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Security Lighting for Nuclear Weapons Storage Sites: A Literature Review and Bibliography

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National Bureau of Standards

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FOREWORD

The Defense Nuclear Agency (DNA) is engaged in a continuing effort to enhance the security of nuclear weapons storage. In this effort, it is receiving technical support from the National Bureau of Standards' Law Enforcement Standards Laboratory (LESL), whose overall program involves the application of science and technology to the problems of crime prevention, law enforcement and criminal justice.

LESL is assisting DNA's physical security program with support in the behavioral science, the chemical science and the ballistic materials areas, among others.

Among the tasks being performed by LESL for DNA are the preparation and publication of several series of technical reports on the results of its researches. This document is one such report.

Technical comments and suggestions are invited from all interested parties. They may be addressed to the authors of the report or to the Law Enforcement Standards Laboratory, National Bureau of Standards, Washington, D.C. 20234.

Jacob J. Diamond, *Chief*
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SECURITY LIGHTING FOR NUCLEAR WEAPONS STORAGE SITES: A LITERATURE REVIEW AND BIBLIOGRAPHY

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The Defense Nuclear Agency (DNA) program to enhance the security of nuclear weapons storage facilities includes the consideration of not only physical barriers and alarm systems but security lighting as well. This report presents a literature review and bibliography dealing with the optimization of Nuclear Weapons Storage Site (NWSS) security lighting through the application of established principles of psychological and behavioral functioning. Three distinct psychological/behavioral processes are relevant to the design of security lighting systems: (1) deterrence, (2) detection, and (3) incapacitation. General recommendations for NWSS security lighting system design are provided, based on the literature review and analysis.

Key words: Contrast; detection; illumination; incapacitation; psychological deterrence; recognition; security lighting; security systems; visibility level; visual processes.

1. INTRODUCTION

During recent years, the Defense Nuclear Agency (DNA) has focused its attention upon the adequacy of contemporary nuclear weapon storage facility security procedures and safeguards, concluding that improvements are essential to meet the threat posed by present-day intrusion capabilities. Recognizing that the ultimate effectiveness of any security system is limited by the human element, both intruder and response force personnel, DNA has elected to augment its development effort by utilizing a technical approach that includes behavioral science investigation as an active research component. The development of security systems having known and measurable behavioral impact will not only result in optimum performance, but also ensure that it has life-cycle cost effectiveness, a major DNA concern.

The DNA program to enhance the security of nuclear weapons storage facilities includes the consideration of not only physical barriers and alarm systems but security lighting as well. While security lighting is accepted as an integral part of a security system for controlled-access facilities, most requirements are based solely upon illumination level, with little consideration of the impact of various lighting techniques upon intruder and response force behavior and operational efficiency.

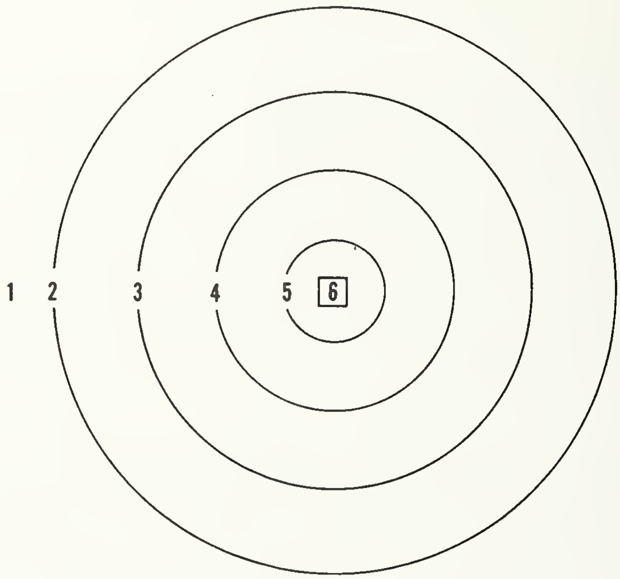
The purpose of this report is to provide DNA with a review of the unclassified literature related to those psychological and behavioral principles that have potential application to the design of optimum security lighting systems for nuclear weapon storage sites (NWSS). It should be noted, however, that the concepts and principles discussed in this report are also generalizable to other potential nuclear theft target areas. Future efforts will expand the analysis of security lighting systems to include the influence of deleterious atmospheric effects, such as fog, snow, rain, smoke and dust, upon the performance of these systems.

2. CURRENT NWSS SECURITY PHILOSOPHY

Detailed information concerning current NWSS security philosophy and the tactical considerations of anticipated nuclear theft threats (e.g., intruder characteristics, probable intrusion scenarios and response force capabilities) has been presented elsewhere [7,86,91].[1] While these reports are highly recommended as background reading for the present study, a brief review of current NWSS security philosophy should suffice as a prelude to the discussion of general security lighting principles presented in this report.

Current NWSS security philosophy emphasizes the "maze" concept as the best approach for deterrence of the full continuum of NWSS intrusion threats, i.e., low-level threats as possibly represented by vandals, medium-level threats as possibly represented by burglars, and high-level threats as possibly represented by terrorists. In this approach, the intruder encounters a series of progressively more difficult, confusing and/or harmful physical barriers and obstructions. The farther into the system the intruder goes, the greater are the risks of his detection, disablement, serious injury or death. Figure 1 presents a schematic representation of the maze concept in NWSS security philosophy. Each "ring" in figure 1 represents a progression (in time as well as space) of successively more sensitive detection and potentially harmful denial systems.

The concept of delay is extremely important in current NWSS security philosophy. Each additional minute consumed by an intrusion force provides additional time for security forces to respond and thwart the intrusion attempt.



1. Extra-perimeter area (clear zone)
2. Perimeter barrier
3. Inner barrier
4. Inner barrier
5. Nuclear Weapons Storage Unit(s)
6. Nuclear device(s)

FIGURE 1. *Nuclear weapons storage site.*

[1] Numbers in brackets refer to the bibliography at the end of this report.

This reliance upon backup security forces implicitly accepts the notion that no automated physical security system should be considered completely foolproof. Well-trained and prepared security forces should represent a reliable line of defense, and are therefore considered to be an important element of the security system—perhaps the most important.

In support of this philosophy, a great deal of emphasis is currently being placed upon the human element in security systems. Communication, logistics, and training are all of primary importance. From a total systems viewpoint, both the physical and psychological/behavioral components of the NWSS security system should be designed primarily to aid security surveillance and response teams in the conduct of their duties.

3. SECURITY LIGHTING—LITERATURE REVIEW

3.1. Introduction

For the purposes of this report, three distinct psychological/behavioral points of view are employed in the analysis and evaluation of optimum NWSS security lighting system design. These points of view involve the design of security lighting systems to achieve optimum conditions for intruder: (a) psychological deterrence, (b) visual detection and identification, and (c) visual incapacitation. Since there is little overlap in the literature most relevant to each of the above points of view, they are discussed independently in sections 3.3-3.6. While general recommendations for NWSS security lighting system design based upon these points of view are presented throughout the text of this report, they are summarized as a unit in section 4. The implications of the findings of this report to future research requirements are presented in section 5.

3.2. Conduct of the Literature Search

The literature search was conducted in three phases:

1. Identification and location of potentially relevant publications. This phase included:
   - (a) computerized searches of Defense Documentation Center (DDC) Abstracts, National Technical Information System (NTIS) Abstracts, and Psychological Abstracts Search and Retrieval Services (PASAR),
   - (b) manual searches of card catalogues and bound abstract volumes found in libraries in the Washington, D.C. area, and
   - (c) contacts with authorities in the fields of security lighting and visual detection.
2. Selection of the publications most relevant to the areas of intruder deterrence, detection, identification and incapacitation.
3. Review of the selected publications. Section 6 provides a complete bibliographic listing of the publications reviewed during the preparation of this report. All reference citations refer to this bibliographic listing.

3.3. Deterrence Value of Security Lighting Systems

An important objective of security lighting installations in and around a NWSS is the deterrence of potential intruders from initiating an intrusion attempt. Theoretically, the magnitude of the deterrence effect should be inversely proportional to the intruders' subjective estimate of the probability of their being visually detected and apprehended by NWSS security forces. The greater this estimate of apprehension probability, the more likely they are to be deterred from initiating the intrusion attempt. It follows, then, that there may be a direct relationship between a security lighting system's illumination effectiveness and its deterrence value. The greater the illumination effectiveness, e.g., the more "visible" it makes the intruder, the greater should be the intruders' estimates of their apprehension probability, and hence the more likely they are to be deterred or to seek alternative targets possessing reduced illumination effectiveness. This relationship assumes, of course, that there are active security surveillance forces within the immediate area of the potential intrusion area, and that these forces pose some real threat to the intruders involved.

3.3.1. "State-of-the-Art" Security Lighting Principles and Recommendations

With the above basic concept in mind, security and illumination experts from both industry and academia have made numerous recommendations and "rules-of-thumb" for designing effective security lighting systems for industrial and residential settings. The most important and widely accepted of these guidelines are those published by the Illuminating Engineering Society (IES) [1,2,93]. Similar guidelines have appeared in numerous other professional publications [13,29,72,74,81,82]. In general, these publications present useful information concerning (a) "state-of-the-art" security lighting hardware design (e.g., luminaries, circuitry, and engineering specifications), (b) general techniques for effective security lighting system design and installation and (c) specific illumination level recommendations for general security lighting situations. The salient principles and qualitative and quantitative recommentations for effective security lighting systems as advocated by IES [2] are as follows:

(A) Effective security lighting is achieved by:

1. Adequately illuminating boundary areas.
2. Directing glare into the eyes of potential intruders.
3. Directing glare away from the eyes of security guard forces.
4. Maximizing luminance contrast between intruder and background.

(B) Two general methods of effective security lighting are:

1. Illuminating boundary and approach areas, and/or
2. Illuminating the area and structures within the boundaries.

(C) To be effective, security lighting should:

1. Deter potential intruders.
2. Make intruder detection certain should entry be effected.
3. Avoid glare which handicaps guards and/or other personnel authorized to be in the immediate area of the security lighting system.
4. Insure complete reliability of the security lighting system components.
5. Provide additional illumination for areas most susceptible to intrusion.
6. Provide adequate illumination.
7. Provide convenient controls and maintenance.
8. Provide supplementary searchlights for searching outside the boundary, or augment fixed lighting systems in emergency situations.
9. Locate all poles and auxiliary equipment within the confines of the secured area, or where they are not readily accessible to damage.

(D) Table 1 presents the minimum illumination levels (measured horizontally at ground level unless otherwise indicated) for various security lighting applications.

TABLE 1. *Minimum horizontal illumination levels (at ground level) for various security lighting applications as recommended by IES*

Application	Width of lighted strip: Inside boundary	Width of lighted strip: Outside boundary	Minimum at any point on ground	Illumination within lighted strip — Maximum permissible variation range: Along boundary line	Illumination within lighted strip — Maximum permissible variation range: Throughout lighted strip
Isolated fenced boundary (glare projection system)[1]	7.6 m (25 ft)	61.0 m (200 ft)	1.6 lux (0.15 fc)	---	10:1
Isolated fenced boundary (all other lighting methods) and semi-isolated boundaries	3.0 m (10 ft)	21.3 m (70 ft)	0.4 lux (0.04 fc)	6:1	25:1
Nonisolated fence boundaries for small and large served areas	6.1 m (20 ft) 9.1 m (30 ft)	12.2 m (40 ft) 9.1 m (30 ft)	0.9 lux (0.08 fc) 1.1 lux (0.10 fc)	6:1 6:1	15:1 19:1
Building faces with at least 20 ft (6.1 m) of clear space between building and fenced boundary	12.2 (40 ft) total width from building face		1.1 lux (0.10 fc)	6:1	15:1
Building faces with un-fenced boundaries	24.4 m (80 ft) total width from building face		0.4 lux (0.04 fc)	10:1	30:1
Waterfront boundaries	3.0 m (10 ft)	15.2 m (50 ft)	1.1 lux (0.10 fc)	8:1	20:1
Entry/Exit points (pedestrian)	7.6 m (25 ft)	7.6 m (25 ft)	21.5 lux (2.0 fc)	---	5:1
Entry/Exit points (automotive)	15.2 m (50 ft)	15.2 m (50 ft)	10.8 lux (1.0 fc)	---	10:1

[1] Illumination levels and uniformity ratios listed are for vertical surface, 0.9 m (3 ft) above ground and parallel to fence.

While the security lighting principles and recommendations advocated by IES and supported by many independent security lighting experts [72,74,82] are of considerable general value, their direct applicability to the lighting of a NWSS is limited. The reasons for these limitations are: (a) the recommendations were originally intended to apply to only industrial and residential settings; (b) the recommendations were derived nearly 30 years ago by primarily intuitive means and hence lack an empirical basis; (c) the recommendations are overly general and do not make allowances for specific environmental conditions known to affect intruder visibility (see sec. 3.4); (d) the recommendations do not take into account the illumination requirements of modern closed-circuit television (CCTV) surveillance monitoring systems [28]; and (e) the recommendations are in illumination terms (foot-candles or lux) and cannot readily be interpreted in terms of human visual information processing needs (see sec. 3.4).

3.3.2. Subjective Impressions or "Mood" Elicited by Security Lighting Systems

The deterrence value of a security lighting system is associated not only with potential intruders' cognitive estimates of apprehension probabilities, but also with the subjective impression or "mood" which the lighting system induces. The more "foreboding" and "hostile" a NWSS is made to appear through special lighting effects, the less inclined a potential intruder should be to initiate a break-in attempt. Unfortunately, very little basic research has been conducted dealing with the relationship between lighting and emotional state. New procedures are being developed, however, to investigate this important lighting effect [45] and useful principles for the design of "emotionally" deterrent lighting systems may be derived in the future.

3.3.3. Empirical Evaluation of the Effectiveness of Security Lighting as a Crime Deterrent

The purported effectiveness of security lighting in the reduction of urban, industrial and residential crime is documented in the literature [31,79,81,104,113]. It is known that approximately 75 percent of all urban burglaries against commercial establishments occur during the hours of darkness against buildings having either no lighting or inadequate lighting [79]. Similarly, the frequency of urban crime is known to be highly correlated with the total number of hours of darkness during the course of a given 24-hour period [31]. Comparisons of urban crime patterns both before and after new urban street lighting was installed tend to show that increased light levels result in a reduction in crime (see table 2 for values typically claimed). With respect to the latter studies, it should be noted that the crime reductions observed frequently occurred in high-crime areas of the cities involved and that crime rates frequently increased in neighboring low-crime areas of the city which had not received the new street illumination system [113]. In some cases, there was evidence of a shift to increased crime in the daytime.

While the above evidence appears to suggest that security lighting is a crime deterrent, the results are not conclusive. In several instances the results are contradictory and misleading. The lack of appropriate experimental control has also been evidenced in past studies. Even if a deterrent effect could be conclusively demonstrated, it is questionable whether such an effect can be generalized to the context of the NWSS. The differences between urban crime and the theft of a nuclear weapon are great [91]. Clearly, a highly motivated, trained, and prepared group of terrorist intruders contemplating a full-scale, overt attack against a NWSS is not likely to be deterred by the mere presence of intense and foreboding security lighting. A more detailed discussion of the appropriateness and limitations of the security lighting systems within the framework of the NWSS security philosophy will be presented in section 4.

TABLE 2. *The relationship between street lighting and crime rate—typical claims*[1]

City reporting	Reported effect in areas of the city receiving improved lighting
Chicago, Illinois	85% decrease in robbery 10% decrease in auto theft 30% decrease in purse snatching
Detroit, Michigan	55% decrease in street crime
Kansas City, Missouri	52% decrease in robbery 41% decrease in assault 26% decrease in property theft
New York, New York	50-80% decrease in vandalism
St. Louis, Missouri	40% decrease in stranger-to-stranger crime 29% decrease in auto theft 13% decrease in burglary
Washington, D.C.	25% decrease in robbery

[1] These statistics are derived from reference [104], with the exception of statistics for Kansas City, Mo., which are from reference [113].

3.4. Intruder Visual Identification

Optimization of intruder visual identification probabilities serves a dual purpose: (a) it may serve as a deterrent against potential intrusion attempts, and (b) it may increase the likelihood of an intruder being apprehended once an intrusion has commenced.

3.4.1. Visual Target Detection Models: One Possible Framework for NWSS Security Lighting System Design

Many variables are involved in the optimization of target (intruder) identification probabilities in an unstructured field of search (the NWSS). These variables are known to interact in complex ways which have only recently begun to be understood. While an exhaustive review of the target detection literature is beyond the scope of this report, a brief discussion of the topic based upon mathematical models developed by the Rand Corporation [3,94] and Honeywell, Inc. [111] should suffice to introduce the major concepts. It should be noted that many of the variables considered in these models are of only indirect relevance to the optimization of security lighting design, per se, yet are extremely important in terms of total security system design. Consideration of these variables is important to ensure harmonious interaction among the various components of the total security system. Those variables which are of direct relevance to lighting design will be discussed in detail in section 3.5.

According to the Rand model, there are three basic factors which, when multiplied, should give an overall estimate of NWSS intruder identification probability:

$$P_{ID} = P_S P_D P_R$$

where:

P_{ID} is the probability of intruder identification,

P_S is the probability that a security observer visually searching the NWSS perimeter will look in the direction of an intruder with his foveal vision,

P_D is the probability that if an intruder is viewed foveally for one glimpse period he will be detected, and

P_R is the probability that if an intruder is detected, he will be recognized by the observer as being an intruder.

Each of the component probabilities in this model is discussed separately in the following sections.

3.4.1.1. The Probability of Successful Visual Search, P_S

Visual search strategies are of three basically different types: (a) random search, i.e., the observer randomly fixates successive points in the field of search, (b) systematic search, i.e., the observer systematically fixates successive points in the field of search according to some preplanned search strategy, and (c) adaptive search, i.e., the observer automatically reacts to both the overall character of the field of search and the anticipated target and alternates between random and systematic search patterns in accordance with his perception of moment-to-moment changes in the search requirements. It is the latter strategy which most observers adopt spontaneously [3,111] and which is assumed by this general target detection model.

It is well known that the eye moves in discrete steps during visual search, ordinarily at a rate of approximately three fixations per second [47]. This rate may vary considerably from second to second, but it does represent a good, overall average for an extended period of visual search. Thus an experienced observer searches by adaptively moving an aperture (i.e., his foveal vision) over an area of interest, making fixated observations at an average rate of about three per second. The distance between successive fixations, and, hence, the effective size of the scanning aperture and the moment-to-moment search rate, are continually being adjusted to meet the *a priori* requirements of the search task. The size of the effective scanning aperture during a single visual fixation (also known as the glimpse aperture, Ag) commonly ranges from 10 to 100 times the area of the anticipated target, a_T, depending primarily upon the amount of "false target congestion" within the field of search.

Based upon the above concepts, Bailey [3] has derived and empirically verified a mathematical expression for estimating the probability of successful visual search. Translated into the context of NWSS security surveillance, this expression is:

$$P_S = 1 - e^{-K\,[3t/(A_s/ka_T)]}$$

where:

- P_S is the probability of looking foveally in the direction of the intruder,
- e is the base of the natural logarithms,
- K is an empirically derived constant (K and k are reciprocally related, i.e., they maintain a constant product),
- t is the amount of time the intruder is visible within the observer's field of view,
- A_s is the total area of the field of search,
- k is a parameter related to "false target congestion" within the field of search, and
- a_T is the target (intruder) area.

It should be noted that the total number of glimpses (each of area $Ag = ka_T$) needed to completely search a total area of A_s is A_s/A_g. At an average rate of three glimpses per second, the number of glimpses available during the time, t, the intruder is visible is 3t. The exponential form of the relationship between P_s and t was suggested by Williams [111] and later empirically demonstrated by Boynton and Bush [20].

The implications of Bailey's expression for P_S for security system design are that to increase the probability of successful visual search, P_S, by a given security observer, the system should:

(a) maximize the amount of time, t, the intruder is visible within the observer's field of search,[2]

(b) minimize the total amount of area, A_s, required to be searched by the guard,

(c) minimize the amount of "false target congestion," k, within the guard's field of search, and

(d) maximize the visual area (size of the foveal image) of the intruder, a_T.

[2] This implies that lighting components must be integrated with other elements of the physical security system; e.g., fences and barriers.

Placed within the context of security recommendations, the above findings imply that NWSS security system effectiveness can be improved by:

(a) increasing the number of guards, or decreasing the size of the NWSS,

(b) decreasing the number of confusing objects and/or shadows which might be mistaken for intruders, and

(c) locating guards as close as possible to likely areas of intrusion, providing guards with appropriate visual aids and/or using special lighting techniques.

3.4.1.2. The Probability of Intruder Visual Detection, P_D

In the Rand model, the probability of target visual detection, P_D, is derived from estimates of the visual contrast detection capabilities of the human visual information processing system under varying environmental conditions. This part of the model is directly concerned with the concept of "intruder visibility." Again, translated into the context of NWSS security, the mathematical expression required for estimating the probability of intruder detection is:

$$P_D = 1/2 \pm 1/2 \left[1 - e^{-4.2[(C/C_T)-1]^2}\right]^{1/2}$$

where:

P_D is the probability of intruder detection,

e is the base of the natural logarithms,

C is the contrast of the intruder's image at the eye, where contrast is defined as the absolute value of the difference between target luminance, L_T, and background luminance, L_B, divided by the background luminance, $C = (L_T - L_B)/L_B$, and

C_T is the contrast threshold (the contrast level detectable 50% of the time) for the average observer for a given target (intruder) size at the retinal image, and the minus sign is used whenever $C < C_T$.

The expression for P_D implies that, to increase intruder detection probability, a security system should:

(a) maximize intruder-to-background contrast, and

(b) maximize observer contrast threshold sensitivity.

Within the context of security system recommendations, this would imply:

(a) designing lighting systems which optimize intruder-to-background contrast by either increasing the luminance of the intruder while decreasing the luminance of the background, or the converse, and

(b) selecting guard force personnel on the basis of visual threshold contrast sensitivity.

While the Rand expression for P_D does provide some generally useful insights into the conditions under which optimum visual detection probabilities should be expected, it is unfortunately based upon an oversimplified view of target visibility based upon Blackwell's earlier work [8]. Recent advances in the measurement and prediction of target visibility are much more sophisticated than those used in the Rand model. These advances are discussed at length in section 3.5.

3.4.1.3. The Probability of Intruder Visual Recognition, P_R

In many respects, the probability of intruder recognition, P_R, is the least important factor in the intruder identification probability model. The reason for this is that within the confines of a highly secured area such as the NWSS, security surveillance forces need only be able to detect the presence of an unauthorized intruder to initiate appropriate countermeasures. These countermeasures may involve the use of more efficient (backup) illumination systems, the activation of Forced Entry Deterrent Systems (FEDS),[3] the activation of additional security force teams, etc. The precise action taken by the observer originally detecting the unauthorized intruder will, of course, depend primarily upon the degree of certainty of detection.

There is, however, an element of intruder recognition implicit in the intruder detection response, i.e., the guard must be able to distinguish between an intruder and possible false targets (e.g., bushes, poles and shadows) which might be mistaken as an intruder. Thus, there is the problem of shape recognition; the guard must be able to distinguish between human and non-human forms. The Rand model gives the following estimate of intruder visual recognition probability:

$$P_R = 1 - e^{-[N_r/2)-1]^2} \quad \text{for } N_r > 2,$$
$$P_R = 0 \quad \text{for } N_r \leqslant 2,$$

where:

P_R is the probability of intruder visual recognition, and

N_r is the number of "resolution cells" contained in the shortest dimension across the target to be recognized.

In the context of the NWSS, "resolution cells" might be interpreted as meaning the number of independently visible "spots" across the image of the target. These "spots" lead back to the concept of target visibility, which is discussed in the following section. At this point, however, it should be clear that the expression for P_R implies that, to increase intruder recognition probability, a security lighting system should maximize N_r or, more appropriately, maximize intruder visibility. The specific implications of these relationships to NWSS security lighting design are also discussed in the following section.

3.5. Intruder Visibility

The concept of target "visibility" and its attempted quantification using a linear scale which reflects the information processing capabilities of the human visual system has been a topic of interest in vision sciences for many years [8,14,42,73,78,98,107]. The culmination of this continued interest has been the achievement of a clear understanding of the major variables involved, and the development of extremely sophisticated mathematical models for the prediction and quantification of target visibility level (VL) [11,73,107]. Since an extensive review of the voluminous literature relevant to the VL concept is beyond the scope of this report, an attempt is made to identify and briefly describe each of the major variables involved. A mathematical model is presented which integrates the most important variables into a single unifying concept (no model has, as yet, been developed which incorporates all of the relevant variables).

[3] The acronym FEDS is defined by DNA as those Forced Entry Deterrent Systems which have a measurable impact on one or more of the five human senses (sensory capabilities). When FEDS is used in this study it refers to one of the several deterrent systems under development which may have such an impact.

A classic paper in the field of VL research is that of Luckiesh and Moss [78]. These authors differentiated between several qualitatively different types of VL variables:[4] (a) characteristics of the observer, (b) characteristics of the target and its immediate background, (c) characteristics of the visual task, and (d) modifying factors. The specific variables associated with each of these classifications are discussed below.

3.5.1. Characteristics of the Observer

The characteristics of the observer represent, without question, the "weakest link" in the application of the VL concept. Because of the great variability among individuals [17,46,56,71] it is extremely difficult to quantitatively predict on a person-by-person basis the VL of a given object under a given set of environmental conditions. While some of this variability can be removed by using appropriate observer selection, training and reinforcement techniques, some inter-individual variability will undoubtedly always remain regardless of the variation reduction techniques utilized.

3.5.1.1. Physiological/Pathological Characteristics

The physiological and pathological characteristics of observers underlying the visual information processing system are too numerous to mention individually. They may be acute or chronic, mild or severe, diagnosed or undiagnosed. Typical examples include brain damage, mental deficiency, impaired vision, illness and fatigue. In general, it must be assumed that the observer is healthy, alert and without visual impairments if the VL predictive models are to be applicable.

3.5.1.2. Psychological Characteristics

The number of psychological characteristics relevant to effective visual information processing is too great to enable a comprehensive listing. It must be assumed that the observer is highly motivated, with a positive attitude toward the visual task.

3.5.2. Characteristics of the Target and Its Immediate Background

The characteristics of the target and its immediate background constitute the VL variables of most direct importance to the design of security lighting systems. The design of the lighting system itself ultimately determines many of the visual characteristics of the target and its background. The target/background characteristics of greatest importance are: (a) target size, (b) target movement, (c) target/background luminance contrast, (d) target/background color contrast, (e) background luminance intensity, (f) background luminance uniformity and (g) background glare.

3.5.2.1. Target Size

Target size, or more precisely the retinal image size of the target, has been emphasized as an important visibility factor in numerous studies [40,54,59,64,106]. As would be expected, the VL of a target increases as the image size of the target increases. For a target of relatively standard physical size (e.g., a human), the retinal image size (area) is inversely proportional to the square of the distance between the observer and the target. Furthermore, visual sensitivity varies

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[4] For purposes of brevity and simplicity the hierarchical structure of VL Variables proposed by Luckiesh and Moss has been altered slightly in the present paper. The basic concepts remain unchanged, however. Several additional variables, which were not addressed by Luckiesh and Moss, have been added.

considerably over the retinal surface, being approximately inversely proportional to the cube of the radial distance from the retinal center [63]. The VL of a target is drastically reduced when both of the above relationships act in conjunction, i.e., as the target-to-observer distance is increased and the target image is removed from the retinal center.

Making the situation even more complex is the perceptual phenomenon known as size constancy. Here, although the retinal size changes with changes in distance, the apparent or judged size tends to remain constant. It is as though the distance were being "taken into account" in judging size.

In terms of NWSS security lighting system design, the preceding discussion implies the great importance of (a) locating security surveillance personnel as close as possible to high-probability intrusion areas, and (b) providing security surveillance personnel with optical enhancement aids.[5]

3.5.2.2. Target Movement

The importance of target movement in determining target VL has been stressed in a number of articles [11,97]. Target movement has been incorporated into a modified version of the Rand target detection model discussed earlier [94]. These studies have shown that moving targets are more readily located than static targets, presumably as a result of lower movement detection thresholds in peripheral as compared to foveal vision. That is, moving targets are found more rapidly during the visual search process because they are detected more efficiently in peripheral vision than are static targets.

The implication of the above findings to NWSS lighting design is that intruder detection is most likely to occur when the intruder can be kept in a continual state of motion. This could be accomplished by (a) designing FEDS which prompt intruder movement, (b) increasing the area of illuminated clear zones around the NWSS, and (c) removing all visual obstructions in and around the clear zones.

3.5.2.3. Target/Background Luminance Contrast

In conjunction with target size, the target/background luminance contrast, defined earlier as $[(L_T - L_B)/L_B]$, is perhaps the single most important factor in determining target VL [8,16,51,94,106]. Furthermore, it is this factor more than any other which greatly complicates the specification of minimum illumination levels for general visual surveillance tasks. The visibility of a target is far less dependent on the total amount of illumination falling on the target and its background than it is on the relative luminance differences (i.e., contrast) between the target and its background. Thus, extremely high illumination levels may not succeed in making a low contrast target visible, while extremely low illumination levels may succeed in making a high contrast target visible. The amount of luminance contrast between a target and its background depends on the relative reflectance of their respective surfaces. To make matters more complicated, the VL of a target with a given target/background luminance contrast value will increase as the overall background luminance increases. This is discussed more fully in section 3.5.2.5.

The general implications of target/background luminance contrast to NWSS security lighting system design have already been discussed (sec. 3.4.1.2). Since there is no way of knowing the reflectance (and hence luminance) characteristics of

[5] The possible utility of image magnification and contrast enhancement aids to NWSS security operations has not been specifically considered in the present report. Such devices undoubtedly offer certain advantages (e.g., increase in image size and contrast) and disadvantages (e.g., distortion and small field-of-view) over unaided visual observation. Further information concerning the effectiveness of such devices may be found in references [4] and [102].

an intruder's clothing prior to the intrusion attempt, it is difficult to make specific recommendations concerning the design of NWSS background surfaces and the corresponding optimum levels of illumination. If an intruder is wearing low reflectance clothing, his immediate background should have high reflectance characteristics, while if he is wearing high reflectance clothing, the reverse should be true. However, if it is assumed that an intruder is most likely to wear dark clothing (to prevent detection during approach in non-illuminated, extra-perimeter NWSS areas), it follows that the intruder's immediate background in illuminated intra-perimeter areas should be as bright as possible. This might be accomplished by spraying or paving intra-perimeter areas with highly reflective materials such as chalk dust or concrete. During winter months, snow might provide an ideal background; however, sensible intruders are likely to adopt the countermeasure of light clothing when the ground is covered with snow.

3.5.2.4. Target/Background Color Contrast

Target/background color contrast has been repeatedly shown in the laboratory to play an important role in the determination of target VL [26,41,52,73]. However, the potential applicability of these laboratory findings to real world situations has not as yet been fully realized. In general, the significance of target/background color contrast increases with increasing overall illumination levels, where photopic (color) vision is more sensitive than scotopic (black-and-white) vision, and with decreasing target/background luminance contrast, where the target and its background are of approximately equal brightness. Color contrast results in the greatest target VL's when the target and background colors are opposite each other on the "color circle," i.e., when they are complementary. It must be emphasized that it is not the color contrast as it appears under normal daylight conditions which is important, but rather the color contrast rendered by the specific artificial illumination system under consideration. Some luminaries provide for "true" color rendition, while others, particularly the monochromatic luminaries, emit illumination only over a limited range of wavelengths and consequently remove most color contrast.

The implications for NWSS security lighting system design are: (a) where high intensity illumination is to be used in conjunction with human eye surveillance, luminaries providing simulated daylight conditions are to be recommended and (b) where low intensity illumination is to be used in conjunction with CCTV surveillance, monochromatic luminaries will work satisfactorily.

3.5.2.5. Background Luminance Intensity

It is well known that the contrast sensitivity of the human visual information processing system increases as a function of increasing background luminance[6] [8,15,16,44,57,89]. Furthermore, relative contrast sensitivity (RCS) is more greatly affected by low-level than by high-level changes in background luminance. This relationship is depicted in figure 2.

It can be deduced from figure 2 that target VL increases with increasing background luminance, which in turn increases with increasing total level of illumination, but that the rate of this VL improvement becomes less-and-less significant as the background luminance increases. In other words, at low initial levels of illumination small increases may result in tremendous improvements in

[6] There is still some debate concerning whether contrast sensitivity asymptotically approaches a maximum level with increasing background luminance (the usual finding), or whether it actually begins to decline after reaching a point of maximum efficiency [114]. This decline may be an artifact of the technique used (sinusoidal luminance gratings), the result of "veiling" glare luminance, or a genuine characteristic of the human visual information processing system.

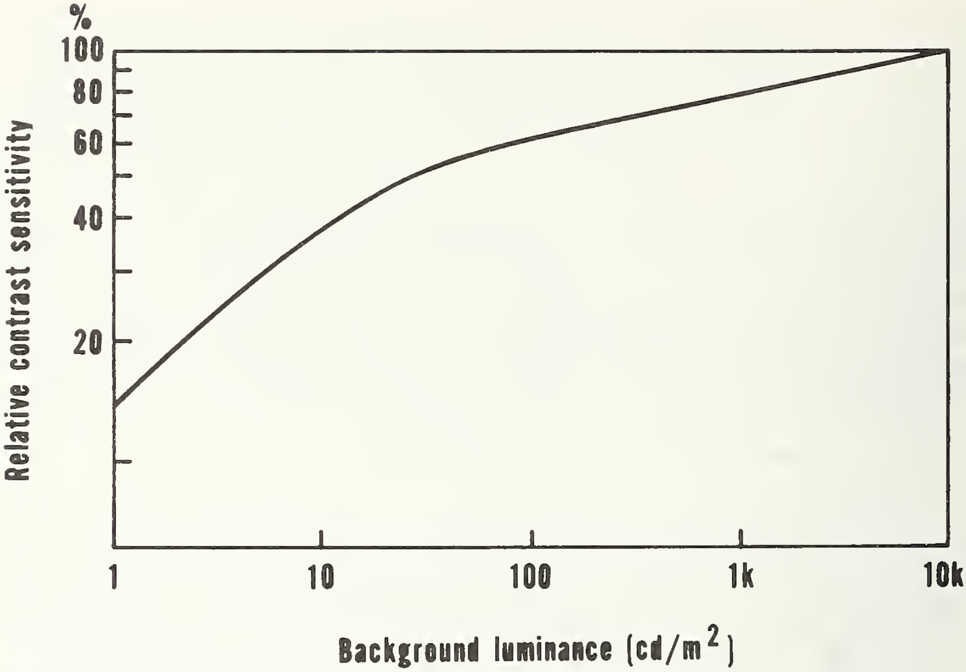


FIGURE 2. *Relative contrast sensitivity as a function of background luminance.*

target VL, while at high initial levels of illumination, large increases may be required to substantially improve target VL.

The implications of the above relationships for NWSS security lighting design are: (a) the greater the amount of total illumination provided at NWSS perimeter areas, the greater the intruder VL's will be, and (b) there is a point of diminishing returns where additional increases in illumination level will not result in substantial increases in intruder VL's. The precise illumination level at which the latter will occur depends primarily upon the many other VL-related variables discussed throughout this report. Furthermore, a complete cost analysis would be required to determine the related financial point of diminishing returns.

3.5.2.6. Background Luminance Uniformity

Uniformity of background luminance influences target VL in three distinct ways. First, it increases the rate at which the search task can be performed by reducing the number of natural fixation points (i.e., dark vs. bright areas) within the search field. Second, it reduces the deleterious effects of transient changes in retinal adaptation level. Third, it causes a drastic constriction of the effective visual field, probably as a result of a narrowing of the attention span. Since the role of false targets in the search task has already been discussed (sec. 3.4.1.1), only the latter two phenomena are discussed here.

Transient adaptation has been repeatedly shown to be an important factor in determining target VL [21-23,96]. A deleterious effect (a momentary loss in visual contrast sensitivity) occurs when the eye momentarily views a bright area and then moves on to view a darker area within which the visual target is located. Although the deleterious effects are not extremely serious when the bright area is in the range of 1370 to 2740 cd/m^2 (400 to 800 fL) or less[7] [2,23], the brief period of insensitivity involved may be sufficient to result in subsequent non-detection of the visual target. The amount of visibility loss to be expected from transient adaptational effects is generally proportional to the ratio of the adaptational change involved [23]. Thus, the greater the amount of luminous non-uniformity within the observer's field-of-view, the greater the potential for deleterious adaptational effects.

Zahn and Haines [115] have shown that visual target detection performance for peripherally presented targets decreases as a function of increasing central (foveal) luminance levels. This "tunnel vision" effect presumably results from a constriction of the active area of directed attention. Since a visual orienting response is known to occur to unusually bright areas [66], it follows that such areas could result in a high degree of distraction and a consequent reduction in the area of effective visual search.

The phenomena discussed in this section indicate that NWSS security lighting systems should be designed such that: (a) illumination sources are of approximately equal intensity, (b) illumination sources are equally spaced around the perimeter areas with sufficient overlap of adjacent ground light patterns to ensure luminous uniformity, and (c) fewer and brighter luminaries with wide-angle beam distributions are used to substantially reduce discontinuous ground luminance patterns.

3.5.2.7. Background Glare

Two forms of background glare are commonly recognized as influencing target VL [68], disability and discomfort glare. Such glare may emanate directly from illumination sources within the observer's visual field, or indirectly from highly reflective objects.

Disability glare results when the retina is peripherally exposed to illumination sources which are considerably brighter than the luminance level to which the eye is foveally centered. It reduces foveal visual performance capability through a process of "veiling" or "masking" the visual target. The magnitude of this veiling effect is a function of both the intensity and location (angular distance from the line-of-sight) of the glare source. For a single illumination source, the amount of visual masking produced can be calculated from the following equation [65,103]:

$$L_v = k \; E\theta^{-n}$$

where:

L_v = amount of veiling (masking) luminance,

k = a constant,

E = illumination from the glare source in the plane of the observer's pupil,

θ = angular distance between the glare source and the observer's line-of-sight, and

n = a constant.

[7] Luminances brighter than 1370 cd/m^2 (400 fL) would not ordinarily be present in the nighttime environment of the NWSS, unless, of course, the observer looked directly into a bright light source. In this case, the observer would suffer from "flash blindness" and "after image" effects, which generally last for a much longer period of time than do transient adaptation effects (see sec. 3.6).

If more than one glare source is present in the field of view the following equation may be used [92]:

$$L_v = 10\,[E_1\theta_1^{-2} + E_2\,\theta_2^{-2} + \ldots E_n\theta_n^{-2}]$$

where n now represents the number of glare sources within the visual field. It should be evident from the above equation that the effects of two or more glare sources are completely additive.

Discomfort glare results in physiological and/or subjective discomfort on the part of the observer, and may or may not result in a degradation of visual performance capability. The most common forms of physiological stress produced by intense glare illumination are repeated blinking of the eyes, abnormal extra-ocular muscle tonus, and excessive tearing (lachrymation). Long exposures to moderate glare levels may result in visual fatigue, leading to an aching of the eyes and head. The total amount of discomfort glare present in a given illumination environment can be specified by an index of Discomfort Glare Sensation (DGS). Guth [53] provides the following formula:

$$DGS = \left[\sum^{n} \frac{L(20.4\,\omega + 1.52\,\omega^{0.2} - 0.075)}{F^{0.44P}}\right]^{a}$$

where:

DGS is the Discomfort Glare Sensation index,

n is the number of glare sources in the environment,

L is the luminance of each source or luminous area,

ω is the visual size or solid angle subtended by each source,

F is the field luminance,

P is a position index for each source, and

a is a constant equal to $n^{-0.914}$.

When the Discomfort Glare Sensation index is calculated, it can be converted to an estimate of the proportion of persons who would be expected to judge the given illumination environment to be "uncomfortable." The procedure for this conversion may be found in the original Guth article [53] or in the Illuminating Engineering Society Lighting Handbook [68]. Glare source color properties have little, if any, effect on the overall deleterious effects of glare source intensity and location [83].

The implications of background glare source effects for NWSS security lighting system design are: (a) intense illumination sources and highly reflective objects should be removed from the line-of-sight of all NWSS security personnel and other authorized persons, (b) where removal is impossible, the glare sources should be shielded and reflective objects modified (e.g., painted) to reduce their reflective properties, (c) conversely, illumination sources should be aimed in the direction of high probability intrusion areas, (d) these illumination sources should be as intense as economically feasible and in the direct line-of-sight of the anticipated intrusion location, and (e) where the above objectives are in conflict with each other, a compromise solution must be attempted.

3.5.3. Characteristics of the Visual Task

All visual tasks involve the use of two basically different psychological processes: (a) detection and (b) recognition. Detection is primarily a sensory process, while recognition is primarily a memory process, i.e., the detected target image is compared with similar memory "images" in an attempt to recognize the target. Depending upon the quality of the memory image, an accurate recognition response may require the detection of more or less target detail than is immediately available to the observer. For example, an observer may detect sufficient detail to recognize a distant object as being a human being, but he may not have sufficient detail to recognize who this person is. Depending upon the amount of detail required to successfully complete a visual recognition task, a given bit of target detail may require greater or less VL.

If it is assumed that NWSS security observers need only detect and identify the presence of an intruder and need not determine his identity (as discussed in sec. 3.4.1.3), VL's appropriate to the task of human form identification can be recommended. These VL's cannot be precisely specified through purely analytical means because of the great number of VL variables involved, but could be specified through the use of empirical investigation on a site-by-site basis. Such an investigation is being planned for the second phase of the present research effort.

3.5.4. Modifying Factors

Target VL is frequently influenced by factors which are of only indirect significance to the visual task itself. The most important of these factors are: (a) method of lighting, (b) retinal adaptation level, (c) background complexity, and (d) simultaneous functioning of other sense modalities.

3.5.4.1. Method of Lighting

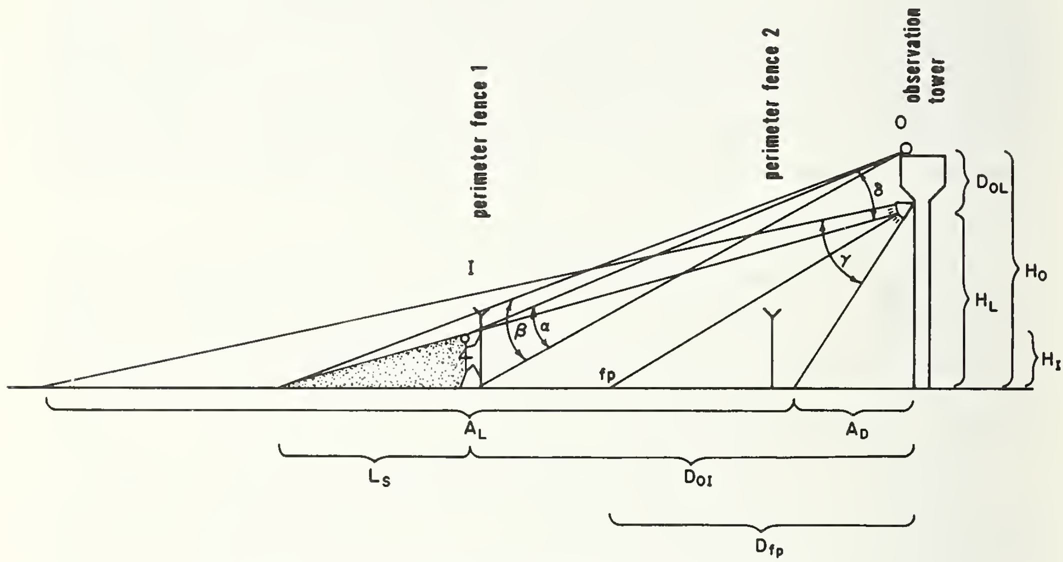
Faulkner and Murphy [44] have identified 17 different methods of illumination for improving the VL of difficult visual tasks. These methods involve the use of: (a) color, (b) trans-illumination, (c) polarization, (d) crossed polarization, (e) shadow-graphing, (f) spotlighting, (g) brightness patterns, (h) diffuse reflection, (i) edge illumination, (j) dark-field illumination, (k) convergent illumination, (l) stroboscopic illumination, (m) moving illumination images, (n) surface grazing or target shadowing, (o) ultraviolet illumination, (p) moire patterns, and (q) "combination" techniques.

While several of the above techniques may prove adaptable to NWSS security lighting problems and should be investigated, two of the methods could be easily adapted to the environment of the NWSS. These are spotlighting and surface grazing.

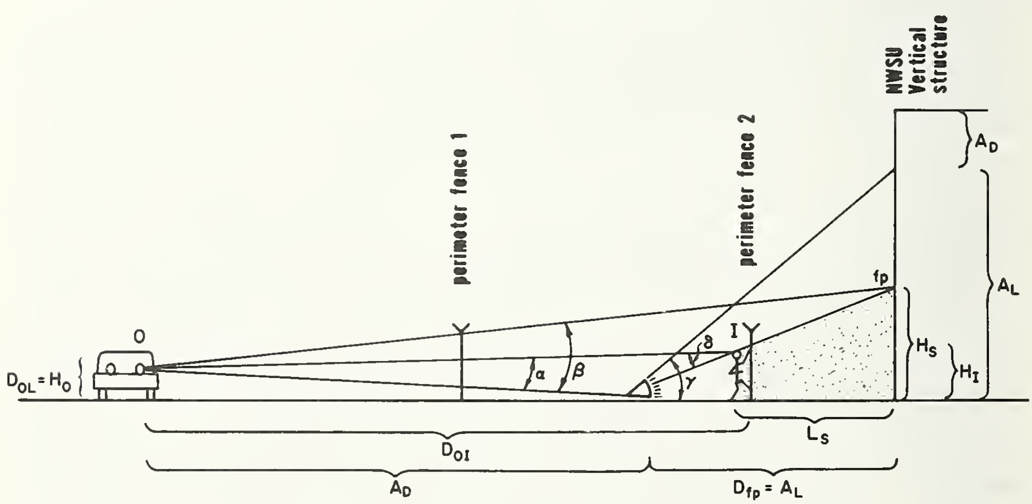
The incorporation of a spotlighting capability into the conventional fixed-luminaire security lighting system offers several important advantages. These advantages include the capability of directing supplemental illumination into suspected areas of intrusion and maintaining this supplemental illumination on the intruder as he proceeds through the NWSS security system. This supplemental illumination should serve to increase the intruder's VL so that he may be more easily tracked through the system and to hinder his progress toward the Nuclear Weapon Storage Unit (NWSU) as a result of high-intensity spotlight glare.

Surface grazing or shadowing involves the direction of collimated illumination at the surface (ground) in the area of the target at a very low (tangential) angle of illumination. The effect is to increase target VL as a result of enlarged, high-contrast, shadow production. Figure 3 depicts the geometric relationships involved in target shadowing for two hypothetical security lighting systems, the first being designed with a stationary security observer in mind, and the second with a patrolling security observer. Table 3 summarizes the geometric results (and their consequent effects upon VL) of various possible design changes in the illumination systems depicted in figure 3.

Table 3 shows that the optimization of intruder VL through the use of target shadowing techniques requires the use of precise geometric analysis involving numerous system design trade-offs. These trade-offs should also attempt to maximize the size and contrast of intruder shadows, while minimizing the angular distance between security observers and illumination (glare) sources (as seen by an intruder). Such trade-offs should maximize the total surface area illuminated,while minimizing the total surface left non-illuminated.



(a) Stationary observer (o) in observation tower observing intruders (I).



(b) Patrolling observer (o) in vehicle observing intruder (I).

FIGURE 3. *Angular relationships in target shadowing.*

Figure 3 Coding

Intruder Parameters

H_I is the height of the intruder. Ordinarily an intruder would be expected to maintain a low profile within the confines of the NWSS; however, in scaling a perimeter fence his whole profile would be revealed. Hence, the locations of perimeter fences can indirectly influence the intruder's height, and must thus be considered as an important element within the overall security lighting system design.

Observer Parameters

H_o is the height of the observer above the ground.

D_{OI} is the horizontal distance between the observer and the intruder.

D_{OL} is the vertical distance between the observer and the light source (assuming the observer and the light source are aligned in the intruder's line-of-sight).

Light Source Parameters

γ is the angular distribution of the light source.

D_{fp} is the horizontal distance between the light source and its focal point.

H_L is the vertical mounting height of the light source.

Visibility Factors

A_L is the total surface area illuminated by the light source.

A_D is the total surface area not illuminated (dark) by the light source.

H_S is the height of the intruder's shadow projected against a vertical surface (e.g., a wall).

L_S is the length of the intruder's shadow projected against a horizontal surface (the ground).

$\propto$ is the angular size of the intruder as seen by the observer.

β is the angular size of the intruder's shadow as seen by the observer.

δ is the angular distance between the observer and the light (glare) source as seen by the intruder.

TABLE 3. *Results of geometrical design changes in two hypothetical security lighting systems with implications for intruder visibility level (VL)*

Lighting system	Result[1]	
Design change	Stationary security observer (a)	Patrolling security observer (b)
Increase γ	Increase A_L (+)	Increase A_L (+)
Increase D_{fp}	Increase $A_L(+)$, $A_D(-)$	Increase $A_L(+)$ Decrease $H_S(-)$, $\beta(-)$, $A_D(+)$
Increase H_L	Decrease $L_S(-)$, $\beta(-)$, $\delta(\pm)$ $A_L(-)$	Increase $A_D(-)$ Decrease $H_S(-)$, $\beta(-)$, $\delta(\pm)$, $A_L(-)$
Increase H_O	Increase $\beta(+)$ Decrease $\alpha(-)$ $\delta(\pm)$	Increase $\beta(+)$ Decrease $\alpha(-)$, $\delta(\pm)$
Increase D_{OL}	Increase $\delta(-)$	Increase $\delta(-)$
Increase D_{OI}	Decrease $\beta(-)$ $\alpha(-)$	Decrease $\beta(-)$, $\alpha(-)$

[1] A (+) refers to a generally advantages change in intruder VL, while A(−) refers to a generally disadvantageous change in intruder VL. A (±) refers to a change in VL which may be either advantageous or disadvantageous depending upon other characteristics of the lighting system.

3.5.4.2. Retinal Adaptation Level

The luminance levels of objects in the immediate vicinity of the observer just prior to the occurrence of the required visual task play an extremely important role in the determination of target VL, for these luminances are primarily responsible for determining the overall state of retinal adaptation of the observer's eyes.[8] While most laboratory studies ensure that observers' retinas have been completely adapted to the luminance conditions of the visual task under consideration, this is not always the case in real-world situations.

For example, a security observer who is stationed in a bright room (e.g., guard house) cannot possibly be expected to detect faint intruder/background image contrasts upon leaving the confines of this room and entering an outdoor environment composed of entirely low-level luminances. Under these conditions it would probably take at least 20 minutes for the observer's eyes to become fully dark adapted and thus reach their former level of contrast sensitivity [5]. During this time he would be at the complete mercy of the intruder he was seeking, as his visual sensitivity would be highly impaired relative to that of the already dark-adapted intruder.

Two methods are available to reduce or eliminate the deleterious effects of improper levels of retinal adaptation. These are to maintain nearby luminance levels at or below those of the observer's required field of search or to brighten the observer's immediate surroundings by means of long-wavelength, orange or red (or even infrared [32]) illumination which will have little, if any, effect upon the observer's dark adapted vision [27,60,66,101], hence maintaining his level of luminance contrast sensitivity.

[8] The concern here is with "steady-state" retinal adaptation as apposed to "transient" adaptation discussed earlier in section 3.5.2.6. In general, the longer the retina is exposed to a given light level, the more stable will be its adaptation, and hence the longer it will take for the retina to readapt to subsequent light level changes.

3.5.4.3. Background Complexity

The role of background complexity in determining target VL is probably the least understood of the major VL variables. In addition to increasing the field-of-view scanning time by necessitating the inspection of additional "false targets" (see sec. 3.4.1.1), complex backgrounds also detract from a target's VL [18,43]. This is especially true when both the target and the background are of similar complex character, e.g., when the target is "camouflaged." In general, the less complex a target's background, the greater will be its "area of conspicuity" [43]. Beyond this, it is extremely difficult to predict a target's VL based solely upon background complexity characteristics.

Fortunately, within the confines of the NWSS, an intruder's visual background may be carefully controlled through the use of appropriate "landscape" design. This would include: (a) the removal of all unnecessary objects from the security observers' field-of-view, (b) the layout of a uniformly reflective background material (e.g., grass and concrete), and (c) the careful leveling of the entire background area. The latter precaution would reduce the number and size of shadows resulting from low-lying terrain features such as depressions and ridges.

3.5.4.4. Simultaneous Functioning of Other Sense Modalities

Intense stimulation of the other senses (especially auditory, but also olfactory, taste, pain, and temperature) may serve to indirectly reduce target VL. This effect can be traced to either of two basic psychological processes. First, non-visual stimulation may distract the observer, thus affecting the attentional process. Second, non-visual stimulation may actually mask incoming visual information, thus affecting the sensory-perceptual process. Intense noise is the most serious of the potential cross-modality visual performance retardants [87,109,110].

For NWSS security system design, all sources of intense, cross-modality, sensory stimulation should be removed from the immediate area of the security observer. Where this is impossible, the observer should be provided with suitable protection devices or garments to diminish the intensity of this stimulation.

3.5.5. Quantification of Target Visibility Level

In view of the number and complexity of variables known to influence target VL, it is not surprising that no single mathematical VL model has as yet been developed which takes into account all the variables involved. However, recent attempts at developing instrumentation and measurement techniques suitable for the quantification of target VL have been extremely successful. Underlying this success has been the development of a wide variety of "visibility meters" [9,42,78,98] which serve to reduce target background contrast to threshold level through the the introduction of veiling luminances, and use the amount of contrast reduction required as a measure of the target's VL. Thus, high-visibility targets will require greater contrast reductions than low visibility targets. The obtained visibility measure is then multiplied by a variety of related visibility terms (e.g., disability glare factor and transient adaptation factor) and an overall measure of "effective visibility level" (VL_{eff}) is obtained.

The most widely accepted approach to VL assessment is that of H. R. Blackwell at Ohio State University. The approach is endorsed by the Commission Internationale de l'Eclairage (CIE; Paris, France) and the Illuminating Engineering Society (IES; New York) [107]. It is much too detailed and complex to be described adequately in the space available in the present report, but is highly recommended to the reader who is unfamiliar with Blackwell's work. Condensed reviews of the Blackwell approach have been presented elsewhere [14,16,30,39,85].

3.5.6. Validity of Mathematical Visibility Models in Real-World Applications

In spite of the complexity involved in the target VL concept, its application to real-world visibility problems has been successful. While Blackwell's original formulation was intended for the prediction of relatively simple indoor target VL's, the model has since been extended to the prediction of more complex outdoor target VL's, with the degree of success being directly proportional to the complexity of the visual environment involved. Thus, driver performance has been accurately predicted based upon a knowledge of roadway obstacle visibility [10,12,26,40,51,64], while military target detection performance could not be adequately predicted for camouflaged targets in a jungle environment [34-38]. The former example is a relatively simple visual environment (uniformly reflective background, and evenly spaced luminaries), while the latter is extremely complex (variation in background luminance uniformity and unpredictable illumination source locations). Furthermore, Gallagher and Meguire [50,51] have shown that, if internal target contrast[9] and background uniformity are sufficiently simple, accurate predictions of visual target detection performance can be made based upon target contrast alone, without requiring the use of the generally more difficult and time consuming visibility meter approach.

For the NWSS, a well-designed security lighting system should result in a visual environment which is not only very simple, but also entirely predictable. This fortunate circumstance arises from the fact that the system designer has almost complete control over the luminance characteristics of the nighttime NWSS visual environment. The intensity, location and/or size of every light source, without or within the NWSS (except those introduced by an intruder), reflecting surface, obstacle and shadow can be precisely designed. Consequently, the VL of a human form at any point in the system should be predictable. The design of such a system requires sophisticated planning and implementation. Until recently, such planning would have been prohibitively expensive and time consuming, but with the advent of high-speed, digital computer techniques, the computerized design of such optimum lighting systems may now be feasible [33,48]. It should be noted, however, that computer modelling approaches in general have limitations. The limitations must be considered in light of the cost of developing the computer-based models. The cost effectiveness of such models must be established.

3.6. Intruder Incapacitation

In accordance with the security philosophy outlined earlier in this report, the intruder deterrence and detection efficiency of the NWSS security lighting system should increase gradually as it progresses toward the NWSU. Taken to its extreme, this philosophy suggests that intruder "deterrence" should be replaced by intruder "denial" as the main objective of the lighting system in the immediate area of the NWSU. Such incapacitation capabilities could be initiated by either automatic intrusion detection sensors or manual security force controls.

The use of illumination as an intruder incapacitation device has many drawbacks, the most serious of which is the ease with which the planned incapacitation effects might be avoided by intruders through the use of appropriate countermeasures. For example, illumination stressors may always be avoided by simply closing one's eyes or redirecting one's gaze. Photosensitive goggles provide a state-of-the-art optical countermeasure. Nevertheless, the necessity of using such countermeasures might significantly decrease the speed of the intrusion attempt.

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[9] Internal target contrast refers to the luminance contrast between adjacent parts of a given target. For example, the contrast between the pants and shirt of an intruder.

Thus, the overall effectiveness of visual incapacitation methods, and the levels of threat to which they are most appropriate, must be carefully analyzed before a reasonable decision can be made concerning their ultimate practical utility and cost effectiveness.

There are four major effects of illumination upon the human organism which might be adapted to incapacitate an intruder: (a) glare, (b) flash blindness, (c) disorientation (stroboscopic effects) and (d) phototropism.

3.6.1. Glare Effects

The physiological effects of excessive glare were discussed in detail in section 3.5.2.7. In summary, these effects include visual performance degradation (disability glare) and ocular irritation (discomfort glare), including excessive blinking and tearing of the eyes. In severe cases, these symptoms might be sufficient to significantly hinder the progress of an ongoing intrusion attempt.

3.6.2. Flash Blindness Effects

Flash blindness refers to the period of visual insensitivity which occurs after the eyes have been exposed to a brief, super-adaptational-intensity burst of illumination [24]. The severity of this insensitivity is usually defined in terms of the duration of incapacitation effects, or more precisely, the time required for complete recovery to normal visual sensitivity levels. In essence, the flash blindness phenomenon is identical to that of the early dark-adaptation process following an exposure to a brief adapting flash, the only difference being that flash blindness studies generally utilized flashes of much greater intensity.

The severity of flash blindness effects are dependent upon a variety of flash presentation parameters, including flash duration, intensity, wavelength composition and the visual angle of the flash relative to the line-of-sight. Severe flash blindness effects generally last no more than two to three minutes for a single flash [24], but may be continued indefinitely by repeated flashes at appropriate intervals.

Flash blindness effects are not necessarily uniformly distributed over the entire retinal surface, but rather are greatest over those areas of the retina which mirror the size, shape and optical position of the flash source [84]. If the flash emanates from a non-discrete source (e.g., as by reflection off of an extended object), the effects may be distributed equally over the entire visual field, whereas if the flash emanates from a discrete source (e.g., a flash bulb), the effects may be restricted to a relatively small area of the visual field and appear as an "after image." Furthermore, the duration and vividness of the resulting blind spot may be increased by suitable modulation of the post-flash ambient illumination level [84]. In this way, multiple, modulated illumination sources might be used to produce a disconcerting array of moving blind spots before an intruder's eyes.

3.6.3. Stroboscopic Effects (Disorientation)

Rapidly flickering levels of illumination (i.e., stroboscopic illumination) are known to have disruptive physiological and/or psychological effects upon certain individuals under certain circumstances [44,95,116]. For example, persons having cerebral lesions are known to experience epileptic seizures when exposed to illumination flicker at rates of approximately 5 to 20 Hz. In normal humans, experiences of illusory motions, colors, and/or patterns within the visual field are more common. These illusions frequently lead, in turn, to distressful feelings of confusion and/or anxiety.

3.6.4. Phototropic Effects

Phototropism refers to the natural tendency of the eyes to be oriented toward light [66]. This innate response, which is only slightly evident in humans (and fully capable of being overriden by cognitive processes), may be exploitable as a subtle intruder behavioral control mechanism for the limited control of intruders within the NWSS. As such, it would not be used as an incapacitation agent, per se, but rather as a means of directing potential intruders into an area where incapacitation by other means (e.g., FEDS), is possible.

The concept is that, as a result of the phototropic response, intruders will tend to orient their sight in the direction of illuminated areas within the NWSS. Their subsequent movements through the NWSS may then be influenced by the location of these lighted areas.[10] Thus, through the appropriate placement of light sources, i.e., through the purposeful design of non-illuminated corridors of shadow, the intruder may be "guided" to an area of high apprehension probability. Similar techniques have been successfully employed in the direction of human traffic in and around museums, retail stores and roadways [105].

4. SUMMARY AND CONCLUSIONS INCLUDING GENERAL RECOMMENDATIONS FOR NWSS SECURITY LIGHTING SYSTEM DESIGN

The purpose of this report was to present a literature review and bibliography dealing with the optimization of Nuclear Weapons Storage Site (NWSS) security lighting through the application of established principles of psychological and behavioral functioning. From this viewpoint, three distinct psychological/behavioral processes were identified as being relevant to the subject of security lighting system design: (a) deterrence, (b) detection, and (c) incapacitation.

Current state-of-the-art principles and recommendations for security lighting system design provide adequate guidelines for general (non-critical) security lighting problems, but are not easily adapted to the diverse environmental condition and specific (critical) security requirements of the NWSS. Furthermore, current security lighting standards were derived through primarily intuitive means as early as World War II, and were originally intended for use in industrial and residental settings only. Nevertheless, these standards continue to be used in NWSS security lighting design.

It is not impossible at present to evaluate the deterrence effectiveness of current NWSS security lighting practices. What little is known about the relationship between lighting and crime deterrence has been learned through the study of urban crime patterns following the installation of new (or improved) street-lighting systems. These limited and, in many cases, poorly controlled studies indicate that street lighting does in fact reduce crime in well-illuminated areas, but may also result in crime increase in adjacent non-illuminated areas of the city. Thus, lighting may reduce crime within its immediate domain, but may not reduce crime, per se. The generalization of these relationships to the NWSS is difficult because the environment and threats involved are of a much different nature. With these limitations in mind, the following conclusion seems warranted: security lighting may serve as an effective deterrent against relatively low-level threats (e.g., vandals and thrill-seekers) at the outer perimeter areas of the NWSS.

[10] Ordinarily, humans have a tendency to move toward a light [105], but in the case of the clandestine intruder, he will presumably seek to avoid lighted areas.

Against higher-level threats (especially the terrorist threat) in more central areas of the NWSS, its deterrent effectiveness is presently unpredictable, but probably extremely limited.

The underlying mechanism through which security lighting deterrence operates is the intruder's perceived estimate of his detection and apprehension probabilities. These probabilities may be analytically estimated by means of modeling techniques, and provide a convenient framework for security lighting system design. Thus, optimization of intruder detection and apprehension probabilities results in a two-fold advantage: (a) it assures a maximum psychological deterrent value of the security lighting system and (b) it assures maximum failure probabilities once an intrusion has been initiated.

Many variables are known to influence the detection and apprehension probabilities of an intruder. These variables are of two types, those related to the security system, per se, but only indirectly related to security lighting design (e.g., number and location of security observers and guard force personnel, number and location of "blind spots" within the observer's field of view and total size of the area to be observed), and those directly related to security lighting design (e.g., light source color, intensity, and location; reflectivity of surfaces within the observer's field-of-view; size and position of the intruder at points of most probable intrusion). The importance of the latter variables lies in their ability to affect a target's visibility level (VL), which can be measured precisely through the use of appropriate "visibility meters." The predictive validity of target VL measures has been repeatedly demonstrated in real-world applications, the most noteworthy success being achieved in the prediction of driver performance in the avoidance of low-visibility obstacles.

The use of illumination stressors to incapacitate intruders momentarily would seem an appropriate goal for a well-designed security lighting system, especially in the immediate area of a Nuclear Weapons Storage Unit (NWSU). The potentially most effective incapacitation techniques would involve the use of glare, flash blindness, and stroboscopic visual effects. The human "phototropic response" might also be used advantageously to subtly guide intruders into areas of high apprehension probability. Unfortunately, the susceptibility of these techniques to countermeasures, and their largely unpredictable visual and psychological effects, cast some doubt on their potential effectiveness. Only further empirical research and detailed, cost-benefit analysis can determine their ultimate usefulness for NWSS security purposes.

The following general recommendations for NWSS security lighting system design were suggested in this report:

A well-designed security lighting system should:

° Maximize the number of security observers and/or minimize the total size of the critical intruder detection area (sec. 3.4.4.1).

° Minimize the number of confusing objects and/or shadows in the observer's field-of-view which might be mistaken for intruders (secs. 3.4.1.1, 3.5.2.3 and 3.5.4.3).

° Locate security observers as close as possible to areas with high probability of intrusion, and/or provide more distant observers with visual aids (secs. 3.4.1.1 and 3.5.2.1).

° Maximize intruder-to-background visual contrast, primarily through the use of highly reflective background materials, e.g., chalk dust and concrete (sec. 3.4.1.2).

° Provide for the selection of security observation personnel on the basis of visual contrast threshold sensitivity (sec. 3.4.1.2).

° Maximize the total area of illuminated clear zones (sec. 3.5.2.2).

° Provide for Forced Entry Deterrent Systems (FEDS) which prompt intruder movement (sec. 3.5.2.2).

° Use simulated daylight ("white light") in conjunction with direct human eye surveillance, and use monochromatic (colored) light in conjunction with closed-circuit television surveillance (sec. 3.5.2.4).

° Maximize the total amount of illumination at perimeter areas (sec. 3.5.2.5).

° Have illumination sources of approximately equal intensity, which are equally spaced around perimeter areas, and provide for uniform illumination of background surfaces, preferably through the use of fewer and brighter luminaries with wide-angle beam distributions (secs. 3.5.2.6, 3.4.1.2 and 3.5.4.3).

° Minimize the number of high intensity luminaries and high reflectivity objects (glare sources) in the security observer's (and other authorized personnel) field-of-view (sec. 3.5.2.7).

° Maximize the number of high intensity luminaries and high reflectivity objects (glare sources) in the intruder's field-of-view at areas where the anticipated intrusion probability is high (sec. 3.5.2.7).

° Use intruder "spotlighting" and "shadowing" as effective means of increasing intruder VL's (sec. 3.5.4.1).

° Position security observers in dimly lit surroundings, or use long-wavelength (e.g., red) illumination to light their surroundings (sec. 3.5.4.2).

° Provide for level background surface areas (sec. 3.5.4.3).

° Minimize the amount of non-visual, high-intensity stimuli in and around the observer's surroundings, and/or provide the observer with suitable protective devices to diminish the distracting effects (sec. 3.5.4.4).

It should be noted that the above recommendations may at times lead to conflicting security lighting design objectives (e.g., increased total illumination levels may result in higher intruder VL's, but may also result in greater glare in the eyes of the security observer). In such cases, appropriate compromise solutions must be arrived at through cost effective means, including further empirical research. Cost-benefit analysis will be required before an ideal combination of lighting design components can be organized into an optimum security lighting system.

5. IMPLICATIONS FOR FUTURE RESEARCH

Maximization of intruder visibility is perhaps the most important consideration in the design of an effective security lighting system, as it may increase the psychological deterrent value of the system and also increase the likelihood of an intruder being detected and apprehended once an intrusion attempt has been initiated. Since research on visibility has now progressed sufficiently to enable accurate prediction of human visual detection performance under a given set of illumination/target/background conditions, the time would now seem right for the application of such prediction techniques to the design of optimum security lighting systems.

Before such an application can be undertaken, however, certain decisions must be made concerning the performance requirements of the security observation task. Thus, if precise visual performance standards can be devised for the NWSS security observer, the illumination requirements needed to ensure the observer's meeting of these standards can be specified. For example, the minimum visual performance standards for a NWSS security observer might be stated with the following degree of exactitude:

> The security observer shall be able to detect an intruder with a high degree of reliability (e.g., 95%) when: (a) stationary, (b) dressed in dark clothing (e.g., 6% reflectance), (c) maintaining a low profile, (d) at a distance of no more than 300 feet (914 m), and (e) against a bright background (e.g., 30% reflectance).

Without recourse to a performance standard such as the above, it would be almost impossible to empirically evaluate the effectiveness of a security lighting system.

As a first step toward the development of visual performance standards and their associated illumination requirements, an in-depth field survey of current NWSS security lighting practices would appear to be highly beneficial. Such a survey would provide information concerning both (a) the adherence of real-world NWSS illumination approaches to current military security lighting specifications [76] and (b) the adequacy of these specifications in rendering minimally sufficient intruder VL's. The latter survey could be readily accomplished with the aid of (a) illumination meters, (b) luminance meters, and (c) visibility meters, and has been proposed as the work to be undertaken in Phase II of the present project.

A specific approach for the determination of camouflaged military target VL's has already been described in the literature [58]. A similar approach may be useful in the evaluation of military security lighting systems. These possibilities will be explored further in Phase II.

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