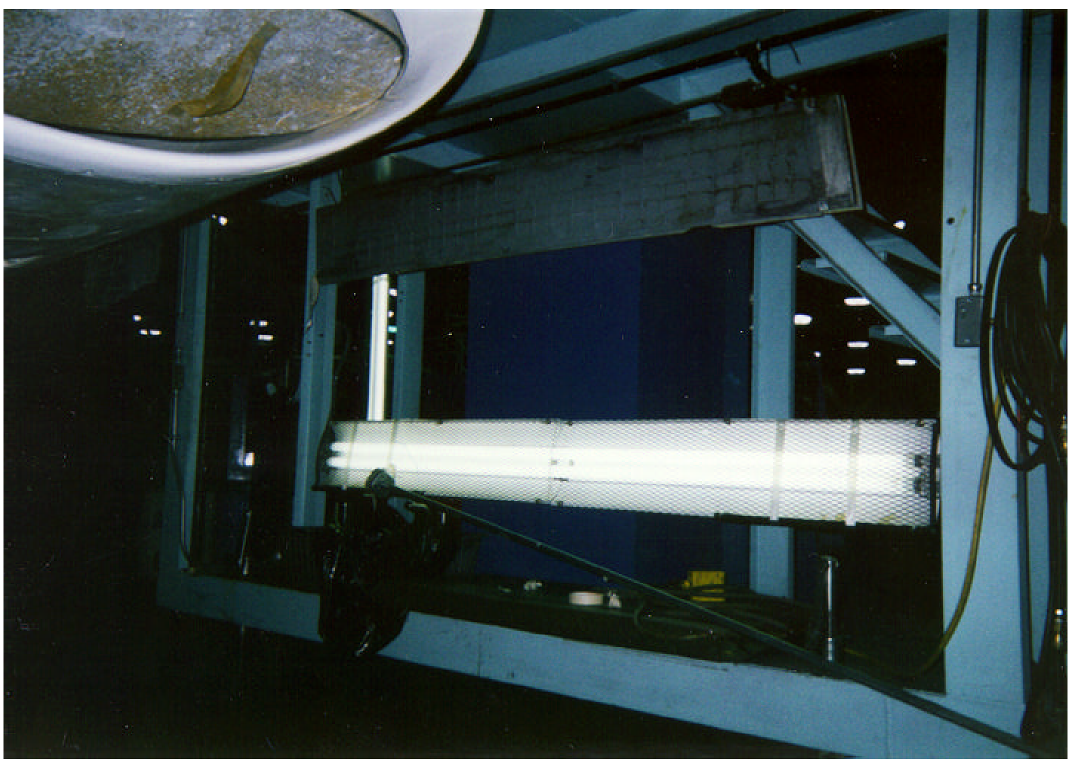
In present applications, the S-lamp source has generally been coupled with a hollow light guide (CIE Technical Committee 1995) as a distribution medium for the high lumen output of the Light Drive™ 1000. The use of hollow light guides has a long history. A hollow light guide is essentially an internally mirrored tube that will transport light from a source to another location. A surge of work occurred in the 1880s with the advent of the high power electric carbon arc lamps. The problem became expense and the efficiency of the mirrors. Over several years, new developments in materials yielded partial solutions to the problems. First was the development of a solid dielectric high efficiency guide using total internal reflection (TIR) which had no absorption of the reflected light rays like the metallic mirrors. A second development involved the application of data from a 1946 publication by Henry Pearson of the Rohm and Haas Company describing the use of acrylic rods and sheets. These materials would allow continuous light emission. However, it was difficult to inject enough light to make them useful. The improvement in optical fibers and the advent of inexpensive high quality polymeric films allowed further development. In 1965, in the former Soviet Union (USSR), the use of a metallic mirrored hollow light guide was proposed and eventually patented in 1975. Eventually, over 47,000 of these devices were installed.

In 1978, Dr. Lorne Whitehead at the University of British Columbia developed the concept of a hollow light guide utilizing total internal reflection rather than metallic mirrors. This device was called the prism light guide, which used transparent walls containing right angle prisms such that light rays continue propagating along the guide. In 1983, these devices began to be manufactured and have been used in North America, Japan, and Europe. They are used in many different applications, with sources ranging from 50 watts to 100.000 watts. The development of precision prismatic film by the 3M Corporation in St Paul, Minnesota hastened the growth of this type of lighting system. However, the precise prisms required in the walls of the light guides were a significant problem to properly produce and control and resulted in excessive manufacturing costs. The advent of the precision prismatic film in 1985 made it practical to produce large prismatic structures that serve as hollow light guides. The development of the hollow light guide continues and at least 15 organizations offer or are developing fixtures for various applications. The size and intensity of the S-lamp system makes it an ideal source for use with various light distribution devices.

Field Test Setup

The test facility is Building 225 at Hill Air Force Base (HAFB), just south of Ogden Utah and approximately 25 miles north of Salt Lake City. This facility is one of several large aircraft repair buildings on the base. Building 225 includes four separate high-bay hangar areas (north and south ends), two large internal low-bay areas (east side), and two large internal mid-bay areas (west side). The four high-bay areas are 200-ft by 250-ft and each is capable of housing up to three C-130 and two F-16 aircraft for maintenance and rebuilding. Each of the low-bay and mid-bay areas (total of four) are 120-ft by 350-ft and include two rows of docking spaces for F-16 aircraft repair with up to seven docks per row. This set of areas is characteristic of the various repair and rebuild activities that are a day-to-day routine at HAFB. These areas typically operate two shifts per day, depending on the backlog of aircraft. Activity includes mechanical repair, electrical systems overhaul, general maintenance, disassembly and re-assembly, surface repair, painting, and other repair functions.

The internal low-bay areas in the east half of Building 225 and all four high-bay areas were included in the Light Drive™ 1000 retrofit project. The mid-bay areas in the west half were previously retrofitted with new standard metal halide fixtures and were not considered in this evaluation. The east half of Building 225 and all four high-bay areas have a total area of 284,000 square feet. The high-bay areas (at the north and south ends of the building) are each lighted with a total of 50 Light Drive™ 1000 lamps. Each area includes 42 high-bay luminaires (45 feet off the floor) with sealed clear lenses and Light Drive™ 1000 lamps that replace the pre-retrofit lights on a one-for-one basis. An additional 8 Light Drive™ 1000 lamps with reflectors feed four light guide systems along the east and west sides of each high-bay area where no lighting existed before. These light guides illuminate the side mezzanine and under-storage areas in the high-bay spaces. The two internal low-bay areas are lighted with a total of 44 (22 each) light guide systems, each 104 feet in length and each with two Light Drive™ 1000 lamps (one at each end) for a total of 88 lamps. The under-aircraft task lights were not removed or modified as part of this lighting test case.



The areas directly under the wings of the aircraft are too dark under any typical lighting system for effective maintenance and therefore require additional task lighting. Figures 1. and 2. show the general location of these task lights.

Figure 1. Task Light Under Wing - Front View

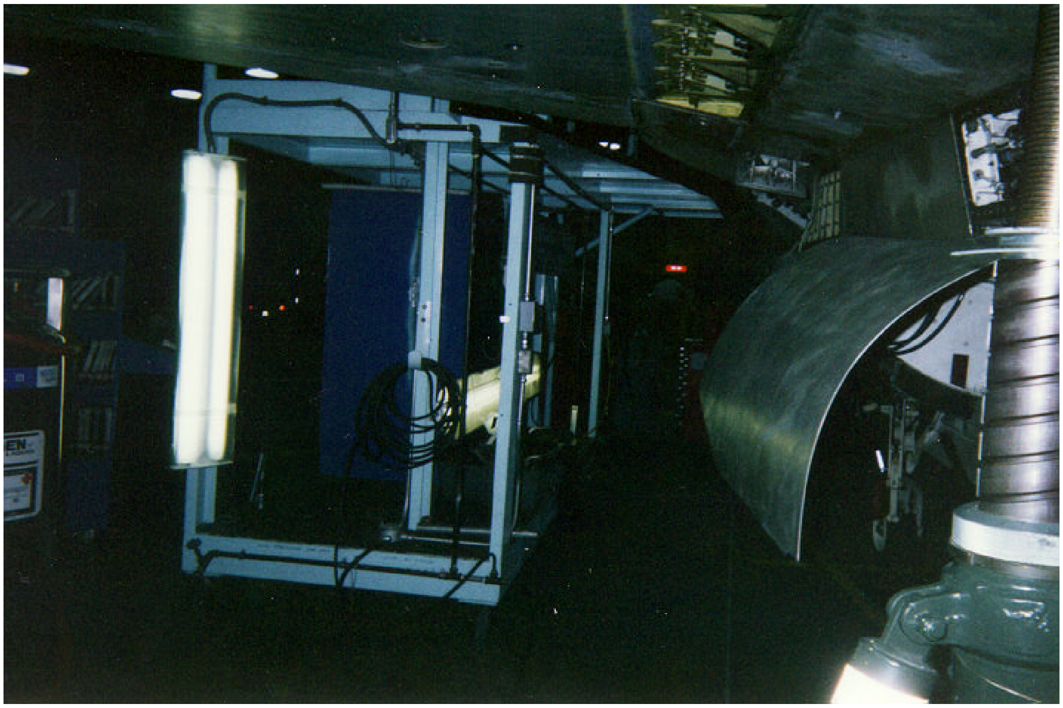


Figure 2. Task Light Under Wing - Rear View

The actual lighting characteristic measurements were taken in two test spaces. The first was the entire F-16 dock area #45 with its adjacent aisleway (125 feet by 150 feet). The second test space was the southwest portion of the northeast high-bay area (hanger 2) which includes the area under a C-130 aircraft and its associated aisleway and storage space (140 feet by 150 feet). These spaces were representative of typical operations and retrofit installation and were of reasonable size to capture any changes in lighting characteristics.

After the initial retrofit installation in early 1998, light levels in the low-bay area began to deteriorate due to darkening of the reflectors in the sulfur lamp fixtures at the ends of the light guides. After investigation by Fusion Lighting and Cooper Lighting representatives, the cause was determined to be solvent and fuel fumes reacting to the reflective coatings causing degradation of the reflective ability of the fixture. During the summer, the degraded fixtures were replaced with a redesigned fixture that included a completely sealed enclosure and a small reduction in light generation (6 percent reduction in power consumption, 9 percent reduction in light output) to reduce any excessive heat buildup caused by the complete sealing.

The original post-installation measurements and the occupant survey described below, occurred shortly after the initial fixtures were placed in operation. After the replacement of the fixtures with the new design models, the light level and electrical measurements were retaken in the low-bay area where the degradation had occurred. The light levels and electrical consumption presented here correspond to the improved fixtures, which produced better lighting than before, despite the reduced lamp output. The occupant survey, however, was not repeated, so the responses correspond to the original installation with lower light levels in the low-bay portion of the facility.

Data Collection and Survey Administration

The function, effectiveness, and operational characteristics of the pre- and post-retrofit lighting systems in Building 225 were defined by specific measured electrical and lighting characteristics data points as well as occupant reactions. This data was used to identify and quantify differences between the systems, which would assist an energy manager in determining the effectiveness of an application of this new technology in their facility. Each lighting system was characterized with color measurements, light level measurements, power consumption, and electricity supply data. An occupant survey was also administered to gauge the reaction of the occupants with respect to both lighting systems.

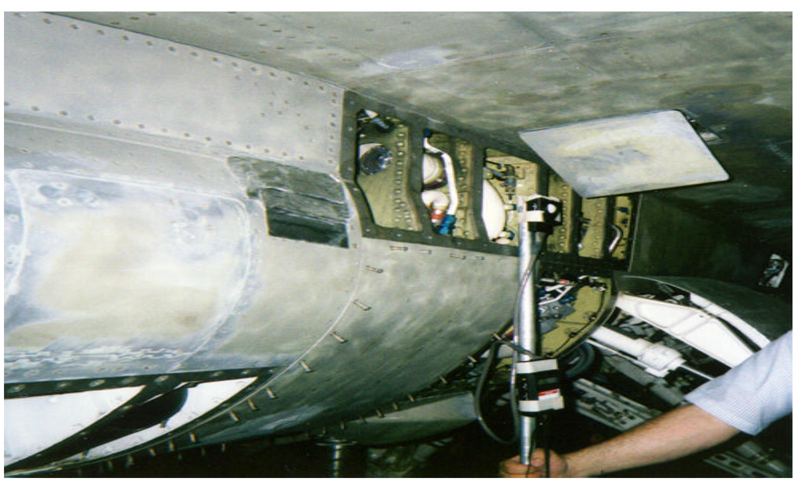
Color Measurements

Color measurements were made in both the Dock 45 and Hangar 2 areas. These consist of grid or random measurements of the true color of the light as it reaches the floor in an open area. The measurements were taken with a Minolta Chroma Meter CL-100 in coordinates of the Uniform Chromaticity Scale (UCS) of u' and v'. These units are used with the 1976 Commission Internationale de l'Eclairage (CIE) diagram to determine the color of a similar brightness object with respect to others (Lighting Handbook 1995). The values were also converted to x and y values for use in the 1931 CIE Chromaticity Diagram.

Light Level Measurements

Light level readings (in foot-candles) were taken 30-in. off the floor and 100-in. off the floor. Each set of measurements was taken at specific points on a grid covering the test areas. The Dock 45 test area covers a total of over 17,000 square feet with 66 measurement points on a 12.5-ft by 12.5-ft grid. The grid was laid out and marked on the floor. Tripod and a pole, or stair units with level bubbles attached, were used to get reasonably accurate measurements at 30-in and 100-in. Vertical foot-candle measurements were also taken at critical maintenance points below and above the wings of the aircraft. Figure 3 shows the format for these measurements. Measurements were taken with a Minolta T-1 illuminance meter.

Figure 3. Vertical Foot-candle Measurements - Under Wing



Power Consumption

Measurement of the complete lighting system at one metering point was not possible with the existing configuration of the multiple lighting and mixed panels. Instead, the measurements were taken for several circuits with amounts and types of existing lighting known for that circuit. This data, along with accurate lamp type and quantity counts, enabled the calculation of an estimated total power consumption value for the test space. Power consumption was measured with a Fluke 41 power harmonics analyzer.

Electricity Supply Data

Other characteristics of the lighting electrical supply were also measured to understand any potential differences in the effect of the lighting systems on the facility power supply. The same Fluke 41 analyzer was used to collect root mean square (RMS) voltage and current, crest factor (CF), total harmonic distortion (THD), and power factor (PF).

Occupant Survey

A survey of the occupants of the hangar areas being retrofitted was used to try to identify any effect the lighting retrofit may have had on the occupants and their operations. The dependent variables of concern in this evaluation generally fall under the categories of visual effectiveness and visual satisfaction. These variables relate to how effective the lighting is, and how well accepted it is by the occupants. The independent variable in this evaluation that will potentially affect user behavior and job satisfaction is the lighting type (existing lighting vs. Light Drive™ 1000 lamp system). The measure for this study is a seven-point self-evaluation questionnaire filled out by occupants on a pre- and post-retrofit basis.

The questions cover brightness, reflections, glare, physical discomfort associated with the eye, and suitability of the light for the tasks they perform. Many extraneous variables exist that could confound the study, and these are addressed or measured to ensure valid results. These variables include age, glasses/contacts, sickness, use of task lighting, background contrast and lighting distribution, and type of task. See Appendix A for a complete copy of the survey.

A standard statistical method was used to determine the approximate survey sample size needed to provide meaningful results. For this test analysis, an estimated error value of 0.5 was chosen representing a fairly tight distribution of responses around the expected response (Snedecor and Cochran 1980). To achieve statistical significance at a 95 percent confidence level with these conditions, at least n=24 occupant responses are needed. From 200 to 300 surveys were made available to ensure that at least the minimum required 24 occupant responses were received under both lighting systems. A total of 86 responses were received for the pre-retrofit conditions and 112 responses for the post-retrofit conditions.

The survey was distributed by HAFB staff to a random set of occupants. The confidentiality of the occupant responses is maintained through a coding system to ensure there are no concerns over potential misuse of the response information. This coding also provides the means of matching specific before and after responses. Prior to retrofit of the existing lighting, a letter of introduction and explanation of the survey was distributed by Hill staff to the selected occupants. This letter requested their voluntary participation in the survey and included the survey form for their response. After the retrofit, the survey was administered again to the same potential group of occupants to get their response to the new lighting system.

Color Comparison of Pre- and Post-Retrofit Lighting Systems

The color measurements taken in the test spaces in Building 225 generally indicate that both the pre- and post-retrofit systems provided reasonably consistent color on working surfaces. Tables 1 and 2 provide the average (and minimum and maximum where applicable) CIE coordinate measurements for each lighting system. The minimum and maximums indicate a fairly uniform color rendering of the lighted space with both pre- and post-retrofit systems for the Dock 45 area (low-bay). However, there does seem to be some variation in the pre-retrofit color in the high-bay areas. This may be caused in part by the fact that individual open high-bay luminaires can illuminate specific areas directly below them without as much additional light from surrounding fixtures. In low-bay applications with low-bay lensed fixtures (distribution of light out towards surrounding area) the mixing of light from groups of fixtures is more probable.

Table 1. Dock 45 (F-16), Hill AFB, Building 225

Pre-Retrofit Color Measurement - March 21, 1997

CIE 1976	u'	v'	y	x
AVERAGE =	**0.2257**	**0.5029**	**0.3789**	**0.3827**
MINIMUM =	0.224	0.502		
MAXIMUM =	0.227	0.503		

Post-retrofit Color Measurement - April 13, 1998

CIE 1976	u'	v'	y	x
AVERAGE =	**0.186**	**0.511**	**0.414**	**0.338**
MINIMUM =	0.184	0.511		
MAXIMUM =	0.187	0.512		

Table 2. Hangar 2 (C-130), Hill AFB, Building 225

Pre-Retrofit Color Measurement - March 21, 1997

CIE 1976	u'	v'	y	x
AVERAGE =	**0.2107**	**0.5011**	**0.382**	**0.3614**
MINIMUM =	0.198	0.492		
MAXIMUM =	0.218	0.508		

Post-Retrofit Color Measurement - April 13, 1998

CIE 1976	u'	v'	y	x
AVERAGE =	**0.1936**	**0.494**	**0.3758**	**0.3314**
MINIMUM =	0.193	0.492		
MAXIMUM =	0.195	0.497		

Figures 4 and 5 show representations of the CIE 1931 (x,y) and CIE 1976 (u', v') charts that are used to graphically represent the position of the color of each area with respect to others. The graphical presentation of color is not a perfect basis for comparison because of all the external factors that effect the way the human eye perceives lighted objects. However, the close grouping of these plotted points indicates that both systems (predominately metal halide vs. Light Drive™ 1000 lamp) provide similar coloring on surfaces.

This does not indicate the color that is observed when viewing the light sources themselves. The pre-retrofit lighting included metal halide and mercury vapor sources that have different appearances. The metal halide sources are also known to experience wide color shifts over their life creating even more variation in source color appearance. The post-retrofit Light Drive™ 1000 lighting system has, to date, not shown any signs of this type of characteristic light source shift.

Portion of the CIE 1931 (x,y) — Chromaticity Diagram

showing the Planckian locus and a set of ISO temperature lines

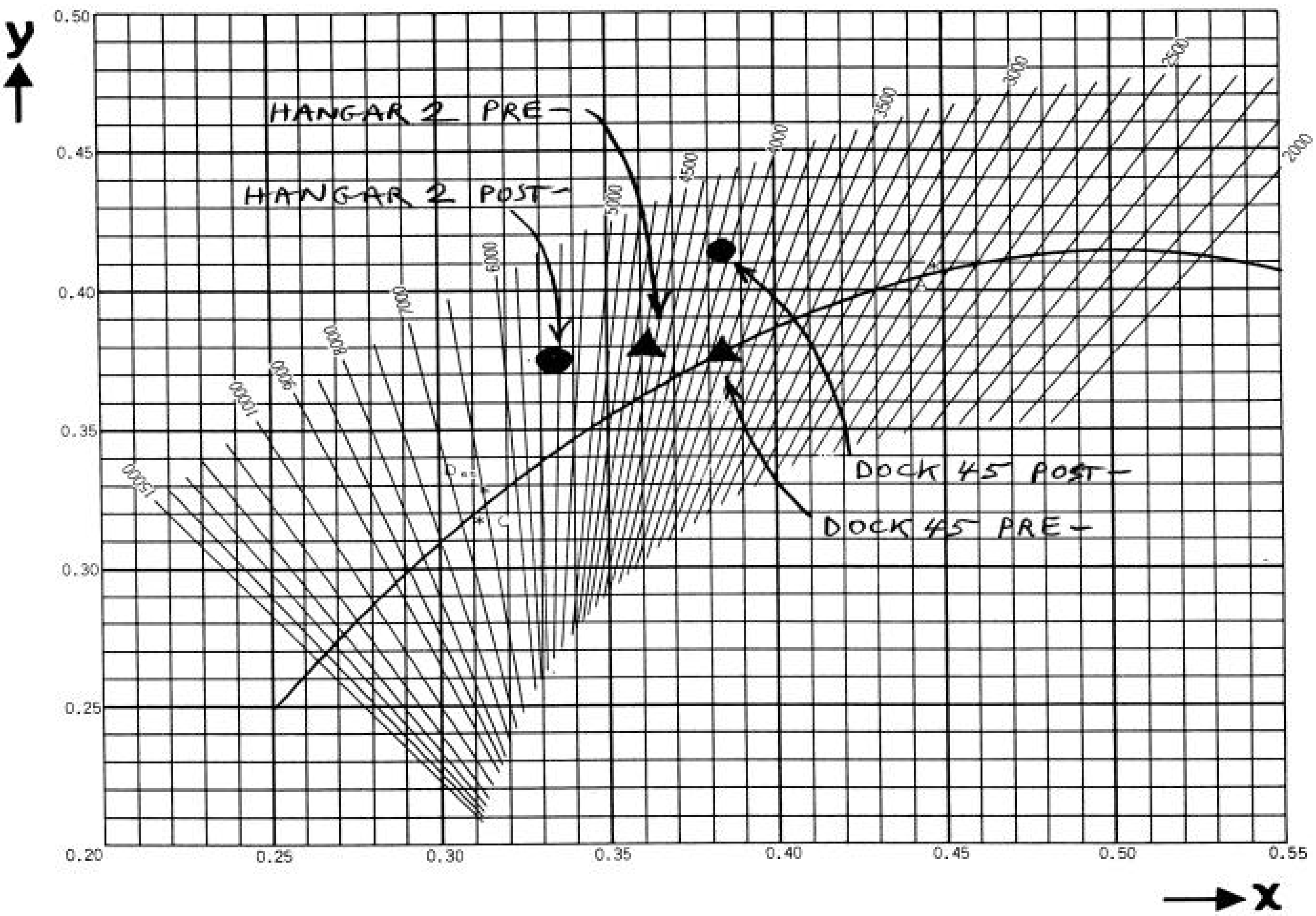


Figure 4. CIE 1931 (x,y) Representation of HAFB Lighting Retrofit Color

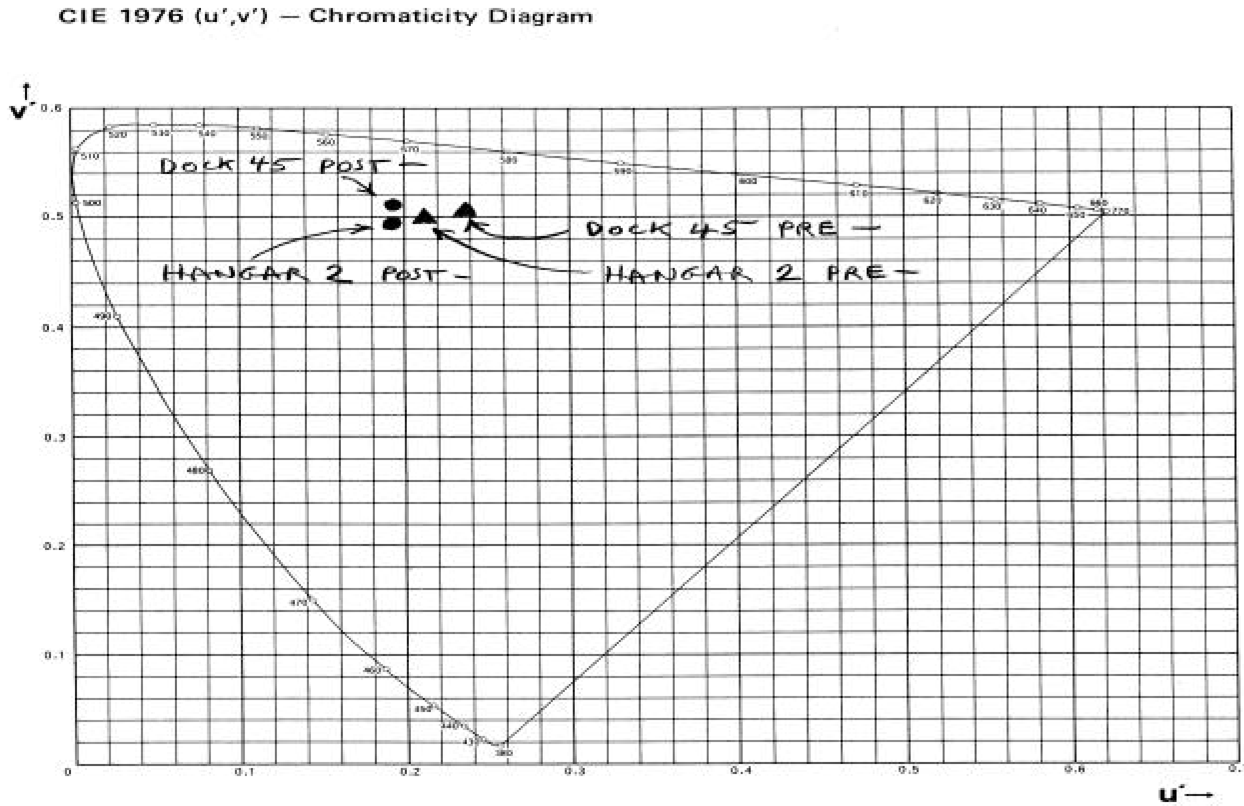


Figure 5. CIE 1976 (u',v') Representation of HAFB Lighting Retrofit Color

Light Level Comparison of Pre- and Post-Retrofit Lighting Systems

Dock 45 (F-16)

Assessments of illumination levels were taken in both low- and high-bay areas. Light levels were measured on a predefined grid measuring system designed to determine the overall average lighting level as well as its uniformity. Table 3 presents the foot-candle data (actual readings and interpolated data between measuring points) for the low-bay ar[illegible]ta was taken with moveable stands and equipm[illegible]acement was not identical for the pre- and post-r[illegible] spaces do not provide valid comparisons. Also, several lamps were not working under pre-retrofit conditions, so the readings were lower then than they would have been had all of the lights been operating properly.

Table 3. Dock 45 (F-16), Hill AFB, Building 225 - Illuminance at 30 inches from floor

Pre-Retrofit Illuminance Measurement (fc) at 30 inches from floor with equipment moved away - March 21, 1997 [Filled data]

Column \ **Row**	Feet	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
		0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0
A	0	45.2	44.4	42.9	41.5	39.3	38.8	36.5	39.3	40.3	42.7	43.0
B	12.5	45.8	45.0	43.0	42.2	41.1	40.7	40.3	41.2	42.7	44.8	44.8
C	25.0	47.2	45.2	41.9	42.9	42.1	42.2	42.8	43.2	44.3	45.8	46.5
D	37.5	46.8	46.8	44.5	45.2	43.1	43.1	42.9	44.6	45.3	47.7	47.7
E	50.0	46.3	45.6	44.1	43.1	42.0	39.8	41.0	42.7	44.6	45.3	48.9
F	62.5	43.7	45.0	42.3	40.9	34.8	32.9	31.7	40.6	41.2	40.1	44.4
G	75.0	39.9	41.2	39.2	30.3	23.2	17.9	12.1	28.5	39.6	42.1	44.1
H	87.5	40.1	40.7	31.4	18.0	11.5	3.3	12.3	21.5	36.4	44.4	40.9
I	100.0	39.8	35.9	27.7	12.9	1.6	5.2	NA	31.4	40.0	39.7	34.3
J	112.5	36.8	35.4	22.4	4.2	8.0	10.8	23.9	32.7	36.9	40.0	35.9
K	125.0	35.2	29.8	22.2	16.2	15.4	19.1	28.2	30.5	35.0	34.4	33.4
L	137.5	30.8	26.4	23.9	23.0	20.1	21.9	25.4	26.0	30.1	29.2	31.8
M	150.0											

Aisleway Only (shaded values)	
Average =	**43.5**
Min =	36.5
Max =	48.9
Std Dev =	2.5
Entire Space	
Average =	35.3
Min =	1.6
Max =	48.9
Std Dev =	11.2

The data presented in Table 3 is for the condition of all equipment moved away from the aircraft to achieve a better comparison. The ultimate comparison of light levels is found in the aisleway spaces that are the first five rows of test measurements (Rows A through E). The statistics of this area's lighting levels for both pre- and post-retrofit lighting indicates good uniformity, with standard deviations of 2.5 fc and 3.8 fc . The overall average retrofit light level (Light Drive™ 1000) is higher (between 43.5 fc to 60.6 fc) than the pre-retrofit lighting by approximately 17 fc or an additional 39 percent. As expected, the standard deviation for lighted areas around the aircraft are much higher (between 11.2 fc and 16.9 fc) relating to the mix of lighting levels caused by aircraft shadowing. A graphical representation of the Light Drive™ 1000 lighting of Dock 45 at 30 in. from the floor is presented in Figure 6. In this figure, th[illegible]rcraft (top right and bottom right of figure), w[illegible]

Post-Retrofit Illuminance Measurement (fc) at 30 inches from floor with equipment moved away - July 28, 1988 [Filled data]

Column \ **Row**	Feet	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
		0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0
A	0	52.9	54.8	51.7	55.0	54.1	55.1	52.5	56.8	56.0	57.2	54.8
B	12.5	58.7	59.9	58.4	59.3	58.8	58.7	59.2	61.9	61.2	60.9	60.7
C	25.0	63.3	62.0	62.6	62.0	63.2	62.7	63.7	64.9	66.0	65.1	66.4
D	37.5	61.3	62.0	61.9	62.9	63.0	65.2	64.5	68.1	66.0	66.9	64.9
E	50.0	58.7	58.9	59.9	59.5	60.8	58.3	60.8	60.3	63.1	61.7	61.3
F	62.5	52.6	55.0	53.4	54.4	47.9	46.2	42.5	49.0	54.0	55.4	54.9
G	75.0	44.0	46.1	44.2	36.5	30.0	23.4	13.8	37.1	48.6	49.3	48.1
H	87.5	41.4	41.2	33.3	17.4	13.3	3.7	8.8	NA	46.1	45.1	45.1
I	100.0	39.0	36.5	30.3	13.1	2.2	9.5	NA	43.0	44.5	43.8	42.1
J	112.5	35.9	35.6	23.4	2.3	12.0	22.6	32.9	41.5	42.7	43.4	42.4
K	125.0	33.2	30.1	25.2	16.8	20.9	25.7	34.7	36.0	41.4	39.0	41.6

Aisleway Only (shaded values)	
Average =	**60.6**
Min =	51.7
Max =	68.1
Std Dev =	3.8
Entire Space	
Average =	45.3
Min =	2.2
Max =	68.1
Std Dev =	16.9

by equipment, show reduced lighting levels because of side shadowing of neighboring equipment.

Figures 7 and 8 are photographs showing the pre-retrofit (top) and post-retrofit (bottom) conditions from two angles in the low-bay area.

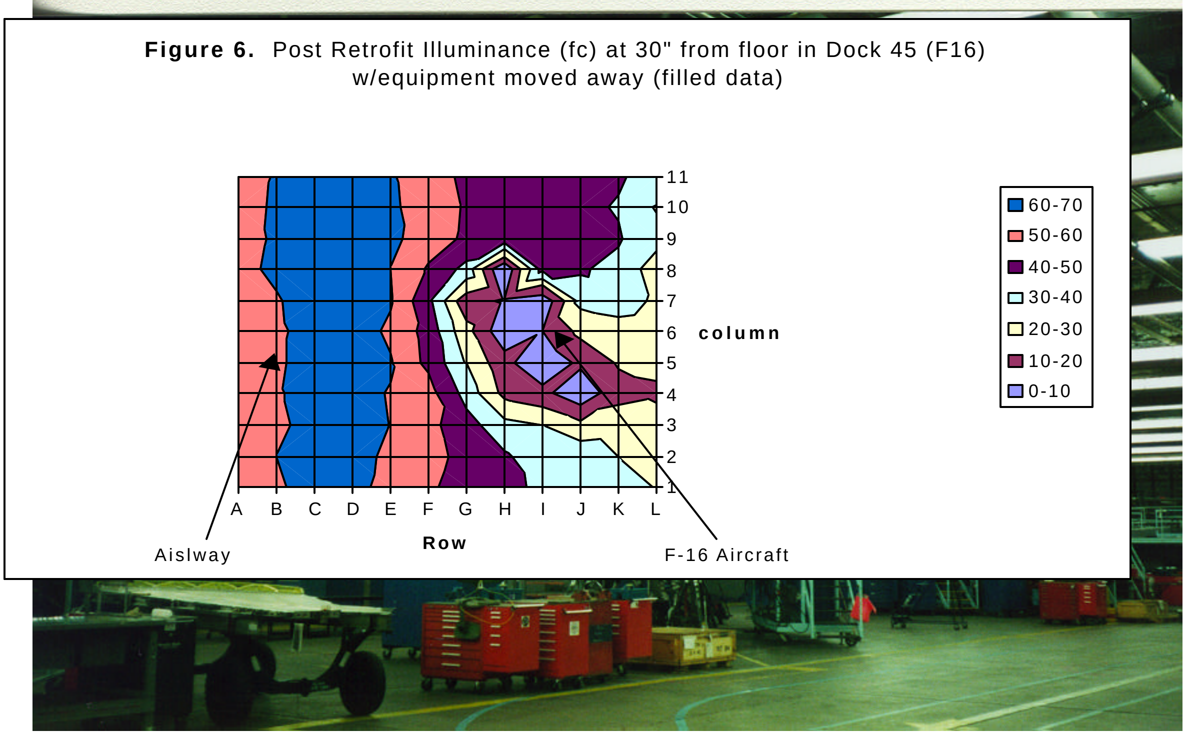


Figure 6. Post Retrofit Illuminance (fc) at 30" from floor in Dock 45 (F16) w/equipment moved away (filled data)

Figure 7. Pre- (top) and Post- (bottom) Retrofit Lighting Systems Facing Aircraft.

Figure 8. Pre- (top) and Post- (bottom) Retrofit Lighting Systems Down Main Aisle.

Table 4 presents the data (actual readings and interpolated data between measuring points) for the low-bay area (Dock 45) at 100 in. from the floor. This is the work height associated with activities at or near the top of the aircraft. For this data set, no equipment was moved because the 100-in. height was above most equipment except for non-movable rails near the aircraft and the aircraft tail section(s). As before, the most directly comparable set of light levels is found in the aisleway spaces, which are the first five rows of test measurements (Rows A through E). The statistics of this area lighting levels for both pre- and post-retrofit lighting indicates good uniformity, with standard deviations between 3.3 fc and 4.7 fc. The overall average light level is higher with the existing Light Drive™ 1000 lighting (between 44.5 fc to 65.4 fc) by approximately 21 fc or an additional 47 percent. As expected, the standard deviation for lighted areas around the aircraft are higher (between 6.5 fc and 10.5 fc) relating to the mix of lighting levels caused by aircraft tail section shadowing.

Table 4. Dock 45 (F-16), Hill AFB, Building 225 - Illuminance at 100 inches from floor

Pre-Retrofit Illuminance Measurement (fc) at 100 inches from floor - March 21, 1997 [Filled data]

	Row	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Column	Feet	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0
A	0	54.9	50.5	47.8	41.3	39.5	39.6	38.3	42.5	42.5	44.9	48.2
B	12.5	50.2	48.8	44.3	36.5	39.4	41.1	42.4	46.6	44.1	43.9	46.2
C	25.0	46.9	45.4	44.0	41.2	40.6	42.1	43.5	45.7	43.3	44.8	46.6
D	37.5	46.1	41.9	42.9	43.6	42.4	43.3	44.8	49.4	46.0	45.3	46.5
E	50.0	49.5	45.8	41.9	43.7	42.2	43.4	43.1	45.7	45.9	47.8	47.5
F	62.5	51.1	50.0	46.4	47.0	44.1	44.8	42.8	44.2	47.3	52.3	50.9
G	75.0	53.9	47.6	46.6	44.0	42.5	41.3	38.9	42.7	46.6	50.9	52.8
H	87.5	48.0	39.9	41.3	40.0	40.0	38.8	38.9	41.0	47.1	51.7	54.1
I	100.0	50.2	42.0	38.8	36.9	38.8	37.0	37.0	41.9	49.2	52.0	57.8
J	112.5	42.4	39.0	35.5	30.0	33.8	33.4	37.7	40.5	45.8	49.4	51.2
K	125.0	38.0	37.0	34.1	32.4	33.1	35.5	39.9	41.5	44.2	46.7	46.5
L	137.5	31.7	25.4	27.9	24.2	27.4	25.0	31.0	28.0	34.0	29.8	38.2
M	150.0											

Aisleway Only (shaded values)
Average = 44.5
Min = 36.5
Max = 54.9
Std Dev = 3.3

Entire Space
Average = 42.6
Min = 24.2
Max = 57.8
Std Dev = 6.5

Post-Retrofit Illuminance Measurement (fc) at 100 inches from floor - July 28, 1998 [Filled data]

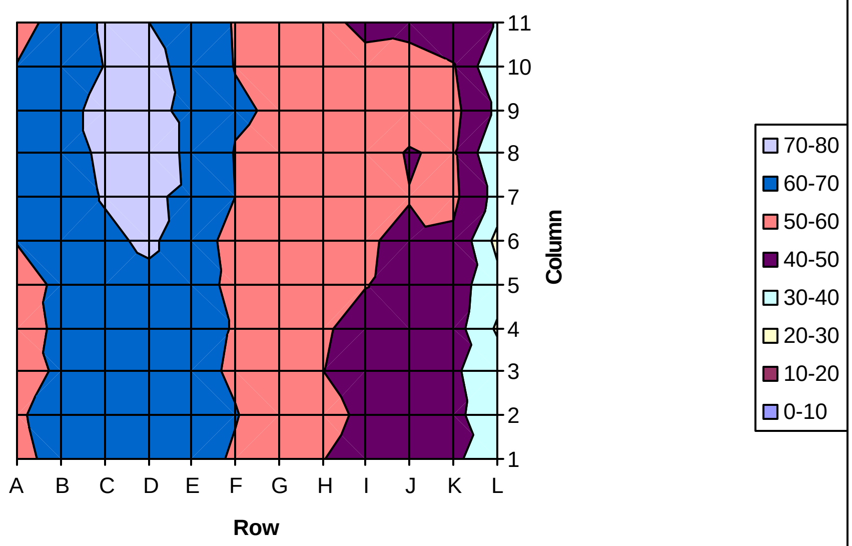
	Row	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Column	Feet	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0	112.5	125.0
A	0	57.2	58.9	55.5	57.8	56.9	60.2	60.9	62.9	61.6	60.4	56.1
B	12.5	63.2	64.1	61.6	61.0	61.5	62.9	65.2	66.3	66.2	63.4	63.6
C	25.0	68.3	66.6	65.8	65.2	65.2	67.7	70.8	71.5	73.4	70.4	71.4
D	37.5	66.8	68.1	66.5	68.8	67.5	71.8	71.6	75.6	72.6	73.3	70.0
E	50.0	63.9	64.0	63.3	63.9	64.0	65.1	68.0	67.7	67.9	66.5	65.2
F	62.5	58.7	60.6	58.5	59.3	57.6	56.5	60.0	59.4	61.4	59.7	59.5
G	75.0	51.6	54.0	50.9	52.9	50.7	53.8	56.0	57.1	58.5	56.3	53.5
H	87.5	50.3	52.8	50.1	50.5	50.9	52.1	53.2	54.3	55.1	53.3	51.7
I	100.0	46.4	48.1	46.2	48.3	50.2	50.4	50.2	52.1	54.2	51.8	48.4
J	112.5	44.8	46.9	45.1	46.2	47.5	49.1	50.2	49.6	51.9	51.4	48.9
K	125.0	41.0	43.0	41.1	43.9	44.5	48.4	51.7	51.2	52.4	50.2	46.9
L	137.5	36.7	32.3	34.1	29.0	33.5	26.9	36.5	31.0	38.3	31.5	39.2
M	150.0											

Aisleway Only (shaded values)
Average = 65.4
Min = 55.5
Max = 75.6
Std Dev = 4.7

Entire Space
Average = 55.9
Min = 26.9
Max = 75.6
Std Dev = 10.5

A graphical presentation of the Light Drive™ 1000 lighting of Dock 45 at 100 in. from the floor is presented in Figure 9. In this figure, the location of the aircraft is not as obvious as in Figure 3 because the readings are taken above most obstructions.

Figure 9. Post Retrofit Illuminace (fc) at 100" from floor in Dock 45 (F16) [filled data]



Hangar 2 (C-130)

The light level measurements and interpolated data at 30 in. from the floor in the high-bay area are presented in Table 5. Data were taken with all stands and equipment in place because only a small part of the equipment was actually moveable without disturbing ongoing operations. The ultimate comparison of light levels is again foundMin the clearest space available, which is the last four rows of test measurements (Rows J through E). The statistics of this area lighting levels for both pre- and post-retrofit lighting indicate a wider variation with standard deviations of 8.2 fc and 16.3 fc. As expected, the standard deviation for lighted areas around the aircraft is much higher (between 11.6 fc and 25.1 fc) relating to the mix of lighting levels caused by aircraft shadowing. The overall average light level is higher with the Light Drive™ 1000 lighting (between 35.6 fc to 93.8 fc) by approximately 58 fc or an additional 163 percent of the pre-retrofit lighting. Since several lamps were not working at the time, the pre-retrofit readings were lower then than they would have been had all of the lights been operating properly. Also, the post-retrofit lighting levels are higher than may have been needed due to the requirement that existing, closely-spaced fixture locations had to be used for the new fixtures.

A graphical representation of the Light Drive™ 1000 lighting of Hangar 2 (C-130) at 30 in. from the floor is presented in Figure 10. In this figure, the location of the aircraft is not very obvious. This is because the C-130 and most of the equipment used around it are approximately twice as tall as the F-16 and associated equipment. The corner area at columns J,K,L,M and rows 6,7,8 was inaccessible, and no data was taken.

Table 5. Hangar 2 (C-130), Hill AFB, Building 225 - Illuminance at 30 inches from floor

Pre-Retrofit Illuminance Measurement (fc) at 30 inches from floor - March 21, 1997 [Filled data]

	Row	1	2	3	4	5	6	7	8
Column	Feet	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5
A	0	35.1	42.6	44.1	34.8	20.7	31.0	42.6	38.0
B	12.5	34.2	48.6	38.5	39.7	27.5	29.6	40.1	33.3
C	25.0	18.9	34.0	21.6	22.1	19.9	34.8	54.8	39.4
D	37.5	37.8	46.9	31.7	7.2	13.6	NA	37.3	30.0
E	50.0	47.6	48.5	51.1	32.9	NA	20.3	27.1	24.9
F	62.5	50.7	48.4	44.0	40.3	20.5	13.5	17.6	17.5
G	75.0	56.0	45.5	36.0	24.7	7.6	21.1	12.2	21.7
H	87.5	49.0	41.7	35.9	15.0	29.2	51.3	35.9	35.5
I	100.0	49.3	45.3	50.9	37.2	43.0	46.3	44.7	40.1
J	112.5	50.7	39.1	42.2	40.0	42.1			
K	125.0	63.6	47.1	38.7	40.6	43.2			
L	137.5	39.9	30.5	35.7	42.1	40.2			
M	150.0	25.6	29.2	31.5	36.3	35.2			

Clear Area Only (shaded values)

Avera	35.6
Min =	7.2
Max =	63.6
Std De	8.2

Entire Space

Avera	35.6
Min =	7.2
Max =	63.6
Std De	11.6

Post-Retrofit Illuminance Measurement (fc) at 30 inches from floor - April 13, 1998 [Filled data]

	Row	1	2	3	4	5	6	7	8
Column	Feet	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5
A	0	59.3	66.9	75.8	69.6	71.5	65.2	53.6	46.6
B	12.5	74.4	65.6	78.3	61.6	78.4	70.4	61.4	39.6
C	25.0	98.4	77.3	110.0	84.1	110.0	87.0	82.1	55.3
D	37.5	45.1	35.2	60.5	54.9	83.5	85.5	73.0	44.1
E	50.0	1.6	38.0	41.7	38.8	NA	81.7	80.4	56.6
F	62.5	61.0	73.4	61.0	19.7	44.2	79.3	70.1	45.4
G	75.0	108.0	92.8	109.0	47.8	33.5	57.7	75.3	55.1
H	87.5	63.3	80.7	62.7	29.0	54.8	42.7	59.5	44.6
I	100.0	1.3	50.3	32.1	58.0	114.0	77.4	75.5	60.1
J	112.5	64.1	86.9	71.9	56.7	95.9			
K	125.0	104.0	101.0	112.0	95.2	117.0			
L	137.5	93.2	74.5	95.7	84.2	103.4			
M	150.0	101.0	95.8	112.0	101.7	109.0			

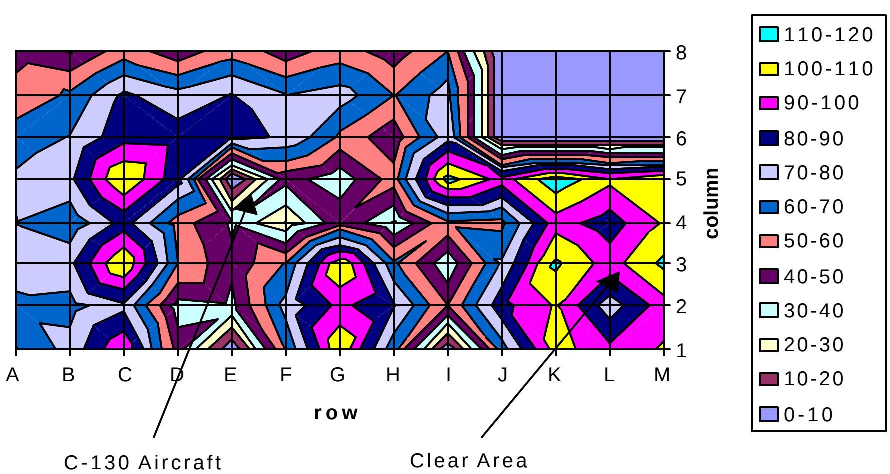
Clear Area Only (shaded values)

Avera	93.8
Min =	56.7
Max =	117.0
Std De	16.3

Entire Space

Avera	70.1
Min =	1.3
Max =	117.0
Std De	25.1

Figure 10. Post Retrofit Illuminance (fc) at 30" from floor in Hangar 2 (C-130) [filled data]



Figures 11 and 12 are photographs show a comparison of the test space between pre- and post- retrofit from two viewpoints.

Figure 11. Pre- (top) and Post- (bottom) Retrofit - High-Bay

Figure 12· Pre- (top) and Post- (bottom) Retrofit in High-Bay - Added Edge Light Pipe

The light level measurements and interpolated data at 100 in. from the floor in the high-bay area are presented in Table 6. Data was again taken with all stands and equipment in place. The ultimate comparison of light levels is also found in the clearest space available, which is the last four rows of test measurements (Rows J through M). The statistics of this area lighting levels for both pre- and post-retrofit lighting also indicates a wide variation with standard deviations of between 9.4 fc and 15.7 fc. The overall average light level is higher with the existing Light Drive™ 1000 lighting (between 42.6 fc to 100.2 fc) by approximately 58 fc or an additional 135 percent. As expected, the standard deviation for lighted areas around the aircraft are much higher (between 14.4 fc and 27.7 fc) relating to the mix of lighting levels caused by aircraft shadowing. A graphical representation of the Light Drive™ 1000 lighting of Hangar 2 (C-130) at 100 in. from the floor is presented in Figure 13.

Lighting measurements were also taken at selected vertical and horizontal locations on both the F-16 and C-130 aircraft. Many of these locations are typically illuminated with task lighting or are subject to variable shadowing and are therefore not included here. See Appendix B for these data as well as a set of schematics for both test areas and aircraft that show the precise measurement locations and methodology.

Table 6. Hangar 2 (C-130), Hill AFB, Building 225 - Illuminance at 100 inches from floor

Pre-Retrofit Illuminance Measurement (fc) at 100 inches from floor - March 21, 1997 [Filled data]

	Row	1	2	3	4	5	6	7	8
Column	Feet	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5
A	0	38.0	46.8	54.4	39.1	18.4	34.5	55.8	45.7
B	12.5	30.1	48.1	41.2	44.5	30.8	29.4	46.2	35.6
C	25.0	4.3	29.2	17.6	22.2	NA	46.6	63.8	44.1
D	37.5	33.0	46.6	31.3	4.5	4.5	NA	47.7	33.0
E	50.0	48.2	49.4	56.3	35.7	NA	24.1	46.4	37.7
F	62.5	53.1	46.5	47.5	46.4	16.1	1.7	23.9	33.7
G	75.0	64.5	47.5	40.7	24.0	0.1	17.0	13.6	28.9
H	87.5	53.7	38.2	35.4	8.7	27.3	52.7	39.2	39.4
I	100.0	58.5	46.9	54.0	37.9	47.7	50.5	51.1	45.3
J	112.5	55.3	36.8	43.6	41.1	45.7			
K	125.0	70.7	50.0	42.4	43.9	48.2			
L	137.5	43.4	29.9	37.3	43.8	44.5			
M	150.0	29.6	30.8	33.0	39.5	41.6			

Clear Area Only (shaded values)

Avera	42.6
Min =	29.6
Max =	70.7
Std De	9.4

Entire Space

Avera	38.3
Min =	0.1
Max =	70.7
Std De	14.4

Post-Retrofit Illuminance Measurement (fc) at 100 inches from floor - April 13, 1998 [Filled data]

	Row	1	2	3	4	5	6	7	8
Column	Feet	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5
A	0	61.3	70.9	76.5	70.5	70.5	72.5	60.8	41.0
B	12.5	80.8	75.0	84.5	64.5	83.8	86.3	66.9	21.1
C	25.0	106.0	83.6	122.0	96.6	114.0	96.0	99.3	53.6
D	37.5	81.4	31.2	61.0	86.0	94.8	84.4	79.6	40.4
E	50.0	107.0	57.7	4.6	45.7	NA	81.5	94.4	56.6
F	62.5	101.0	88.1	63.5	46.4	37.4	65.6	71.3	35.1
G	75.0	108.0	100.6	115.0	48.8	0.1	47.3	90.2	53.6
H	87.5	101.7	91.1	69.1	33.8	48.3	33.3	60.2	35.5
I	100.0	106.0	81.6	36.4	62.4	126.0	80.3	81.6	58.6
J	112.5	101.0	92.9	75.7	53.4	99.5			
K	125.0	104.0	105.6	120.0	97.5	119.0			
L	137.5	97.9	84.7	104.4	91.7	107.6			
M	150.0	105.0	103.6	121.0	108.2	112.0			

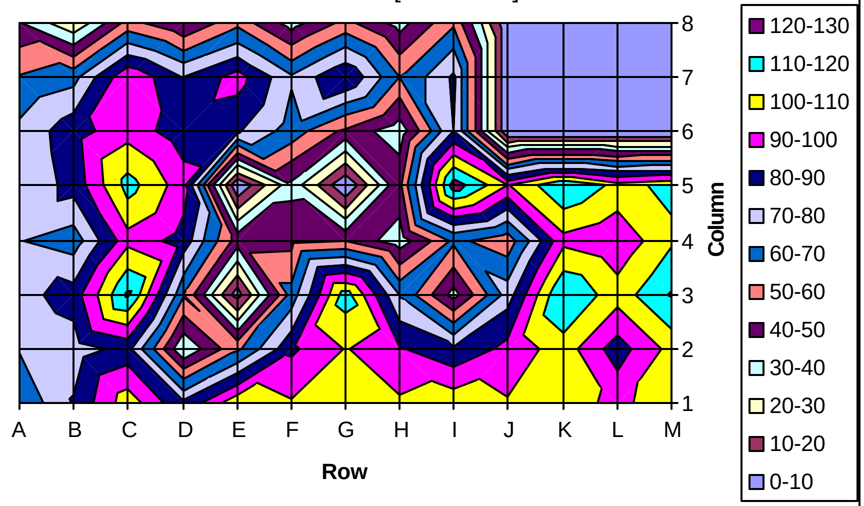
Clear Area Only (shaded values)

Avera	100.2
Min =	53.4
Max =	121.0
Std De	15.7

Entire Space

Avera	77.4
Min =	0.1
Max =	126.0
Std De	27.7

Figure 13. Hangar 2 (C130) 100" from floor w/equipment as is [filled data]



Power Consumption Comparison of Pre- and Post-Retrofit Lighting Systems

The power consumption measurements were made for representative lighting circuits where quantities and types of lamps were known. From these data, extrapolations of energy use based on lamp counts and identification could be made. The lamp counts of the pre-retrofit system identified a total of 338 working Metal halide lamps, 149 working mercury vapor lamps and 41 inoperable fixtures or burned out lamps. The energy consumption of specific circuits was used to algebraically determine an estimated operational wattage for each fixture type. These values were used to estimate the total wattage for the test area.

Tables 7 and 8 present the power consumption data for the pre- and post-retrofit conditions of two of the four retrofitted high-bay hangar areas (northeast and southeast) and the two large internal low-bay areas (east side). The estimated total consumption is smaller for the Light Drive™ 1000 lighting (pre-retrofit of 254 kW vs. post-retrofit of 224 kW). This is only an estimate and will be expected to vary depending on time and temperature conditions. Also, the pre-retrofit estimate must be considered low because of the unlighted fixtures that should be lighted for a more true comparison. With these conditions, the retrofit is estimated to save 30 kW or 12 percent. Assuming the unlighted fixtures were working raises the pre-retrofit value to 273 kW for a 49 kW savings or 18 percent. The power values indicate potential energy savings for the installation as it currently exists.

The post-retrofit high-bay energy consumption also includes an additional 16 sulfur lamps (22 kW) that were added during the retrofit to illuminate the side mezzanine and under-storage areas in the high-bay spaces that were not specifically illuminated previously. Without these additional lamps, the estimated energy savings increases to 52 kW (19 percent) with burned out lamps in the pre-retrofit condition or 71 kW (26 percent) if all original lamps were working. Additional energy savings would have been possible if the designer were free to increase the space between fixtures.

The current retrofit installation also provides a significant increase in lighting levels throughout the space, from 39 percent to 160 percent. This "before and after" comparison does not provide a complete picture of the efficiency of the sulfur lamp application, because the light levels were inadequate prior to relamping in the high-bay area, and the antiquated fixtures that were replaced in the low-bay area consumed excessive energy. To provide a better basis of comparison, with greater applicability to new installations elsewhere, PNNL estimated the energy required by modern metal halide systems designed to light the same spaces comparably. The lamps, with characteristics that appear in Table 9, would provide nominal light levels of 90 foot-candles in the high-bay area and 75 foot-candles in the low-bays, possibly with excessive glare. Table 10 presents a comparison of the energy consumption and associated light levels achieved from the pre-retrofit, pre-retrofit estimated with all lamps working, an efficient metal halide technology redesign, and the current retrofit sulfur lamp system. In this case, the metal halide redesign in the low-bay area would require 22 kW more power than do the sulfur lamps, and in the high-bay area the sulfur lamps' advantage becomes 71 kW. The sulfur lamps would thus have an overall efficiency advantage of 29 percent, with most of the advantage corresponding to the high-bay application.

Table 7. Pre-Retrofit Electrical Characteristics, Lamp Counts, and Estimated Wattage

Low Bay Electrical Characteristics

Panel/	Circuit	Voltage Data		Amperage Data			Wattage Data		Lamps
Circuit	Description	RMS	CF	RMS	CF	THD-R	KW	PF	(all 400 W)
I-18/29	17,18 west	274	1.44	14.2	1.46	NA	2.7	0.69	8 MH
I-18/27	16,17 east	274	1.44	12.0	1.35	15.8	3.2	0.98	1 MH, 5 MV, 2 out
I-18/25	16,17 west	274	1.44	14.0	1.44	16.6	3.6	0.96	7 MH, 1 MV
-/30R	Dock 30 Rear	274	1.44	13.4	1.35	15.3	3.6	0.98	1 MH, 7 MV

High Bay Electrical Characteristics

	Circuit	Voltage Data		Amperage Data			Wattage Data		Lamps
Panel	Description	RMS	CF	RMS	CF	THD-R	KW	PF	(all 1000 W)
L4B1/6	7th row west	273	1.44	10.2	1.31	8.9	2.8	0.99	3 MV
L4B1/8	6th row west	273	1.43	10.8	1.43	6.7	2.9	0.99	1 MH, 2 MV
L4B1/2	4th row west	273	1.44	11.6	1.39	7.7	3.0	0.99	2 MH, 1 MV
(east)/9	beam J28	273	1.40	9.7	1.40	9.8	2.2	0.81	1 MH, 1 MV, 1 out
(east)/7	beam J29	271	1.44	8.2	1.33	13.5	2.2	0.98	1 MH, 2 MV
(east)/4	beam J26	273	1.44	11.7	1.38	6.7	3.1	0.97	2 MH, 1 MV

Low Bay Lamp Count

Lamp Type	Lamp Count	Estimated Watts/Lamp	Estimated Total KW
MH	304	436	133
MV	106	436	46
Out	34	55	2
Totals	**444**		**181**

High Bay Lamp Count

Lamp Type	Lamp Count	Estimated Watts/Lamp	Estimated Total KW
MH	34	947	32
MV	43	947	41
Out	7	75	1
Totals	**84**		**73**

Total Estimated Wattage	**254**

Table 8. Post-Retrofit Electrical Characteristics, Lamp Counts, and Estimated Wattage

Low Bay Electrical Characteristics

Panel/	Circuit	Voltage Data		Amperage Data			Wattage Data		Lamps
Circuit	Description	RMS	CF	RMS	CF	THD-R	KW	PF	(all 1000 W)
I-18/6		274	1.42	9.08	1.45	2.7	2.5	0.99	2 sulfur lamps
I-18/10		276	1.43	8.22	1.44	2.7	2.25	0.99	2 sulfur lamps

Low Bay Lamp Count

Lamp Type	Lamp Count	Estimated Watts/Lamp	Estimated Total KW
Sulfur	**88**	1190	**105**

(44 pipes, 2 lamps per pipe)

High Bay Lamp Count

Lamp Type	Lamp Count	Estimated Watts/Lamp	Estimated Total KW
Sulfur	**100**	1190	**119**

(84 pendants plus 16 pipe lamps along edges)

Table 9. Characteristics of Efficient Metal Halide Redesign of Hangar Space

Area	Light Level (Estimate)	Lamp Type	Lamp Count	Watts/ Lamp (Estimate)	Total kW
Low-bay	75 fc	MH	280	455	127
High-bay	90 fc	MH	176	1080	190

Table 10. Power Consumption (kW) and Light Output (fc) Comparison

	Pre-Retrofit		Post-Retrofit	Standard Design
Lamp	As found	All lamps	Light Drive 1000	Efficient 450 W
MH 400W	133	148	NA	NA
MH 1000W	32	39	NA	190
MH 450W	NA	NA	NA	127
MV 400W	46	46	NA	NA
MV 1000W	41	41	NA	NA
Ballast Only	3	0	NA	NA
Light Drive 1000	NA	NA	224	NA
TOTAL	**255**	**274 (estimate)**	**224**	**317 (estimate)**
Low Bay light level	**44**	unknown	**61**	**75 (estimated)**
High Bay light level	**36**	unknown	**94**	**90 (estimated)**

Electricity Supply Comparison of Pre- and Post-Retrofit Lighting Systems

The quality of power supplied to buildings and their equipment is important with today's reliance and sensitive electronic control and application functions. Therefore, the effect any new lighting system may have on the building's power supply is important. For this test demonstration, power quality was measured at individual lighting circuits to obtain at least a rough idea of the change in power quality with the Light Drive™ 1000 lamp system.

Tables 7 and 8 include crest factor (CF), total harmonic distortion (THD-R), and power factor (PF) values for pre- and post-retrofit situations. The CF for all situations appears fairly stable, from around 1.4 to 1.45, where values approaching 1.7 are associated with poor quality (Power Quality 1995).

The THD-R of the pre-retrofit systems varies from around 7 percent to 16 percent. This is below the generally expected metal halide value of around 19 percent and is not expected to contribute greatly to the recommended total building distribution THD-R value of 5 percent (Specifier Reports 1993). The post-retrofit THD-R is 2.7 percent. These much lower values for the Light Drive™ 1000 system indicate that this system will not contribute to total building THD-R above recommended levels.

Power factor (PF) for the pre-retrofit system appears fairly good at around 98 percent for most circuits. A few circuits have much lower values and are likely attributable to worn out or older technology lamp ballasts. The post-retrofit PF is 99 percent indicating negligible effect on power quality.

Occupant Survey of Pre- and Post-Retrofit Lighting Conditions

A total of 195 people filled out the survey in the pre-retrofit conditions in August-September 1997, and in the post-retrofit conditions in April 1998. As discussed earlier, the low-bay lighting fixtures were replaced after the post survey, because of deterioration in output. Therefore, results presented here thus correspond to less than optimal sulfur lighting (post) conditions experienced where work on F-16 aircraft generally takes place. Almost 80 percent of the occupants were between the ages of 36 and 55. Two-thirds worked on the F-16 aircraft, with the remainder focused on the C-130.

The survey included questions on demographics, work tasks, problems related to lighting, general evaluation of lighting conditions, pre- and post-retrofit, and ratings of the ease with which they could read sentences printed in different font sizes from 11 pt down to 5 pt. See Appendix A for the full survey form.

Nature of the work

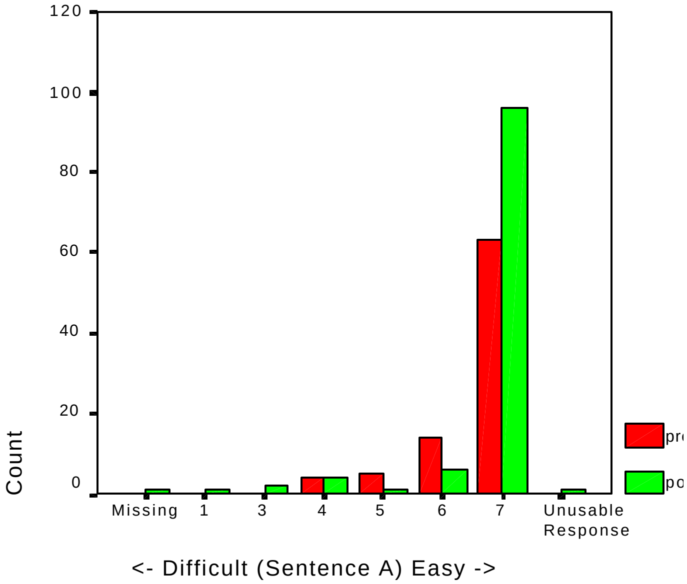
The survey asked the occupants to rate the extent to which their jobs required them to do different kinds of tasks. The responses shown in Table 11 indicate that the work requires a high level of detailed visual engagement and difficult physical movement (e.g., moving in confined space, viewing things from awkward angles). In carrying out their work, slightly more than one-third of the occupants said they use a movable task light, and 87 percent use a flashlight often or always.

Table 11. Characteristics of Tasks by Percentage of Sample

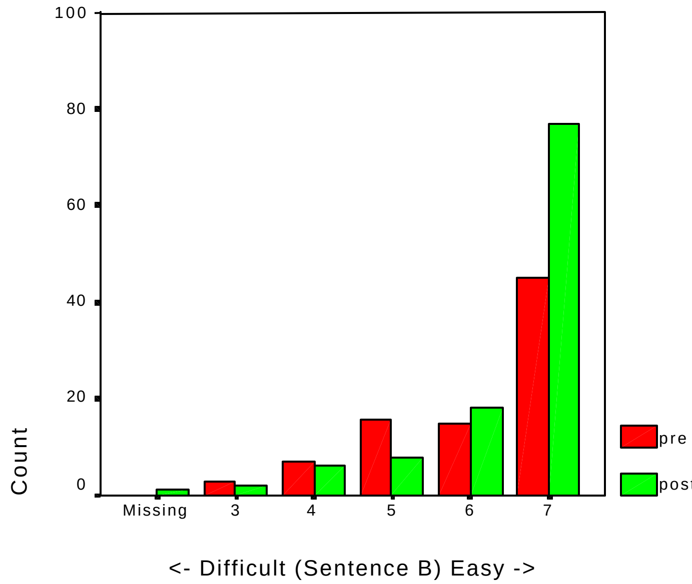
Task	Percent Doing “Moderately” or “Very Much”
Read paper-based materials	94
View things from an awkward angle	90
View objects with fine details	85
Read small print	81
Manipulate small objects	81
Move about in confined spaces	73
Distinguish between different colors	57
View computer-based materials	39
Enter data into a computer	18

Ease of reading different font sizes

One section of the survey asked the occupants to rate how easy or difficult it is to read each of four sentences, each printed in a different font size. Across all font sizes, the occupants in the sulfur lamp condition rated the test sentences as significantly easier to read. The results are shown for each sentence in Figures 14 through 17 where the vertical axis ("count") is the number of respondents and the horizontal axis denotes how easy the sentence was to read (1 = “Unable to read”; 7 = Very easy to read”). The point size for each sentence was: Sentence A -- 11 pt., Sentence B -- 9 pt., Sentence C -- 7 pt., and Sentence D -- 5 pt.



Responses to 11 pt. type



Responses to 9 pt. type

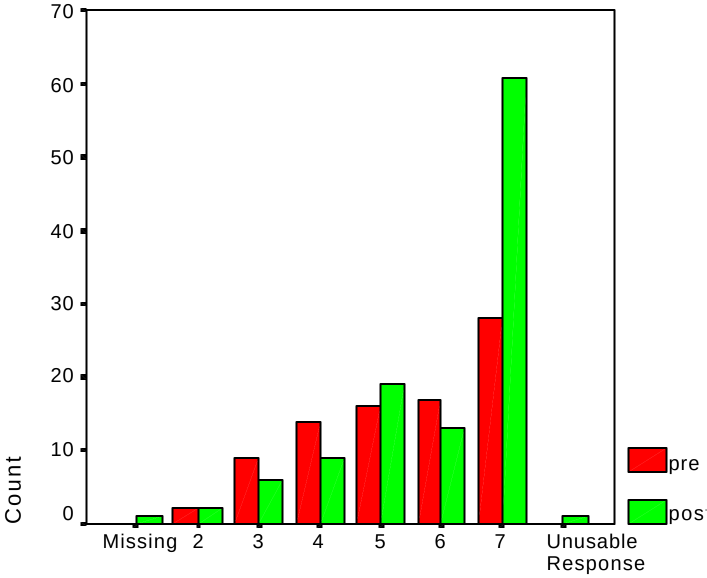
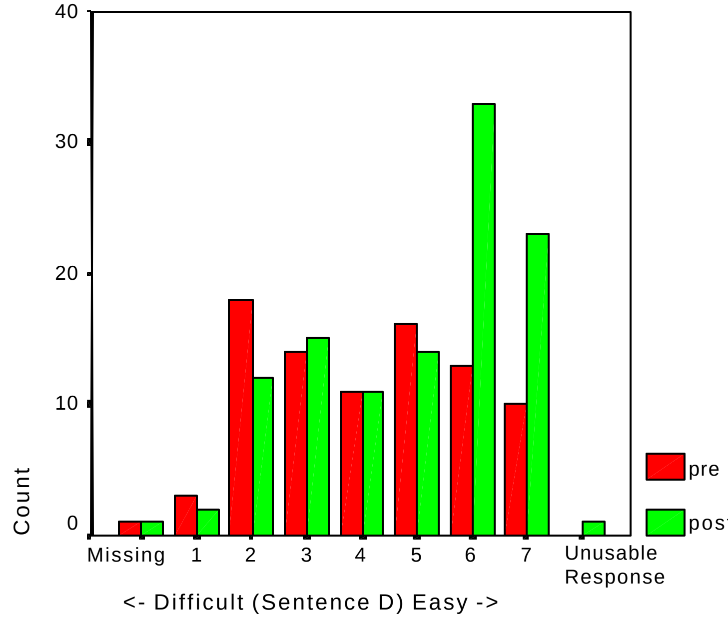


Figure. 16 Distribution of Responses to 7 pt type



Responses to 5 pt type

Ratings of lighting problems

The survey asked occupants to rate the degree to which they experienced different kinds of lighting problems under the two different conditions. Table 11 shows the percentage who rated each situation as "moderately" or "very much" a problem. The Chi-Square statistic was used to analyze the difference in the distribution of responses between the two lighting conditions.

There were significant differences on the ratings of lighting problems for 4 our of the 14 variables: reflections on the computer screen, flicker from ceiling lights, noise from light fixtures, and lack of view to the outdoors. The overall distribution of responses for these variables is shown in Figures 18 through 21. The remaining 10 variables did not show any statistically significant change between pre- and post-retrofit conditions.

For ratings of noise, the distribution of responses is somewhat mixed, as seen in Figure 18. There was an increase in the number of responses rating noise as "somewhat" or "very much" a problem under the sulfur lamp conditions, but also a decrease in those rating noise as "moderately a problem."

Figure 19 indicates that the sulfur lamp condition is rated as somewhat more negative for reflections on the computer screen. There was a large increase in the number of occupants rating reflections as "somewhat" of a problem under the sulfur lamp condition as compared to the baseline. This likely a result of the increased lighting levels provided by the new lighting system.

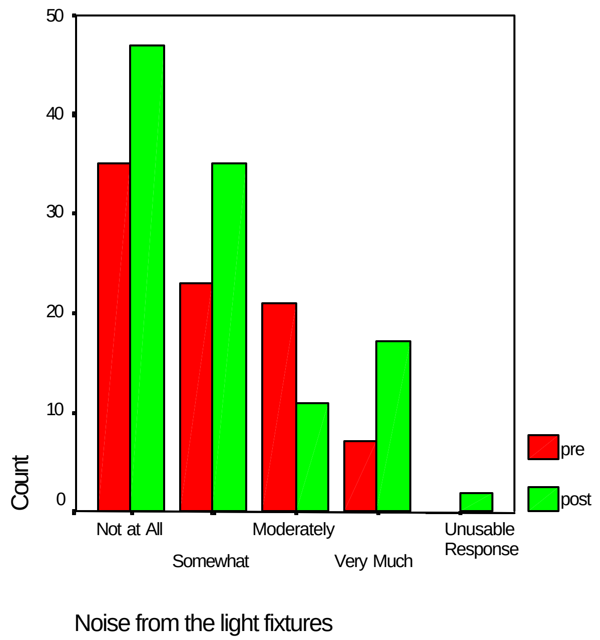


Figure. 18 Number of Occupants Experiencing Noise from Lights

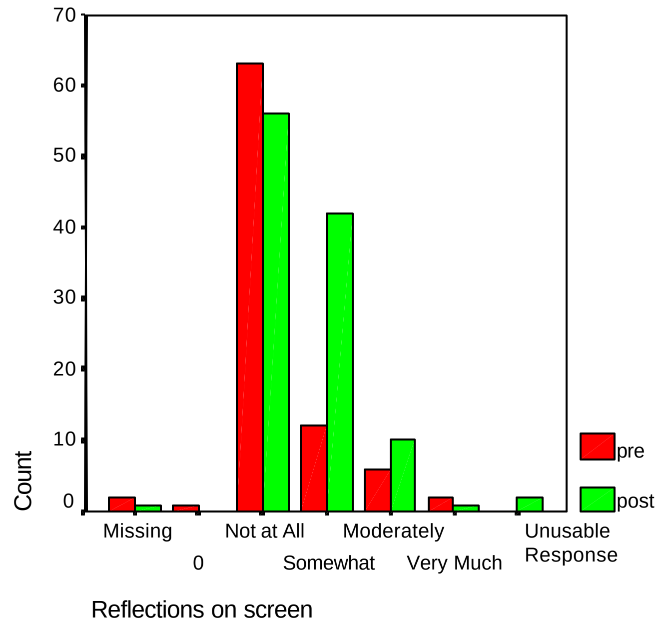


Figure. 19 Number of Occupants Experiencing Video Display Terminal Reflections

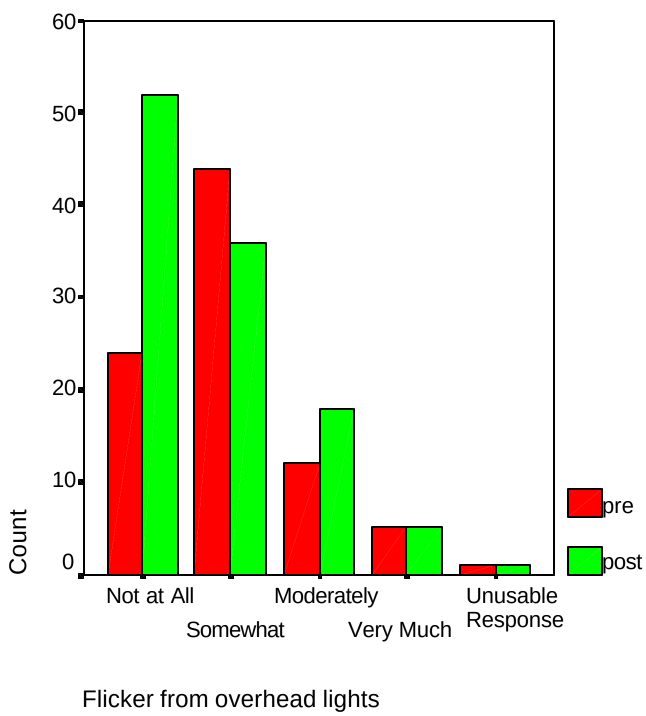


Figure. 20 Number of Occupants Experiencing Flicker from Lights

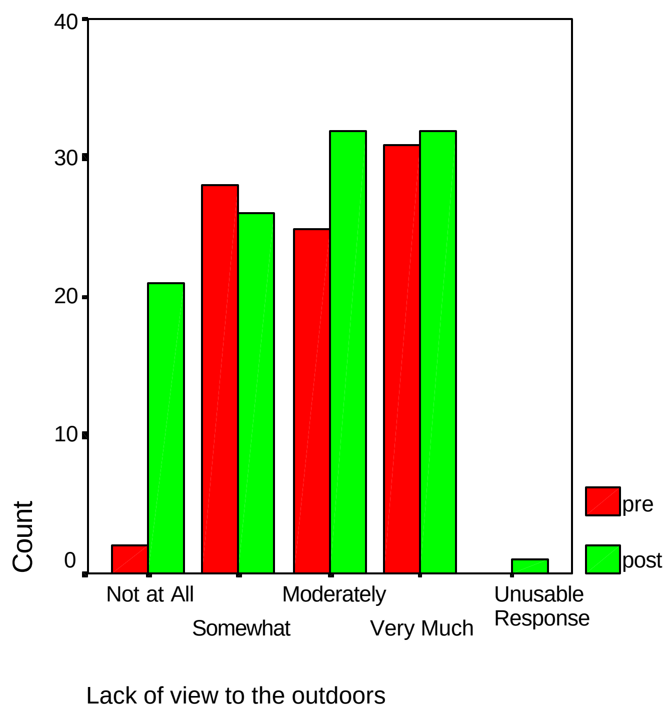


Figure. 21 Number of Occupants Experiencing Lack of View to Outdoors

On ratings of flicker from overhead lights, there was a positive shift under the sulfur lamp, with a large increase in the number of occupants stating that flicker was "not at all" a problem. Figure 20 also shows that flicker was moderately or very much a problem for about one-fifth of the occupants under both conditions. Figure 21 indicates that the ratings for lack of an exterior view differ primarily in the number of occupants saying this was "not at all" a problem under the sulfur lamp conditions. The reason for this difference is not clear. It may, be caused by the timing of the survey administration. The bay doors to the hangers may have been open more during the second survey administration in April 1998.

Table 12 confirms that a number of lighting problems were apparent under both conditions. For instance:

- 69 percent to 72 percent of the occupants said shadows in the task area were a problem.
- Inability to control the light was also a problem for 45 percent to 53 percent of respondents.
- Lack of daylight was rated as a problem for 55 percent to 58 percent.
- Over half of occupants in both conditions said there was not enough light where it is needed.
- Lack of a view to the outdoors was also a problem in both conditions—57 percent to 65 percent said lack of view was a problem.

Table 12. Percent of Occupants Experiencing Lighting Problems

Problem	Baseline Conditions (%)	Sulfur Lamp Conditions (%)	Chi-Square*
Variables showing significant differences between conditions:			
Noise from light fixtures	33	25	10.29 (p=0.036)
Lack of view to outdoors	65	57	14.48 (p=0.006)
Reflections on computer screen	10 (Somewhat=14)	10 (Somewhat=38)	18.02 (p=0.003)
Flicker from ceiling lights	20	21	9.06 (p=0.06)
Variables that did not different significantly between conditions:			
Not enough light to see fine detail	68	65	2.29 (ns)
Glare from ceiling lights	21	14	1.89 (ns)
Glare from task lights	25	23	1.99 (ns)
Shadows in task area	69	72	1.60 (ns)
Too much heat from lights	15	15	2.39 (ns)
Inability to control light	53	45	2.76 (ns)
Too little light between aircraft	33	36	1.22 (ns)
Light makes colors look unnatural	19	27	5.71 (ns)
Light not available where needed	51	54	5.30 (ns)
Not enough daylight	58	55	0.32 (ns)

*"ns" signifies that the difference is not significant

Ratings of the importance of environmental features

Because the hanger facility has large bay doors that can alter the look and feel of the interior environment, the survey asked several questions regarding the potential importance of several factors associated with the open doors – fresh air, breezes, views, and daylight availability. Table 13 shows the number who rated these features as "somewhat" or "very" important. The data indicates that each of these attributes is considered personally important to a majority of the occupants. There were no statistically significant differences between the two lighting conditions on the distribution of the ratings ("ns" = not significant). This suggests the ratings of these features are independent of the ceiling light.

Table 13. Ratings of the Importance of Environmental Features:
(Percent rating as "Somewhat" or "Very" Important)

Feature	Baseline	Sulfur lamp	Chi Square
Daylight	66%	62%	2.88 (ns)
View to outdoors	65%	58%	3.41 (ns)
Fresh air	83%	76%	8.35 (ns)
Breezes	77%	70%	4.63 (ns)

Overall ratings of lighting conditions

The survey asked occupants to rate the lighting on three dimensions: (1) the lighting as compared to other work settings; (2) an overall rating of the lighting in the hanger facility; and (3) the ceiling light by itself.

The data show that pre- and post-retrofit conditions differed significantly on two of these dimensions. Specifically:

- Under the sulfur lamp conditions, 47 percent of the occupants said the overall lighting was better than in other work settings. In contrast, 27 percent in the baseline conditions rated the hanger lighting as better (Chi Square = 10.18, p=0.07).
- In judgements of ceiling light only, the sulfur lamp conditions were also more highly rated, with a 19 percent increase in ratings of "good" or "excellent" – from 26 percent under the baseline conditions, to 44 percent under the sulfur lamp conditions. (Chi Square = 11.68, p=0.02).

There were no significant differences in overall ratings of the lighting, taking into account all sources. This may be because many problems existed under both conditions and these were not affected by the introduction of the sulfur lamp.

Physical symptoms

The survey asked occupants to rate the frequency with which they experienced various physical problems (e.g., sore back, headaches, sore neck). Sore backs and sore necks were prevalent under both conditions. Almost half of the workers experienced sore backs, and slightly more than 80 percent had sore neck or shoulders "often" or "always" under both lighting conditions. In addition, 30 percent experienced sore eyes and 20 percent experienced headaches "often" or "always" under both lighting conditions. There were no differences between the two lighting conditions on any of these measures indicating there is no correlation between these conditions and the lighting system. The nature of the work around and under an aircraft is a likely source of these conditions regardless of lighting conditions.

References

1) CIE Technical Committee 1995. "Brief History of Illumination With Hollow Light Guides" *Hollow Light Guide Applications*, TC 3-30, Vol. I, pp.-3, March 1995.

2) J.T. Dolan, M.G. Ury and C.H. Wood. 1992 "A Novel High Efficiency Microwave Powered Light Source." Presented as a landmark paper September 2, 1992, at Sixth International Symposium on the Science and Technology of Light Sources Technical University of Budapest.

3) *Lighting Handbook*, Eighth Edition, Chapter 4 - "Color", pp. 107-134, The Illuminating Engineering Society of North America, New York, NY 10005, 1995.

4) "Power Quality". *Lighting Answers*, National Lighting Product Information Program, Vol 2, Number 2, February 1995.

5) Snedecor and Cochran. 1980. *Statistical Methods*, 7th. ed.

6) "Specifier Reports - Screwbase Compact Fluorescent Lamp Products," National Lighting Product Information Program, Vol. 1, Issue 6, April 1993, page 5.

APPENDIX A

Hill Air Force Base Retrofit Lighting Study Survey Questionnaire

Hill Air Force Base

Lighting Study Survey Questionnaire

BACKGROUND INFORMATION

Age group: ☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ over 55

Gender: ☐ M ☐ F

At work do you normally wear:

- ☐ Contacts?
- ☐ Eyeglasses? (Do the glasses have bi-focal or tri-focal lenses? ☐ Y ☐ N)
- ☐ Reading Glasses?

To your knowledge are you colorblind/color deficient? ☐ Y ☐ N

Do you have cataracts or other vision impairments that currently effect your vision? ☐ Y ☐ N

IF YES, please describe: ____

To what extent does your job require you to:	Not At All	Somewhat	Moderately	Very Much
View written materials/drawings on a computer screen?	☐	☐	☐	☐
Enter data into a computer?	☐	☐	☐	☐
Read paper manuals or texts?	☐	☐	☐	☐
Distinguish between different colors?	☐	☐	☐	☐
Move around in confined spaces?	☐	☐	☐	☐
View things from awkward angles?	☐	☐	☐	☐
Read small print?	☐	☐	☐	☐
View objects with fine detail?	☐	☐	☐	☐
Manipulate small objects?	☐	☐	☐	☐

How frequently do you use:	Never	Rarely	Sometimes	Often	Always
A flash light?	☐	☐	☐	☐	☐
A movable, stand mounted task light?	☐	☐	☐	☐	☐
Overhead lighting only (no flash light or additional task light)?	☐	☐	☐	☐	☐

Listed below are some problems people can experience with lighting in their work place. For each of these, please rate how much of a problem each of these situations presents for you.

	Not At All	Somewhat	Moderately	Very Much
Not enough light to see fine details	☐	☐	☐	☐
Reflections on the computer screen	☐	☐	☐	☐
Glare or too much light from ceiling lights	☐	☐	☐	☐
Glare or too much light from task lights	☐	☐	☐	☐
Shadows in the task area	☐	☐	☐	☐
Noise from the light fixtures	☐	☐	☐	☐
Flicker from the overhead lights	☐	☐	☐	☐
Too much heat from the lights	☐	☐	☐	☐
Inability to control the lighting	☐	☐	☐	☐
Too little light in spaces between aircraft	☐	☐	☐	☐
Lighting makes colors look unnatural	☐	☐	☐	☐
Light not available where it is needed	☐	☐	☐	☐
Not enough daylight	☐	☐	☐	☐
Lack of view to the outdoors	☐	☐	☐	☐
Other: ________________________	☐	☐	☐	☐

If you experience any of the above problems:

To what extent are you able to take actions that resolve the problems?

Not at all	Somewhat	Moderately	Completely
☐	☐	☐	☐

To what extent do these problems interfere with your ability to do your work?

Not at all	Somewhat	Moderately	Very much
☐	☐	☐	☐

Please use the following 7-point scale to indicate how easy or difficult it is to read each of the four sentences·

	Unable ~~To Read~~ 1	2	3	4	5	6	Very Easy ~~To Read~~ 7
While other plants put the sun's energy to work, the fungus must look elsewhere	☐	☐	☐	☐	☐	☐	☐
The end result of this project will be a sky atlas that includes 1,870 photographs of celestial bodies and their statistics.	☐	☐	☐	☐	☐	☐	☐
Whenever you see a pile of leaves turning to compost, you are watching a fungus eating. The fungus has become the earth's scavenger.	☐	☐	☐	☐	☐	☐	☐
Sky Survey astronomers have made scores of important discoveries including the fact that our universe is probably twice as old as previously believed. The Sky Survey indicates that the universe is probably more than 4 billion years old	☐	☐	☐	☐	☐	☐	☐

Listed below are a number of work related experiences. Please indicate how frequently each experience occurs for you on average. Check the number that best reflects your feelings:

	Never	Rarely	Sometimes	Often	Always
Feeling soreness in your neck or shoulders at work	☐	☐	☐	☐	☐
Experiencing soreness in your lower back	☐	☐	☐	☐	☐
Experiencing headaches while at work	☐	☐	☐	☐	☐
Having difficulty focusing your eyes	☐	☐	☐	☐	☐
Having a sore throat while at work	☐	☐	☐	☐	☐
Experiencing tired or sore eyes while at work	☐	☐	☐	☐	☐

OVERALL LIGHT RATINGS:

Compared with similar kinds of work settings, do you think the lighting in this facility is:

Much Worse	Somewhat Worse	About the Same	Somewhat Better	Much Better
☐	☐	☐	☐	☐

How would you rate the lighting overall, taking into consideration all light sources (ceiling, task mounted lights, daylight, flash lights)

Excellent	Good	Fair	Poor	Very Poor
☐	☐	☐	☐	☐

How would you rate the ceiling light?

Excellent	Good	Fair	Poor	Very Poor
☐	☐	☐	☐	☐

When the bay doors are open how does this affect the lighting quality in the facility? Is it:

Much Worse With Doors Open	Somewhat Worse With Doors Open	No Difference	Somewhat Better With Doors Open	Much Better With Doors Open
☐	☐	☐	☐	☐

With the bay doors open, you can also see outdoors as well as have fresh air and daylight. How important to you are each of these features?

	Very Unimportant	Somewhat Unimportant	Neutral	Somewhat Important	Very Important
Daylight	☐	☐	☐	☐	☐
View to the outdoors	☐	☐	☐	☐	☐
Fresh air	☐	☐	☐	☐	☐
Breezes	☐	☐	☐	☐	☐
Other: ________________	☐	☐	☐	☐	☐

Are there any other comments you would like to make about the lighting or other aspects of the environment that we have not asked about?

____
____
____
____

Please fill in the last four digits of your social security number: ☐ ☐ ☐ ☐

(This information will not be used to identify you; it will be available only to the research team and will only be used for matching your responses to the first and second lighting surveys.)

Thank you for your help

APPENDIX B

Aircraft Work Location Pre- and Post-retrofit Light Level and Luminance Data, Daylight Characterization, and Measurement Location Sketches

Aircraft Work Location Pre- and Post-retrofit Light Level and Luminance Data, Daylight Characterization, and Measurement Location Sketches

Vertical illuminance values were taken along known work areas of the F-16 aircraft in order to compare the capabilities of the pre- and post-retrofit lighting systems. The following tables present the values measured in foot-candles. The attached measurement sketches are necessary to determine exact measurement points. The results of these test (while mixed due to equipment shadowing and non-exact placement of pre- and post- aircraft) do indicate a definite increase in the illumination in these locations.

Dock 45 (F-16) - Vertical ILLUMINANCE at 72 and 100 inches from floor at HAFB March 21, 1997 (Pre-) and April 13, 1998 (Post-) BLDG 2

These measurements were taken along the aisleway side of the F16.
One set at approximately 100 inches from the floor, the other set at 72 inches from the floor.
Another set at 72 inches from the floor.
Accompanying drawings are necessary to determine exact measurement locations.

At 100" from floor above edge of wing

distance from first protrusion of wing (ft)	Pre- vertical fc	Post- vertical fc
0	23.6	30.4
2	25.5	30
4	25.6	29.7
6	26.1	27.6
8	25.2	28.4
10	25.3	27.8
12	26.4	27.5
14	22.9	23.6
16	NA	NA
18	NA	NA
20	NA	NA
22	NA	NA
24	NA	NA
26	NA	NA
28	28.5	29.2
30	28.9	29.3
32	29.5	30.9
34	31.1	32.1
Average	26.6	28.9

Centered at top of each access panel at top of aircraft on aisleway side at ~100 in.

Panel code	Pre- vertical fc	Post- vertical fc
P1	23.6	31.1
P2	23.7	31.5
P3	23.2	32.5
P4	26.9	34
P5	25.7	24.9
P6	27.2	32.6
P7	26.9	32.8
P8	28.3	31.5
Average	25.7	31.4

At 72" from floor under wing along fuselage with both stand task lights on

distance from first protrusion of wing (ft)	Pre- vertical fc	Post- vertical fc
0	18.5	12
2	16.8	20.6
4	22.4	9.8
6	30	10.1
8	35.8	31.8
10	37.2	35.5
12	36.4	39.2
14	16.3	33.6
16	31.2	25
18	21.5	17.8
20	15.2	11.6
22	9.8	8.9
24	6.4	10
26	9.1	18.4
28	8.8	20.1
30	7.7	18.3
32	5.8	15.1
34	4.9	27.8
Average	18.5	20.3

Vertical illuminance values were also taken along known work areas of the C-130. These values indicate more drastic increases in light levels with the retrofit lighting with light levels at least doubled. Individual measurements indicate the variability associated with equipment placement.

Hangar 2 (C130) - Vertical/Horizontal ILLUMINANCE on aircraft at HAFB March 21,1997 (Pre-) and April 13, 1998 (Post-) BLDG 22

Vertical and Horizontal measurements taken at specific points
Top front edge of elevator (1,2,3)
Along side seam between elevator and wing (4,5,6,7)
At bottom of right rear door (1 ft, 2ft, 3ft out)
Accompanying drawings are necessary to determine exact measurement locations.

Mid-heighth of C130 along elevator and between elevator and wing

	Vertical fc		Horizontal fc	
Location	Pre-	Post-	Pre-	Post-
1	13.0	17.4	22.5	91.4
2	16.9	37.3	62.7	113.0
3	22.9	53.9	53.7	122.0
4	11.0	46.0	48.5	124.0
5	9.2	39.6	55.2	118.0
6	8.9	27.1	58.1	111.0
7	8.7	16.3	61.0	109.0
8	13.2	41.3	51.7	98.5
9	11.6	26.7	46.4	95.0
10	9.9	15.4	46.3	85.0
11	13.6	35.0	50.5	109.0
12	12.8	31.9	66.9	106.0
13	20.5	35.2	65.1	113.0
14	12.9	24.1	27.9	83.7
Average	13.2	31.9	51.2	105.6

At bottom of right rear door

	Vertical fc		Horizontal fc	
Location	Pre-	Post-	Pre-	Post-
1 ft out	9.6	10.3	14.9	20.2
2 ft out	10.4	24.9	21.9	40.8
3 ft out	10.3	25.0	23.6	66.8
Average	10.1	20.1	20.1	42.6

The luminance (light exiting a surface) was also measured at selected locations for both aircraft. The following data for the F-16 locations shows strong increases as expected.

Dock 45 (F-16) - Vertical LUMINANCE on aircraft at HAFB April 3, 1997 (Pre-) and April 13, 1998 (Post-) BLDG 225
All values taken after dark, with litemate II and spotmate, all overhead lights on but no task lights ~ 20-30 feet away.

Luminance (footlamberts)			
Location	Pre-	Post-	Notes:
1	6.3	13.35	near tip of aircraft in middle of gray nose cone (NE side)
2	12	18.9	at top edge of aircraft just below back edge of black cockpit console (NE side)
3	1.3	1.56	just under wing 2.5' forward of the vertical centerline of the rear wheel (NE side)

For the C-130 locations, the luminance of the surfaces also increases with the retrofit lighting and in these cases the levels double and triple.

Hangar 2 (C130) - Vertical LUMINANCE on aircraft at HAFB April 3, 1997 (Pre-) and April 13, 1998 (Post-) BLDG 225
All values taken after dark, with litemate II and spotmate, with all overhead lights on but no task lights ~20-30 feet away.

Luminance (footlamberts)			
Location	Pre-	Post-	Notes:
1	4.2	9.9	just to left of rear side door at level of top of gear housing protrusion (NW side)
2	5.3	18.6	just to right and below funnel shaped pull out bracket near front of gear housing protrusion (NW side)
3	6.0	18.3	just above middle small circular window ahead of gear housing protrusion (NW side)

A characterization of the contribution of daylight within the hanger space is shown in the chart below. The daylight contribution to the light level directly on the floor when the door is fully open is greatly reduced after approximately 60 feet in from the hanger door. However, the contribution at this point is still approximately 20 foot-candle above the light level provided by the pre-retrofit lighting. The daylight contribution with the doors partially open ranges from doubling the pre-retrofit artificial lighting level near the door to an insignificant contribution at between 50 and 60 feet into the hanger.