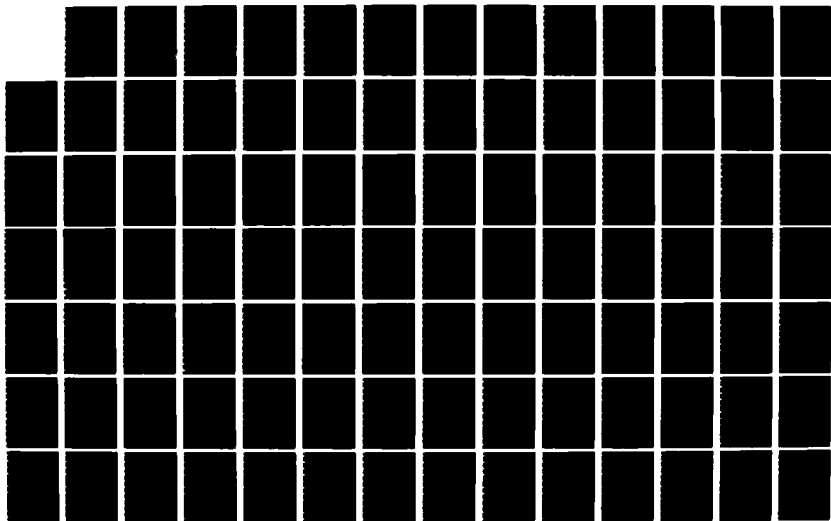


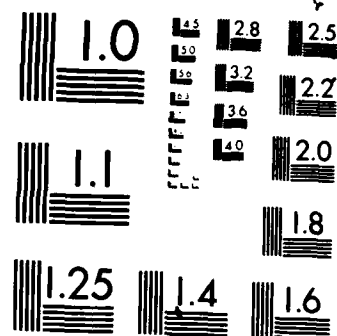
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THERMAL EFFECTS ON A
ROTATING MISSILE
THESIS

David H. Kristensen
Captain, USAF

AFIT/GNE/ENP/86M-9

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THERMAL EFFECTS ON A
ROTATING MISSILE

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Nuclear Engineering

David H. Kristensen, B.S.

Captain, USAF

March 1986

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Preface

I would like to thank my advisor, Maj. John. F. Prince, Assistant Professor of Physics, Air Force Institute of Technology, for proposing this thesis topic and for his instruction, guidance, and encouragement during months spent working on this project. I'd also like to thank my classmates for their help in solving problems, writing computer code, and proofreading the manuscript. Finally, I'd like to thank my wife Elaine. She was my typist, problem solver, time manager, and expert organizer. She quietly allowed me weeks with the computer, but never permitted me to lose my perspective, or my patience. Without her help, I would not have completed this study. Thanks, I owe you.

- David H. Kristensen



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Table of Contents

	Page
Preface.	ii
List of Figures.	v
List of Tables	vi
List of Symbols	vii
Abstract	ix
I. Introduction.	1
Background	1
Problem and Scope.	4
Assumptions and Limitations.	6
Approach	8
Presentation	10
II. Theory.	11
Derivation of the Model for the Missile's Cylindrical Shape	11
Rotation of Missile Nodes.	16
Derivation of the Equation for Laser Energy Absorption	18
Calculating Laser Spot and Missile Surface Rotation.	19
Adapting Models to Computer Programs.	22
III. Conditions and Limiting Parameters.	27
Determining Minimum Intensity on Target	27
Laser Threat Conditions	30
IV. Results and Discussion.	34
Comparison between 8, 16, and 32 Node Models.	35
Effect of Rotation on Maximum Temperature and Probability of Survival for Multiburst Case	37
Comparing the Rotating and Nonrotating Cases	39
Comparing Cumulative Thermal Effects to Blast Effects.	42

Probability of Survival and Maximum Temperature for the 4-on-1 Attack	44
Effect of Rotation on Maximum Temperature for the Laser Threat. .	48
Comparison of Spot Size to Probability of Survival	48
V. Conclusions and Recommendations	52
Conclusions.	52
Recommendations.	53
Appendix A. Calculating Rotation Factor	55
Appendix B. Skin Depth and Absorption Coefficient .	59
Appendix C. Calculation of Minimum Energy Density .	61
Appendix D. Data for Figures in Chapter IV.	64
Appendix E. Computer Program.	67
Bibliography	79
Vita	81

List of Figures

Figure	Page
1. Close-spaced Basing Missile Field	5
2. Missile Characteristics	7
3. Missile Circumference and 8 Node Model. . .	14
4. Node Positions at $t = 0$	17
5. Node Positions at $t = .59$	18
6. Laser Spot and Cell Strip	20
7. Model Comparison - Probability of Survival vs. Rotation Rate	36
8. Maximum Temperature vs. Rotation Rate . . .	38
9. Probability of Survival vs. Rotation Rate - 16 Node Model	40
10. Location of Sure-kill and Sure-safe Regions	43
11. Location of Sure-kill and Sure-safe Regions	45
12. Probability of Survival vs. Rotation Rate - 4-on-1 Attack	47
13. Maximum Temperature vs. Rotation Rate - Laser Threat	49
14. Effect of Spot Size on Probability of Survival	50
A-1. Sample Burst-Missile Encounter	57

List of Tables

Table		Page
I.	Algorithm for Finding MaxT for Thermal Effects.	25
II.	Conditions and Parameters for Cumulative Thermal Threat.	28
III.	Conditions and Parameters for Laser Threat	29
IV.	Spot Radii for Various Distances from Laser to Target	31
V.	Comparison of Maximum Temperatures and Probability of Survival for No Rotation vs. Rotation	41
VI.	Results of Noncumulative Blast Effects. .	44
D-I.	Data Used to Plot Figure 7.	64
D-II.	Data Used to Plot Figure 8.	65
D-III.	Data Used to Plot Figure 12	65
D-IV.	Data Used to Plot Figure 14	66

List of Symbols

CF	correction factor
CT	thermal energy emitted from burst
C_p	specific heat capacity (J/kg-K)
d	missile skin thickness (m)
DGZ	designated ground zero
drd	down-range-distance
F_{incident}	radiant exposure from a burst (J/m^2)
GR	ground range (m)
h	heat transfer coefficient ($\text{J/m}^2\text{-s-K}$)
I_{ss}	sure-safe intensity
I_{sk}	sure-kill intensity
j	time step
k	thermal conductivity (J/m-s-K)
k	burst #
lt	launch time (s)
MaxT	maximum temperature (K)
P_d	probability of damage
P_s	probability of survival
Q	thermal fluence incident on the missile skin during time step j (J/m^2)
SR	slant range

t	time after a burst (s)
t'	normalized time $t/t_{\max}$
t_{b1}	time of first burst (s)
$t_{\max}$	time after second thermal maximum (s)
T_1, T_2	skin temperature at beginning and end of time step j (K)
T_{air}	ambient air temperature (K)
t_f	thermal fraction
W	yield in megatons
Y	yield in kilotons

Abstract

Survivability studies have shown that intercontinental ballistic missiles are vulnerable to thermal effects. In particular, the cumulative thermal effect from a multiburst attack, and laser thermal energy can seriously damage or destroy a missile. One possible defense against the thermal threat is rotation of the missile. The purpose of this thesis was to determine if rotation decreased the maximum skin temperature of the missile, increasing the missile's probability of survival.

The study investigated several different scenarios. The first scenario was the Peacekeeper Dense Pack missile system. The missile field was subjected to a walk attack of 2 MT weapons, with the incoming RV's exploding every two seconds. The second scenario was a 4-on-1 attack of a missile launching system. More specifically, one missile was subjected to four bursts located in various positions surrounding the missile. The intent was to determine if rotating a missile, even when surrounded by thermal radiation, would increase the probability of survival. Finally, the missile is attacked by a space-based laser with a maximum absolute

power of 10 megawatts. In all cases, the rotation rate was limited to a maximum of 1.6 radians/second, as established by studies at the Air Force Institute of Technology. Using computer programs, the maximum skin temperature was calculated, with the resultant probability of damage determined using a cumulative log-normal distribution function. Comparisons were made between the rotating and nonrotating missiles to determine if rotation did increase the probability of survival for the missile system.

In all scenarios studied, rotation significantly decreased the maximum skin temperature, increasing the probability of survival for the missile. The decrease was most dramatic for the walk attack, where an optimum rotation rate of .8 radians/second was established. For the 4-on-1 attack, rotation was effective, but required the maximum 1.6 radians/second rotation rate for best results. Finally, for the laser threat, rotation was effective for the scenarios studied, with the maximum rotation rate providing the greatest amount of protection. As a consequence, even at these relatively low rotation rates, rotation is an effective defense against the thermal threat.

THERMAL EFFECTS ON A ROTATING MISSILE

I. Introduction

Background

Thermal energy is electromagnetic radiation travelling from a source at the speed of light. Normally, thermal energy, such as from the sun, produces no harmful effects. However, when enough thermal energy is absorbed in a short amount of time, it produces heating and melting of the absorbing material. This phenomenon is referred to as the thermal effect.

Past survivability studies have shown that missiles, because of their thin, metallic skin, are vulnerable to the thermal effect. This is because the missile surface absorbs enough energy to raise the skin temperature beyond the melting point, causing structural failure and destruction of the missile. Two sources capable of causing thermal damage to a missile are: the thermal pulse from a nuclear explosion, and a laser beam pulse.

When a nuclear weapon explodes near the surface of the earth, it creates a fireball emitting thermal radiation. The radiation from a single burst is emitted as a double pulse, the first pulse lasting less than a tenth of a second, and containing approximately one

percent of the energy. The second pulse may last several seconds (up to ten seconds for a one megaton explosion) and contains ninety-nine percent of the total thermal energy.

Recent studies have shown that when a missile is subjected to multiple bursts, the thermal pulses overlap, having an additive or cumulative effect on the missile. For these cumulative burst scenarios, the thermal effect had a significantly larger lethal range than for multiple bursts considered separately. This lethal range was even greater than the lethal range for the blast effect. Thus, a missile is especially vulnerable to the cumulative thermal effect from a multiple burst attack.

If a missile survives the nuclear thermal threat, it may still be vulnerable to the thermal effect from a space-based laser. While the concept of a laser in space is not new, the Strategic Defense Initiative (SDI) has sparked a renewed interest in this type of weapon. Laser light has several properties that make it useful for weapons application. First, the intensity, or power per unit area, a laser can deliver to a target is very large. Secondly, laser energy is highly directional, allowing the intensities to be confined to a small area and to remain collimated for long ranges. Thus, a laser is capable of depositing a large amount of energy in a

short amount of time on a relatively small area.

Regardless of the source of thermal energy, the extent of damage to a target depends on the amount of radiation absorbed by a unit area of missile surface in a short interval of time. For a given surface material, only a small amount of the absorbed energy will be dissipated away by conduction, convection, or re-radiation. As a consequence, the absorbed energy is contained in a shallow depth of the surface, resulting in high temperatures that could damage the material. The purpose of a survivability study is to determine the amount of damage to the target and express it as a probability of survival. For thermal effects on a missile's skin, the probability of survival was calculated using the cumulative log-normal distribution function. Using this technique, a probability of survival was determined for each missile as a function of the missile's maximum skin temperature. A detailed discussion of the distribution function is in Hall (Hall, 1984: 94).

One possible way to decrease the amount of absorbed energy, and thus the skin temperature of the target, is to rotate the missile. Rotation moves radiated surfaces of the missile out of line of sight view from the source. The missile, in effect, acts as a shield against the thermal radiation. Also, rotation exposes

more surface, distributing the energy over a larger area, keeping the skin temperature below the sure-kill level.

Problem and Scope

The purpose of this thesis project was to show the effect of missile rotation on the skin temperature of a missile subjected to thermal radiation. The study focused on the cumulative thermal effects from a multiburst attack, and the thermal energy deposited by a hypothetical space-based laser on a missile during flight. The rotation rate was varied from 0-1.6 radians per second, with a maximum skin temperature and probability of survival calculated for each rotation rate. These maximum temperatures and probabilities of survival were compared to the nonrotating missiles to determine if rotation increases survivability. Also, an optimum rotation rate (one which keeps the missile skin temperature the lowest) was determined. The intent was to show that since rotation distributes thermal radiation over larger areas of the missile's surface, the thermal effect is reduced, and the missile's probability of survival increases.

For the multiburst scenarios, the burst-target missile system was the Peacekeeper close-spaced basing (CSB) system (see figure 1). This system was useful in

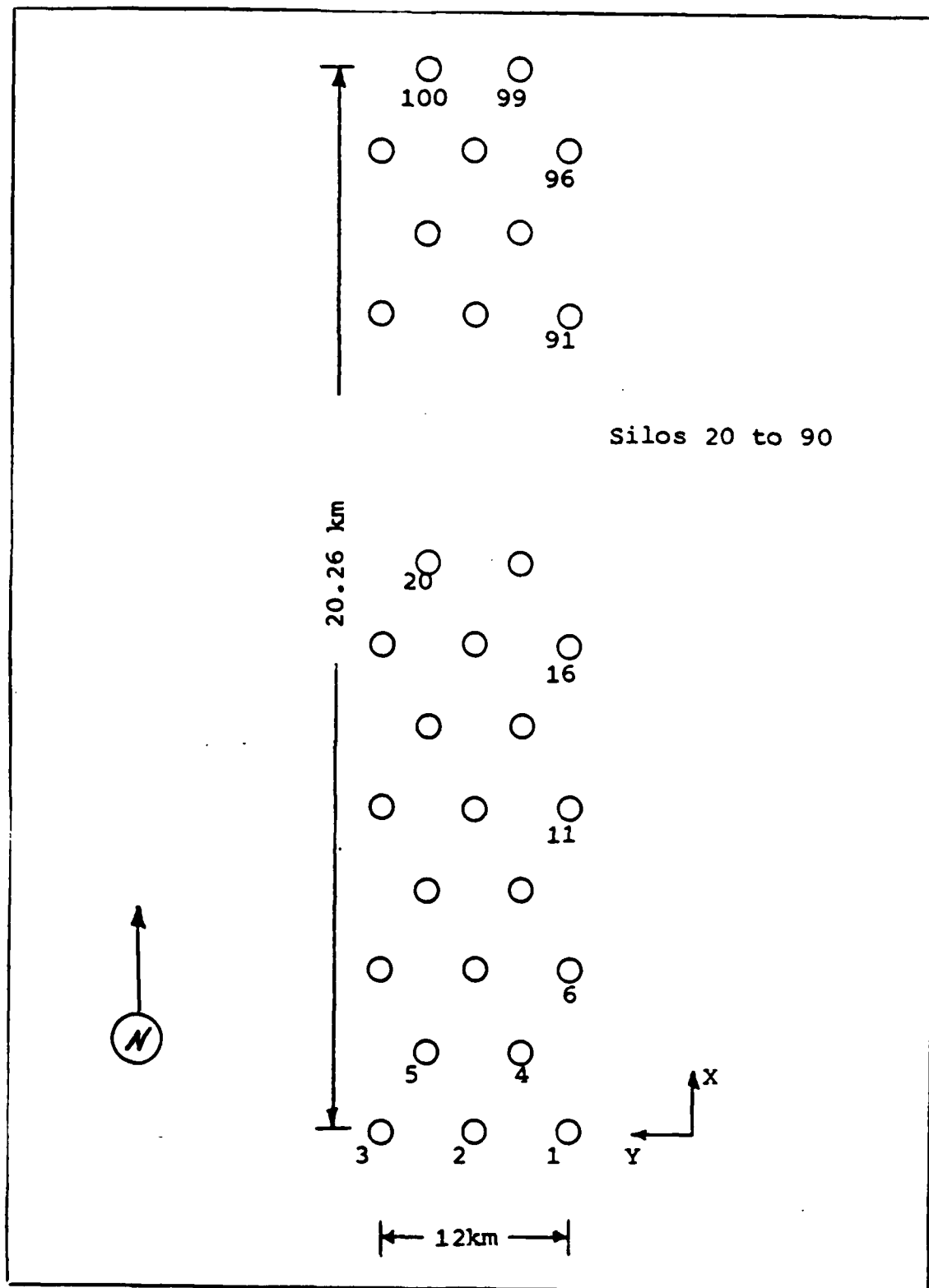


Fig. 1. Close-spaced Basing Missile Field

modelling how a rotating missile would survive a walk attack. Also, several 4-on-1 attacks were studied. These scenarios involved an isolated missile subjected to four bursts, one burst occurring every two seconds. The burst locations, relative to the launching missile, were varied. The intent was to determine if an optimum rotation rate was scenario dependent. The laser weapon was a hypothetical space-based design with a maximum absolute power of 10 megawatts. While no such system exists, weapons of this type are considered possible. Finally, the rotation rate was limited to 1.6 radians per second. This maximum value was established by studies conducted at the Air Force Institute of Technology, Department of Aeronautics (Bandstra, 1985: 4).

Assumptions and Limitations

The following assumptions and limitations were made to simplify the study:

1. Existing computer programs were used to calculate skin temperatures for this analysis. Missile flight characteristics were modelled using the information in figure 2. The programs were modified to account for the missile rotation, and the missile's cylindrical shape.

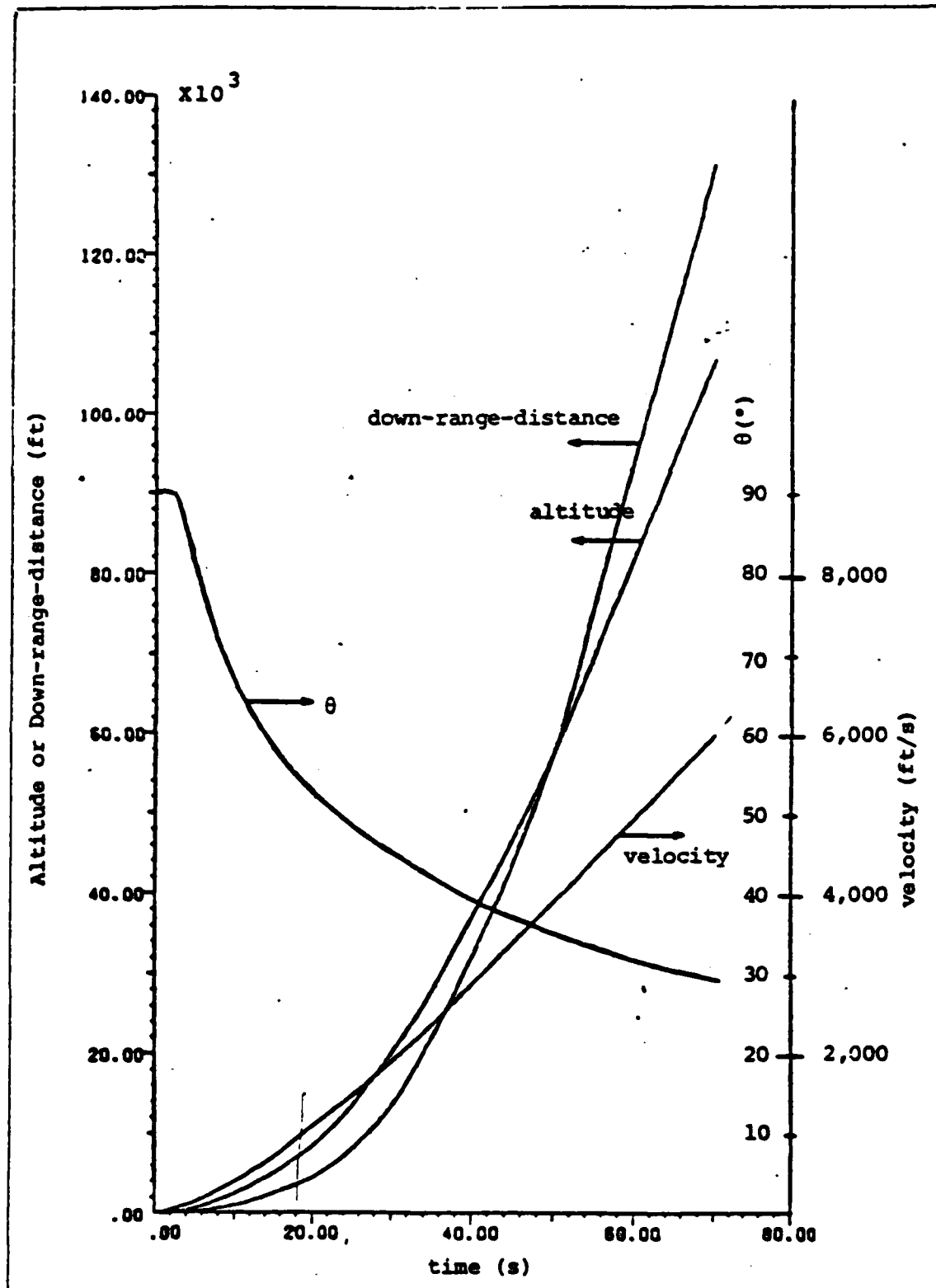


Fig. 2. Missile Characteristics

2. The reentry vehicles landed on their designated targets, i.e. no aiming error. This step allowed the programs to run on a personal home computer.

3. The rotation rate was constant. The system was assumed capable of reaching and holding the exact rotation rate.

4. The missile's cylindrical shape was modelled as a set of evenly spaced nodes of unit area. Three models (8, 16, and 32 node) were evaluated.

5. The laser weapon was a hypothetical space-based design. Beam generation, power requirements, or other beam propagation phenomena were not modelled.

6. The laser beam spatial profile was assumed to be flat. In otherwords, the intensity in every square centimeter of the beam spot was assumed to be constant. Exact spatial profiles are hard to determine for a high power laser, and thus a constant intensity profile was considered appropriate for this study (Bailey, 1985).

7. Laser beam pulses were restricted to one second. This was considered an appropriate tracking and power limitation (Bailey, 1984:41).

Approach

The following approach was used in calculating the probability of survival for a missile subjected to the

cumulative thermal effects from a multiburst attack. Existing computer programs were used to calculate the temperature on the missile's skin. These programs were derived from an energy balance over a unit area of the missile skin surface and a simplification known as the thin skin approximation (Hall, 1984:12). The programs were modified in two ways. First, the temperature was calculated at several locations or nodes around the circumference of the missile, simulating the cylindrical shape of the missile. Second, the nodes were repositioned for each time step, simulating the rotation of the missile. In this manner, a distribution of temperatures around the missile could be estimated. The probability of survival for the missile was found by using the highest temperature of any node on the missile surface.

The following approach was used to find the probability of survival for a missile subjected to a laser pulse. Considering the inherent limitations in focusing laser light, the spot size varied from 10 to 40 cm in diameter. Also, since the laser pulse was limited to one second and the rotation rate was limited to 1.6 radians per second, the area of missile actually irradiated was very small. Therefore, the missile surface was modelled as a flat slab, divided into cells of one cm^2 area. Using an iterative process, the amount

of radiation absorbed and the temperature in each cell was calculated. At the end of the iteration, the cell with the largest amount of absorbed energy and thus the highest temperature was used to calculate the probability of survival for the missile.

Presentation

Chapter II contains a derivation of the model for the cylindrical shape of the missile, and missile rotation, as well as a discussion of the equations used to model laser energy deposition. Then, how these models were incorporated into existing computer programs is presented. Chapter III summarizes some of the parameters and conditions used in this study, and why certain parameters were chosen. Finally, Chapter IV presents the results of the study and Chapter V details the conclusions and recommendations.

II. Theory

This chapter contains the theory used to determine the probability of survival for a rotating missile subjected to thermal radiation. The first part of this chapter deals with the cumulative thermal effect from multiple nuclear weapon explosions. First, a derivation of the missile's cylindrical shape is presented, followed by an explanation of how the rotation of the missile was calculated. The second half of the chapter examines laser radiation. Specifically, the equation used to calculate the amount of laser energy absorbed by the missile surface is derived. Next, the laser spot and missile surface are modelled to simulate rotation. Finally, the technique used to calculate maximum temperatures and probabilities of survival for the missile, using these models, is explained.

Derivation of the Model for the Missile's Cylindrical Shape

The missile's probability of survival for the thermal threat from a nuclear weapon is calculated using the maximum temperature reached during a burst scenario. The temperature is calculated over a unit area of missile skin surface using a simplification known as the thin skin approximation. This approximation leads to

the following differential equation:

$$a \frac{dT(t)}{dt} = \alpha \frac{dF_{\text{incident}}}{dt} - h[T(t) - T_{\text{air}}(t)] \quad (2.1)$$

which can be solved using the method of finite differences. After making the appropriate substitutions, equation (2.1) becomes:

$$T_2 = \frac{[T_1(a - \frac{h \cdot t_{\text{max}}}{2}) + h \cdot t_{\text{max}} T_{\text{air}} + \alpha \Delta Q]}{(a + \frac{h \cdot t_{\text{max}}}{2})} \quad (2.2)$$

where

T_2 = temperature at the end of the jth time step
(K)

T_1 = temperature at the beginning of the jth time
step (K)

$a = C\rho d$

α = absorptivity of missile skin

Q = total thermal fluence incident on the missile
during the jth time step (J/m^2)

h = local convective heat transfer coefficient
($J/m^2 \cdot s \cdot K$)

T_{air} = temperature of ambient air at missile altitude
(K)

t_{max} = time step (sec); $t_{\text{max}} = .0417 \cdot Y^{.44}$,
(Y-yield in kilotons)

For a more detailed derivation of this equation, refer

to Hall (Hall, 1984:12-18). Using equation (2.2), the temperature of the missile surface can be found.

In past studies the missile's cylindrical shape was not considered, but rather the missile surface was modelled as a single flat slab. This model, however, does not adequately correct for the geometry between the slab and each burst point. For example, when a missile was subjected to more than one burst, the thermal radiation from each burst was assumed to strike the slab. A correction factor was calculated for the missile's flyout angle, but no correction was made to account for the angle between the burst point and the slab. Using the cumulative thermal energy, equation (2.2) was used to calculate the temperature of the missile. In reality, the amount of radiation absorbed by the slab also depends on the geometry between the slab and the burst. In the extreme case of four bursts completely surrounding a missile, it would be incorrect to assume one spot, or slab, received all of the thermal energy from all four bursts. Actually, the thermal radiation would be distributed around the surface of the missile, and the resultant temperature anywhere around the missile's circumference would be much less than the temperature calculated assuming one slab received all of the thermal radiation. In addition, a rotating missile would also distribute the thermal radiation, reducing

the amount any one point on the surface absorbed.

For this study a simple model was developed to approximate the cylindrical shape of the missile. Instead of one flat slab of unit area, several evenly placed slabs, or nodes were used. Figure 3 shows how an eight node model would appear.

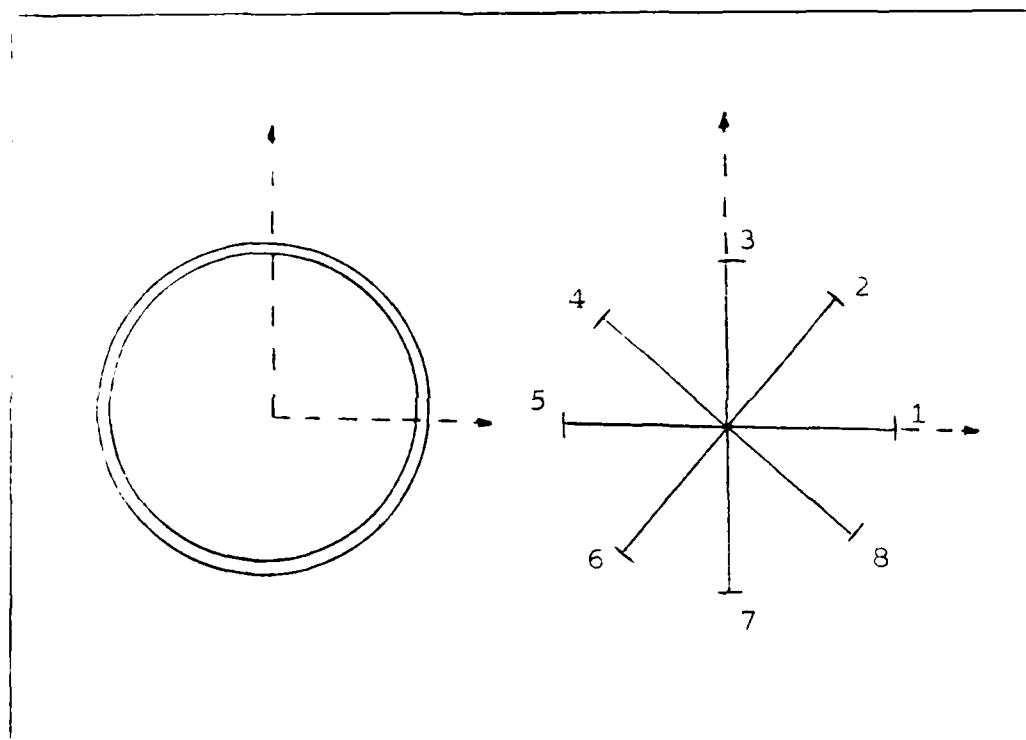


Fig. 3. Missile Circumference and Eight Node Model

The temperature for each node is calculated for each missile-burst encounter using equation (2.2). Thus, for each time step j , equation (2.2) was calculated eight times, once for each node. The difference in temperature for each node is related to

how much energy was incident perpendicular to the surface. Obviously, when the shape of the missile is considered, the surface facing the burst receives the most energy, while the surface on the back receives no energy. Also, when allowed to rotate, the nodes could be removed from the side receiving radiation decreasing the amount of energy any one node would receive. Therefore, to account for the fact that each node receives a different fraction of thermal energy, dependent on its position relative to the burst, a correction factor was needed. This rotational correction factor (RF) determines the fraction of thermal energy incident perpendicular to each node. Appendix A has a complete derivation of the rotation correction factor. Now, with the RF term included, equation (2.2) becomes:

$$T_2(n) = \frac{[T_1(n)(a - \frac{h \cdot t_{\max}}{2}) + h \cdot t_{\max} T_{\text{air}} + \alpha \Delta Q \cdot \text{RF}(n)]}{(a + \frac{h \cdot t_{\max}}{2})} \quad (2.3)$$

where

n = the node of interest, $n=1,2,\dots,8$.

$\text{RF}(n)$ = rotation correction factor for node n ,
determines the amount of thermal energy
incident on each node at time step j .

Thus, by examining equation (2.3) the temperatures at various nodes are related to the amount of energy absorbed by each node. The value for each rotation factor was determined by its position relative to the burst, and rotation constantly changed these positions.

Rotation of Missile Nodes

The following definitions are needed to describe the rotation of the missile:

t = time of missile skin exposure to thermal radiation. t is also equal to the time of thermal energy emission since radiation travels at the speed of light.

ω = rotation rate of missile in radians per second, rotation rate is constant, no angular acceleration

Δt = time, in seconds, between succeeding time steps (i.e. $\Delta t_j = t_{j+1} - t_j$)

As stated before, the cylindrical shape of the missile was modelled using a set of evenly spaced nodes of unit area. The position of the nodes is determined by their angular displacement, theta (θ), and position vector (r). Figure 4 shows an eight node model with the appropriate theta and r values.

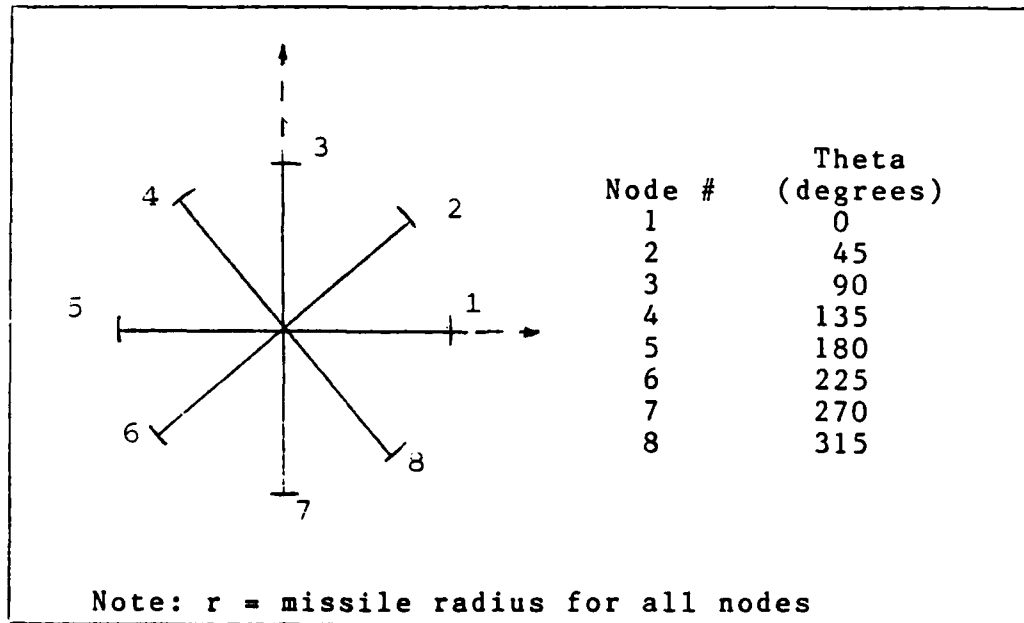


Fig. 4 Node Positions at $t=0$

Since the missile radius, r , remains constant the nodes' new positions will be defined by changes in their angular displacement only. Therefore, for a constant rotation rate, the new positions can be found using the equation:

$$\theta_{\text{new}} = \theta_{\text{old}} + \omega * \Delta t \quad (2.4)$$

For example figure 5 shows the eight nodes at new positions for a rotation rate of .5 radians/sec, and a t of .59 seconds.

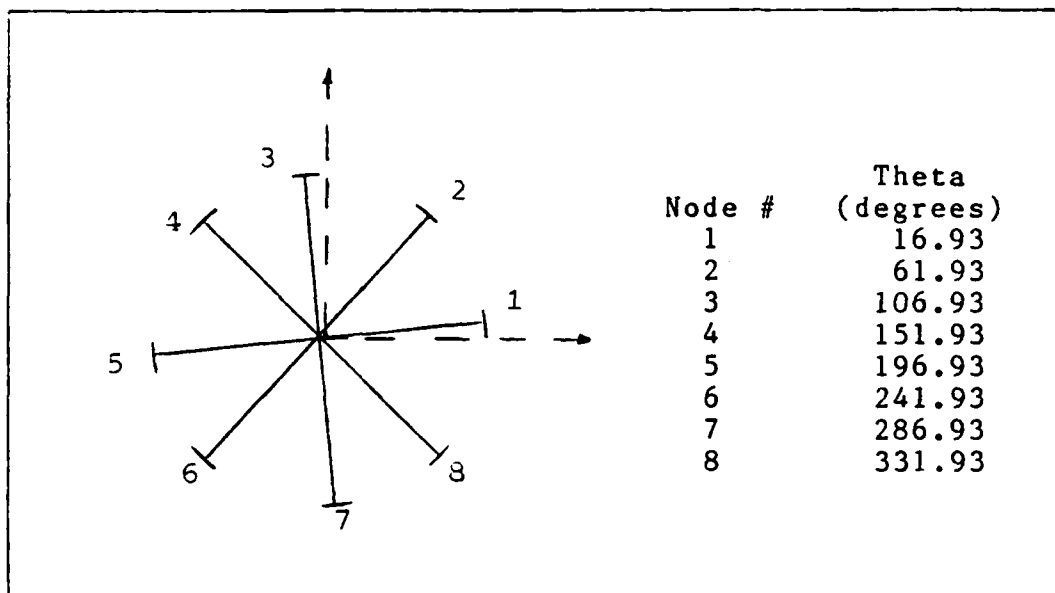


Fig. 5 New Node Positions

Thus, the new node positions can be found for each time step, simulating the rotation of the missile.

Derivation of the Equation for Laser Energy Absorption

Like the thermal radiation from a nuclear explosion, only a fraction of the laser energy is absorbed by the missile surface. This fraction is known as the absorption coefficient, α . Also, the depth of penetration, or skin depth, δ , is very small. Thus, the surface is subjected to local heating and melting (Bailey, 1984:42). Appendix B contains sample calculations for skin depth, and absorption coefficient for laser energy.

Assuming the absorption coefficient is known, the

rate of energy transfer into a material surface is:

$$\frac{dH}{dt} = \alpha I \quad (J/cm^2-s) \quad (2.5)$$

where

I = radiation intensity (J/cm^2-s)

α = absorption coefficient, or absorptivity

The total energy absorbed in a given time interval will be:

$$\Delta H = \frac{dH}{dt} t = \alpha I \Delta t \quad (J/cm^2) \quad (2.6)$$

If Δt is replaced by a finite time step, j , arbitrarily chosen as .01 seconds, then equation (2.6) gives the amount of energy deposited in each square centimeter of the laser spot during any time step. Knowing the amount of laser energy deposited into the missile, equation (2.2) can be used to find the temperature on the missile surface.

Calculating Laser Spot and Missile Surface Rotation

For this study, the laser spot size was calculated using information from Bailey (Bailey, 1985:42-66).

Using optimistic laser power and focusing capabilities, the spot size was still quite small when compared to the missile surface. For this reason, the missile surface was modelled as a flat slab. In order to model missile rotation, the missile surface was divided into cells, one cm^2 in area. Also, the intensity of the laser was assumed constant across the spot area. This is a reasonable assumption for a very high powered laser (Bailey, 1985). Thus, using equation (2.6), the energy deposited in each cell during each time step j , can be calculated. Since the intensity is constant, only a strip of cells were considered in the calculation. Figure 6 shows a laser spot and a strip of cells.

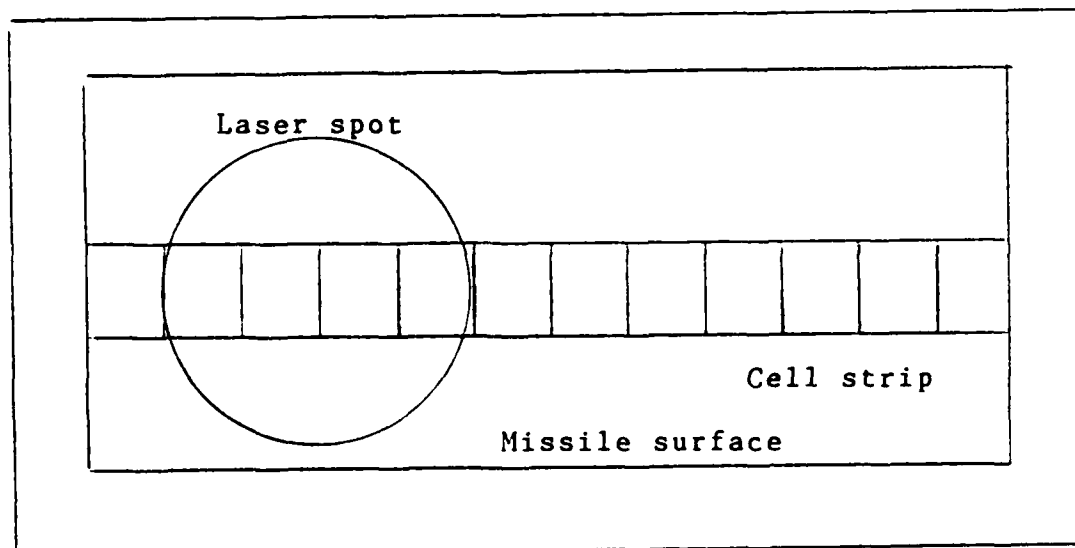


Fig. 6. Laser Spot and Cell Strip

With no rotation, the spot would deposit the laser energy on the same cells for each time interval, with heating and possible melting of the surface. For rotation, however, the spot would deposit energy on different cells as the missile surface moved, distributing the energy and reducing the amount of energy any one cell absorbs.

The rotation of the slab through the laser spot was determined by first calculating the linear velocity of the surface of the missile using the equation:

$$v = \omega * r \quad (\text{cm/sec}) \quad (2.7)$$

where

v = linear velocity of missile surface
(cm/sec)
 ω = rotation rate (radians/sec)
 r = missile radius (cm)

For example, for a rotation rate of .8 radians/sec and missile radius of 116.84 cm, the surface velocity is approximately 93 cm/sec. The distance, s , the slab travels in any time interval is found by:

$$s = v * \Delta t \quad (\text{cm}) \quad (2.8)$$

If t is replaced by j , then for each time step, the distance the surface moved in relation to the spot is known. The distance, s , determines which cells are

radiated by the laser spot. The amount of energy each cell receives for each time step is stored in a one dimensional array. Obviously, when the laser spot overlaps a cell on the surface, the energy in the cell increases, causing higher temperatures.

Adapting Models to Computer Programs

Because direct experimentation is impossible, computer programs are used extensively to model nuclear weapons effects. The groundwork for this study was introduced in NE 6.95, Nuclear Survivability of Systems. Also, Hall modified and improved the thermal model to include the cumulative thermal effects from a multiburst attack (Hall, 1985:121-134). This program, called "Therm", was modified to account for the missile's cylindrical shape, missile rotation, and laser energy deposition.

In order to solve equation (2.3), an iterative method using a finite time step was used. Specifically, once the missile launch time, t_l , the first burst time, t_{b1} , and the total number of time steps were known, the midpoint of each time step was calculated. At these times, missile characteristics, ambient air temperature, and the heat transfer coefficient were calculated and stored in one dimensional arrays. In addition, using

equation (2.4), new node positions were found. Then, using equation (A.4), the new rotational correction factors were calculated to determine the amount of radiation incident on each node. As the temperature for each node was calculated, a distribution of temperatures around the circumference of the missile was found. The iteration process continued, with the maximum temperature achieved used to calculate the probability of survival for the missile.

The same computer program was changed slightly to calculate the probability of survival for a missile subjected to a laser attack. Again, at the midpoint of each time step, the missile characteristics, ambient air temperature, and heat transfer coefficient were calculated and stored in arrays. Using equation (2.8), the distance the missile surface had moved was calculated. Representing the missile surface as a one dimensional array, this distance determined which cells, or array locations, were radiated for that time step. With the appropriate cells identified, the amount of energy for each cell was calculated using equation (2.6), and stored in the array. At the end of the iteration, the cell with the largest amount of energy was used to determine the maximum temperature, and probability of survival for the missile.

The basic algorithm for these two models is shown

in table I. In addition, Appendix E. has a complete listing of the computer program "Therm".

TABLE I

ALGORITHM FOR FINDING THE MAXIMUM SKIN TEMPERATURE
FOR A ROTATING MISSILE

1. Knowing l_t and t_{b1} , calculate and store missile velocity, altitude, down-range-distance, at $t = t_0 + (j-.5)*T_{max}$, where $j=1,2,...,11$.

Calculate and store T_{air} and h at same times

Knowing the burst number, and the times of the burst, calculate and store the amount of energy emitted by the thermal source, and, if applicable, the height of burst.

2. Set $j=1$, $T_1 = T_{air}$ at $t = t_0$, T_2 to be any number greater than T_1 , and the number of bursts $nb = 1$.
3. If $T_2 < T_1$ and $j <= 10$ then:
 - a. The current time step is $j = j + 1$
 - b. At time $j*t_{max}$, determine if another burst has occurred. If so, $nb = nb + 1$.
 - c. For each burst k that occurs:
 1. Calculate SR , θ , and θ' . If burst k has just occurred within the time step, missile characteristics must be re-calculated.
 - 2a. Calculate the total thermal energy emitted by the burst. Calculate $RF(n)$ for each node, and store the amount of absorbed energy of each node
 - 2b. Calculate the distance the slab moved if laser energy problem, and identify and store the energy received by each cell.

d. Calculate T_2 knowing h ; and the total energy² absorbed by each node, or each cell whichever is applicable.

e. For each node, or cell:
If $T_2 < T_1$ then $T_2 = T_1$

f. Return to condition in step 3. If either test fails, go to step 4

4. $\text{MaxT} = T_1$

Chapter III. Conditions and Limiting Parameters

In order to calculate the probability of survival for a missile against any thermal threat, several conditions and limiting parameters were required. For the thermal threat from multiple nuclear explosions, the conditions and parameters were the same as those used in a similar study by Hall (Hall,1985:31-34). A brief description of some of the conditions is presented first, and the remaining values listed in table II. The remainder of this chapter deals with the conditions and parameters required to determine the probability of survival for a missile against a laser threat. These values were developed from notes given by Dr. W. Bailey (Bailey,1985), and are summarized in table III.

From a similar study by Hall, several simplifying conditions and parameters were developed and used in this study. First, the RV aiming error was zero, thus deleting the requirement for calculating a circular error probable. This assumption reduced computing time significantly, but did not affect the results (Hall,1985:48). Second, the location for calculating the local heat transfer coefficient, h , was assumed to be the third stage joint on a generic missile. This position ($X_m = 5.5 \text{ m}$) represents a point where an average amount of convective cooling occurs along the

missile skin (Hall, 1985:34). Finally, the maximum number of bursts was limited to four. While this was a rather arbitrary limit, the cumulative effects of four bursts adequately demonstrates the difference between a rotating and nonrotating missile. In addition, increasing the number of bursts increases the computing time, but does not change any other aspect of the attack.

Determining Minimum Intensity
Required on Target

For this study, a laser kills a target if it deposits enough thermal energy per unit area in a short amount of time, to raise the missile skin temperature above the sure-kill level (809 K). Using the thin skin approximation, the minimum intensity (W/cm^2) required to insure a thermal kill can be found. Sample calculations are in Appendix C, and they show that approximately 2000 W/cm^2 , delivered for one second, will kill a nonrotating missile. Therefore, for this study, regardless of the spot size considered, the minimum intensity incident on the surface of the missile was 2000 W/cm^2 .

TABLE II

CONDITIONS AND PARAMETERS FOR CUMULATIVE THERMAL THREAT

System:

Close-Spaced Basing, of Peacekeeper Missiles
(see figure 1)

Threat Conditions:

Walk attack starting at silo #1 and continuing
every 2 seconds on successive silos
Weapon Yield: 2 MT
Height of Burst: 0 m
For surface bursts, $t_f = .18$
(Glasstone and Dolan, 1977:319)

Missile Conditions:

Missile velocity, altitude, down-range-distance,
and flight path angle shown in figure 2 as
a function of time
Skin material: Aluminum
 $K = .0001 \text{ m}^2/\text{s}$
 $\rho = 2700 \text{ kg/m}^3$
 $\alpha = .50$
 $C = 900 \text{ J/kg-K}$
 $I_p = 619 \text{ K}$
 $I_{ss} = 809 \text{ K}$
 I_{sk}
Skin thickness: $d = .001 \text{ m}$
Rotation Rate: 0 - 1.6 radians/s

Probability Conditions:

RV aiming error: none
Probability of damage based on intensity and
calculations using the cumulative log-normal
distribution function
 $P_d(I_{ss}) = .98$
 $P_d(I_{sk}) = .02$

Parameters:

Maximum number of bursts considered: $\text{maxb} = 4$
Maximum number of time steps needed: 11
Heat transfer coefficient calculated at $x_m = 5.5 \text{ m}$

TABLE III
CONDITIONS AND PARAMETERS USED IN LASER THREAT STUDY

System:

Peacekeeper Intercontinental Ballistic Missile

Threat Conditions:

Laser: Space based, continuous power,
chemical laser

Maximum Power = 10 MW

Aperture = 10 m

Altitude = 400-800 km

Spot size = 10 - 40 cm

Minimum Intensity required on target:

2000 W/cm² incident normal to surface

Maximum pulse time = 1 second

Missile Conditions:

Velocity = 5 km/s

Altitude = 100 km

Skin material: Aluminum, properties in table II

Skin thickness: $d = .001$ m

Rotation Rate: 0 - 1.6 radians/s

Probability Conditions:

Same as table II

Parameters:

Maximum number of pulses on target: 1

Determining Laser Threat Conditions

As stated before, the laser weapon was assumed to have a maximum absolute power of 10 MWs, with an aperture of 10 m. While these are optimistic parameters, the possible deployment of such a weapons in the future is considered feasible (Bailey, 1985). In order to calculate the probability of survival for a missile subjected to a laser pulse, a specific laser-missile scenario was developed from notes given by Dr. W. Bailey (Bailey, 1985: 42-62).

The laser's initial intensity is given simply by the equation: Intensity = Power/Area. For this particular laser, $I_0 = 1.27 \times 10^5 \text{ W/cm}^2$. To be a lethal beam, it must be focused to a small spot on the target. The spot radius for a given distance, Z , is determined by:

$$W(z) = \frac{.6 * \lambda * Z}{W_1} \quad (3.1)$$

where

λ = laser wavelength (m)

Z = distance from laser to target

W_1 = laser aperture radius (5m)

Table IV shows several values of Z, and the appropriate spot radii.

TABLE IV
SPOT RADII FOR VARIOUS DISTANCES FROM LASER TO TARGET

Distance (km)	Spot Radius (cm)
250	10
420	20
625	30
800	40
2000	100

Assuming no beam jitter, the intensity on target is defined as:

$$I_t = I_o \frac{W_1^2}{W(z)^2} [\text{absorption} + \text{scatter}] \quad (3.2)$$

where

I_t = intensity on target (W/cm^2)

I_o = initial intensity of laser (W/cm^2)

W_1 = laser aperture radius (5m)

$W(z)$ = spot radius (cm)

According to Bailey, for the altitudes considered in this scenario, absorption and scatter of the beam is negligible (Bailey, 1985:9-11). Therefore, the intensity on target is simply:

$$I_t = I_o \frac{W_1^2}{W(z)^2} \quad (W/cm^2) \quad (3.3)$$

The maximum spot size, and thus the highest altitude the laser could be stationed and still deliver a lethal intensity can be found using equation (3.3) and solving for $W(z)$. Rearranging the equation:

$$W(z) = \left[I_o \frac{W_1^2}{I_t} \right]^{.5} \quad (m) \quad (3.4)$$

where, for this specific case,

$$I_o = 1.27 * 10^5 \quad W/m^2$$

$$I_t = 2.00 * 10^7 \quad W/m^2$$

$$W_1 = 5m$$

$$W(z) = \text{maximum spot size}$$

$W(z)$ is approximately 40 cm. This means that a 10 MW laser, attacking targets approximately 800 km away, will produce a spot with a 40 cm radius, and deposit approximately 2000 J/cm^2 on the target in one second. This is sufficient to kill the target. For closer distances, the power required to produce the desired intensity is decreased as the spot size decreases. However, for this study, the intensity on target was assumed to remain constant at 2000 W/cm^2 , regardless of the spot size being considered.

Chapter IV Results and Discussion

The main objective of this thesis was to determine whether rotation increased the probability of survival for a missile subjected to the thermal threat. The results from the rotating case were compared to the nonrotating case for both sources of thermal energy: nuclear weapons explosions, and laser pulses. The comparison showed that rotating missiles experience a significant decrease in the maximum skin temperature regardless of the source of the thermal energy. Thus, rotation is an effective defense against thermal radiation.

The results for a missile subjected to the cumulative thermal effect from multiple bursts of a walk attack are presented first. In all cases the time step was $t_{\max}/2$. As a result, the maximum temperature change between time steps was less than seven degrees. Thus, accurate temperature rises were calculated while keeping the computing time to a minimum. To begin, a comparison between the 8, 16, and 32 node models was made to determine which model best simulated the missile's cylindrical shape. Next, the effect of rotation on the maximum temperature, and probability of survival of a missile are given. These results show that an optimum rotation rate exists. Next, the scenario is extended to

show the sure-kill and sure-safe regions for the entire missile field when every missile is rotating at the optimum rotation rate. In addition, the results for a missile subjected to a 4-on-1 attack are presented. Under this type of attack, a faster rotation rate is desirable. Finally, a comparison is made between the blast effect, and the thermal effect when rotation is considered. These results show that rotation decreases the sure-kill region significantly, reducing the devastating effect of cumulative thermal radiation.

In a similar manner, the effect of rotation on maximum temperature and probability of survival are presented for the laser energy threat. This comparison shows that for the scenarios investigated, rotation can significantly increase the probability of survival for a missile. Finally, the effect of spot size on rotation is examined, emphasizing that large spot sizes, when coupled with sufficiently high energy densities, are difficult to defend against.

Comparison between 8, 16,
and 32 Node Models

Figure 7 shows the probability of survival versus rotation rate for missile #41 using an 8, 16, and 32 node model. The 16, and 32 node models agree over the

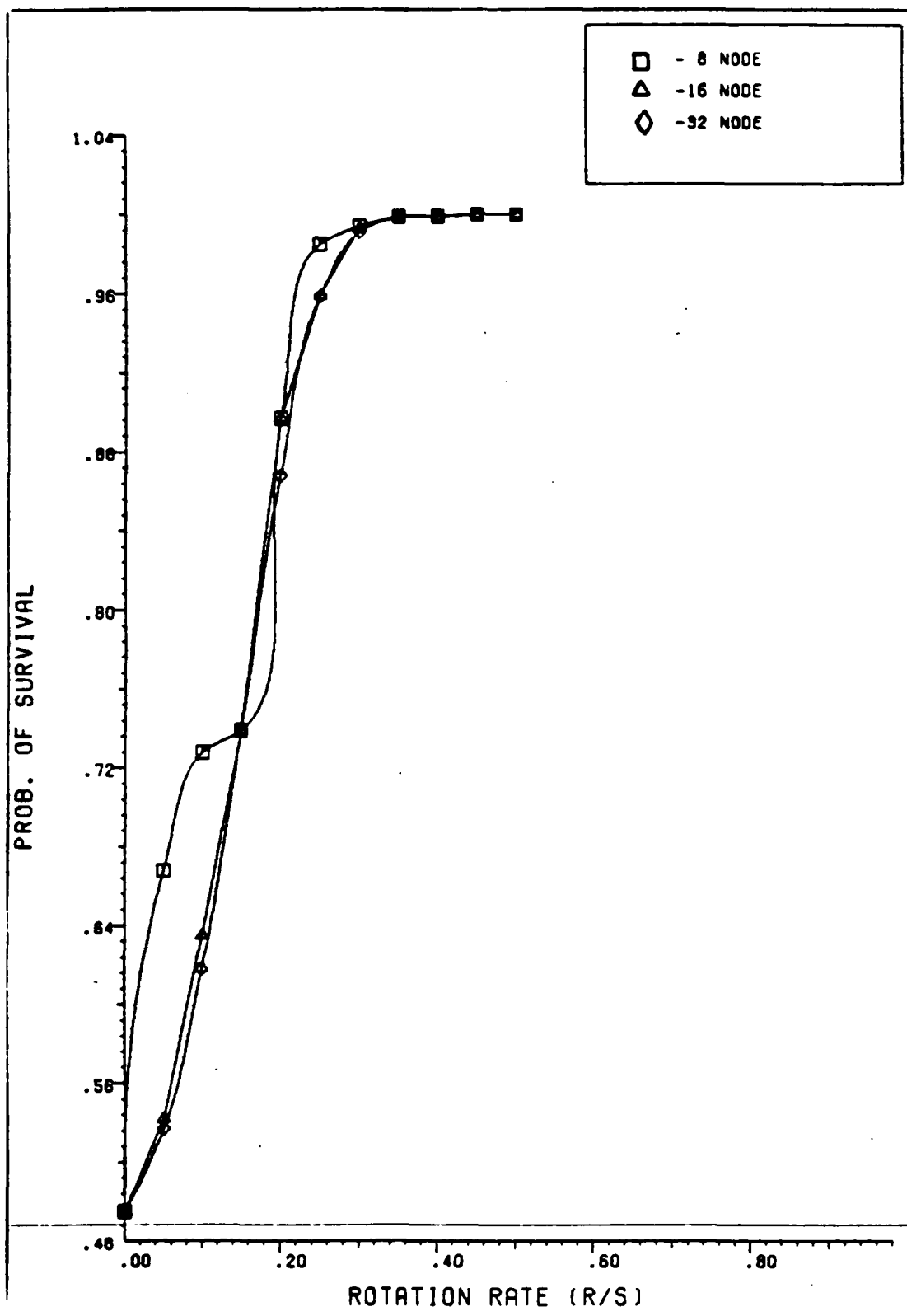


Fig. 7. Model Comparison - Ps. vs. Rotation Rate

entire range of rotation rates, but the 8 node model oscillates in the lower rotation rates. Computing times did increase, but not significantly. Therefore, to insure accuracy while keeping the computing time to a minimum, the 16 node model was chosen for all subsequent results.

Effect of Rotation on Temperature
and Probability of Survival for
Multiburst Case

Figure 8 shows the maximum temperature of any node versus rotation rate for missile #41 subjected to four bursts. The missile was launched at the same time that silo #1 was hit, and fireball rise was considered. Tabulated data for the curve is in Appendix D.

The effect of rotation on maximum temperature is clearly illustrated in figure 8. As the rotation rate increases, the temperature decreases to a minimum, and then remains relatively constant, oscillating approximately 20 degrees above the absolute minimum. The minimum rotation rate corresponds to a period of rotation of approximately eight seconds. For faster rotation rates the nodes return to their beginning positions too quickly, causing higher temperatures. Another minimum is seen at approximately twice the period (1.6 radians/sec). The drastic temperature

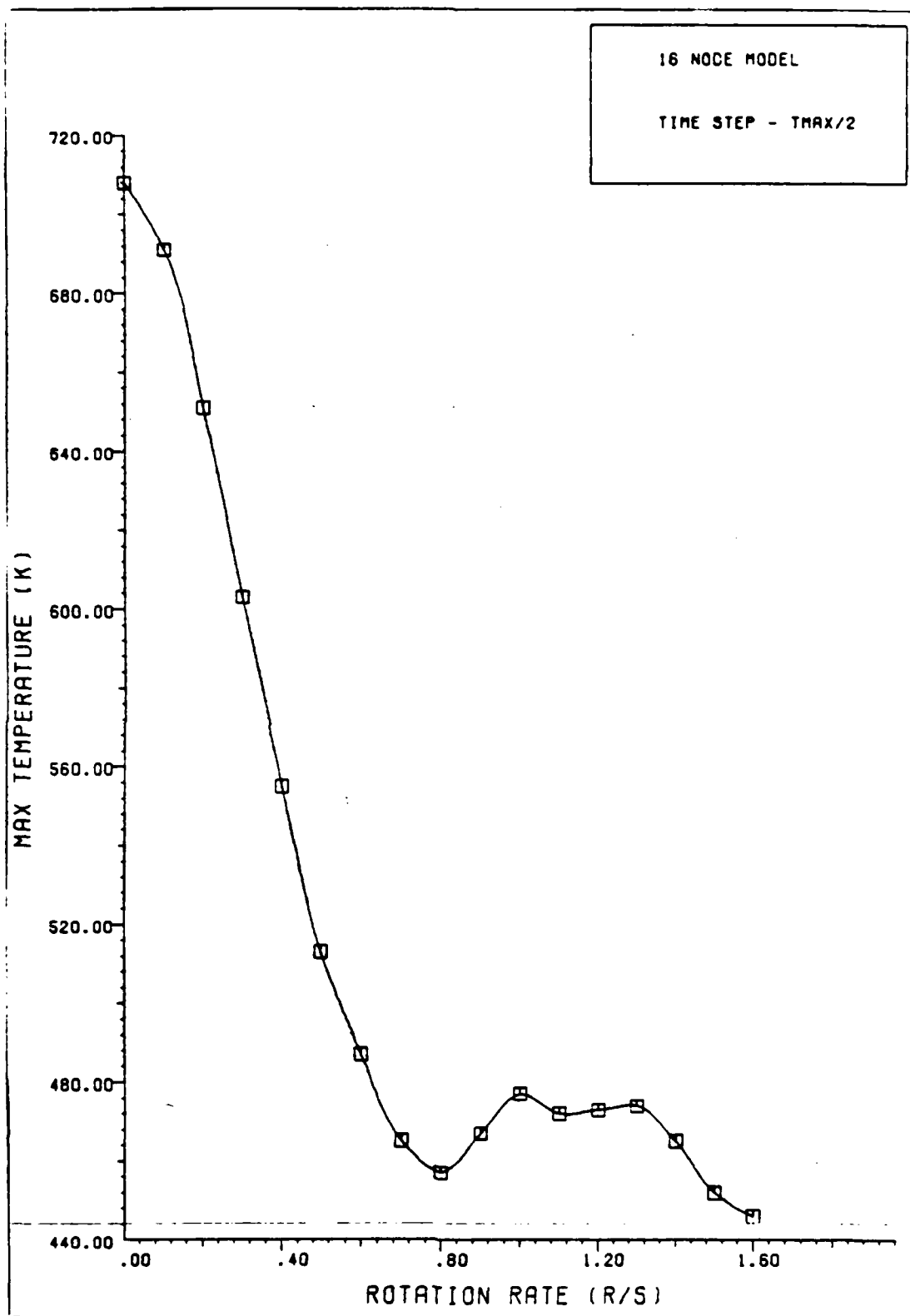


Fig. 8. Max Temperature vs. Rotation Rate

decrease occurs because the rotation constantly moves the nodes, shielding them from radiation, while exposing new nodes (missile surface) to the radiation. This prevents any one node, or point on the surface of the missile from receiving too much radiation. Also, when shielded, convective cooling can be more effective, allowing the nodes to reach lower temperatures before being reradiated on their return trip.

Figure 9 shows the probability of survival versus rotation rate for the same missile. This figure shows how increasing the rotation rate increases the probability of survival. However, the probability of survival is one at a much lower rotation rate (.4 radians/sec) than the rotation rate where the minimum temperature occurs (.8 radians/sec). This happens because the probability of survival is calculated using a cumulative log-normal function. Thus, once the sure-safe temperature is reached, the probability of survival is essentially one. Therefore, the optimum rotation rate was defined to be the rotation rate that produced the lowest missile skin temperature. For all missiles in the close-spaced base system, the optimum rotation rate was .8 radians per second.

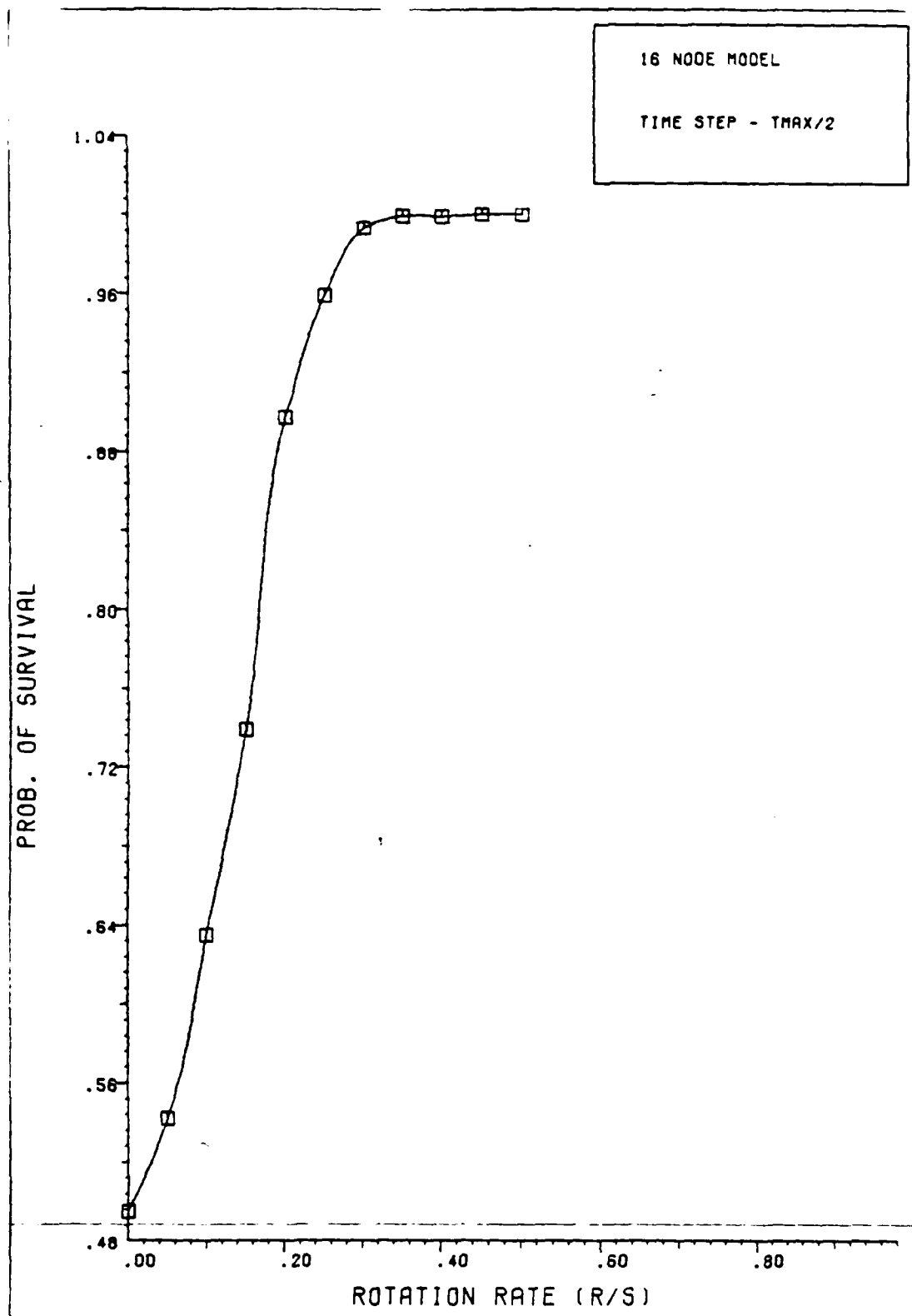


Fig. 9. Prob. of Survival vs. Rotation Rate

Comparing the Rotating
and Nonrotating Cases

Table IV shows a comparison of maximum temperature and probability of survival for several missiles at no rotation, and at the optimum rotation rate.

TABLE IV
COMPARISON OF MAXIMUM TEMPERATURES AND PROBABILITY
OF SURVIVAL FOR NO ROTATION AND OPTIMUM ROTATION

Missile launch time: 0 sec
Time of first burst: 0 sec
Time between bursts: 2 sec
1 cell CEP
Optimum rotation rate: .8 radians/sec

Missile#	No Rotation		Optimum Rotation	
	MaxT (K)	Ps	MaxT (K)	Ps
28	1638	0.00	843	0.00
29	1390	0.00	735	0.28
30	1383	0.00	731	0.31
31	1169	0.00	645	0.92
32	1178	0.00	645	0.92
33	1160	0.00	640	0.93
34	1015	0.00	578	0.98
35	1011	0.00	577	0.98
36	885	0.00	527	0.99
37	889	0.00	527	0.99
38	880	0.00	524	0.99
39	789	0.05	486	1.00
40	787	0.05	486	1.00
41	708	0.49	454	1.00
42	680	0.50	440	1.00
43	670	0.54	436	1.00
44	645	0.92	430	1.00
45	640	0.93	430	1.00

For this thesis, the sure-safe limit is defined by a probability of damage of .02, and the sure-kill limit by the probability of damage of .98. Any values lower than .02 are rounded to 0, and any values higher than .98 are rounded to 1. Any missile not listed on table IV has a probability of survival of 0 or 1, depending on the missile's position.

Another way of presenting the values given in table IV is by using figure 1 to illustrate the sure safe and sure-kill regions. Figure 10 shows the two regions for the values in table IV. Comparing these results shows that rotation significantly decreases the sure-kill region for thermal effects.

Comparing Cumulative Thermal Effects to Blast Effects

According to a recent study, the cumulative thermal effect from a multiburst attack is more lethal than the (noncumulative) blast effect (Hall, 1985:52). Table V shows the probability of survival for noncumulative blast effects.

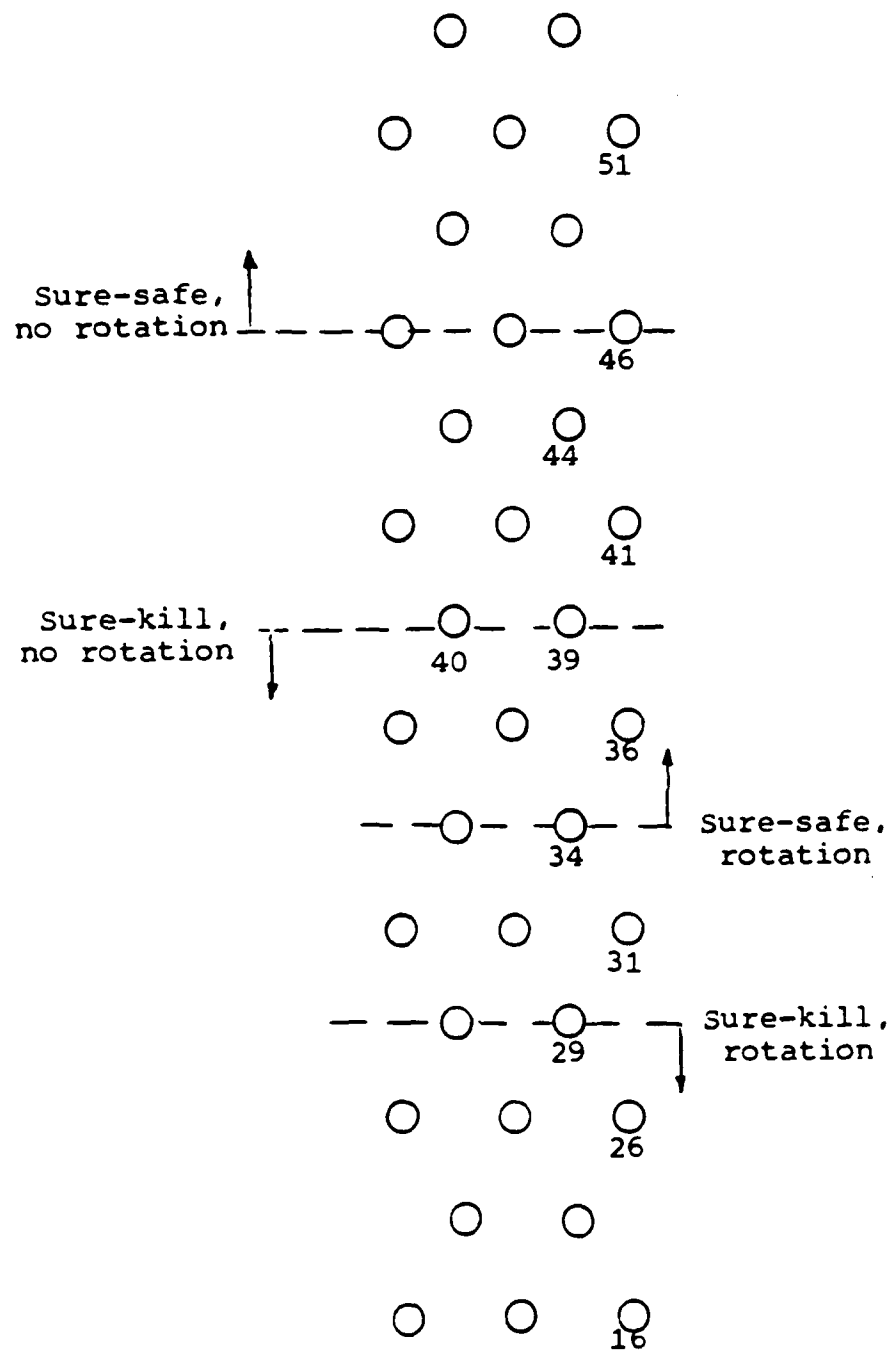


Fig. 10. Location of Sure-kill and Sure-safe Regions

TABLE V
RESULTS FOR NONCUMULATIVE BLAST EFFECTS

Missile launch time: 0 sec
Time of first burst: 0 sec
Time between bursts: 2 sec

Missile #	Prob. of Survival
23	0.000
24	0.072
25	0.096
26	0.590
27	0.626
28	0.750
29	1.000

Comparing these results to table IV shows that the blast effect is overwhelmed by the cumulative thermal effect for nonrotating missiles. However, for missiles rotating at the optimum rotation rate, the sure-safe and sure-kill regions are decreased significantly. Figure 11 shows these regions for rotating and nonrotating missiles compared to the blast effect. If cumulative blast effects were considered, the gap between thermal and blast sure-kill and sure-safe regions would probably be decreased even more. These results emphasize how rotation reduces the dominance of the cumulative thermal effect from nuclear weapons explosions.

Probability of Survival
and Maximum Temperature for
4-on-1 Attack

The previous results concerned the thermal threat

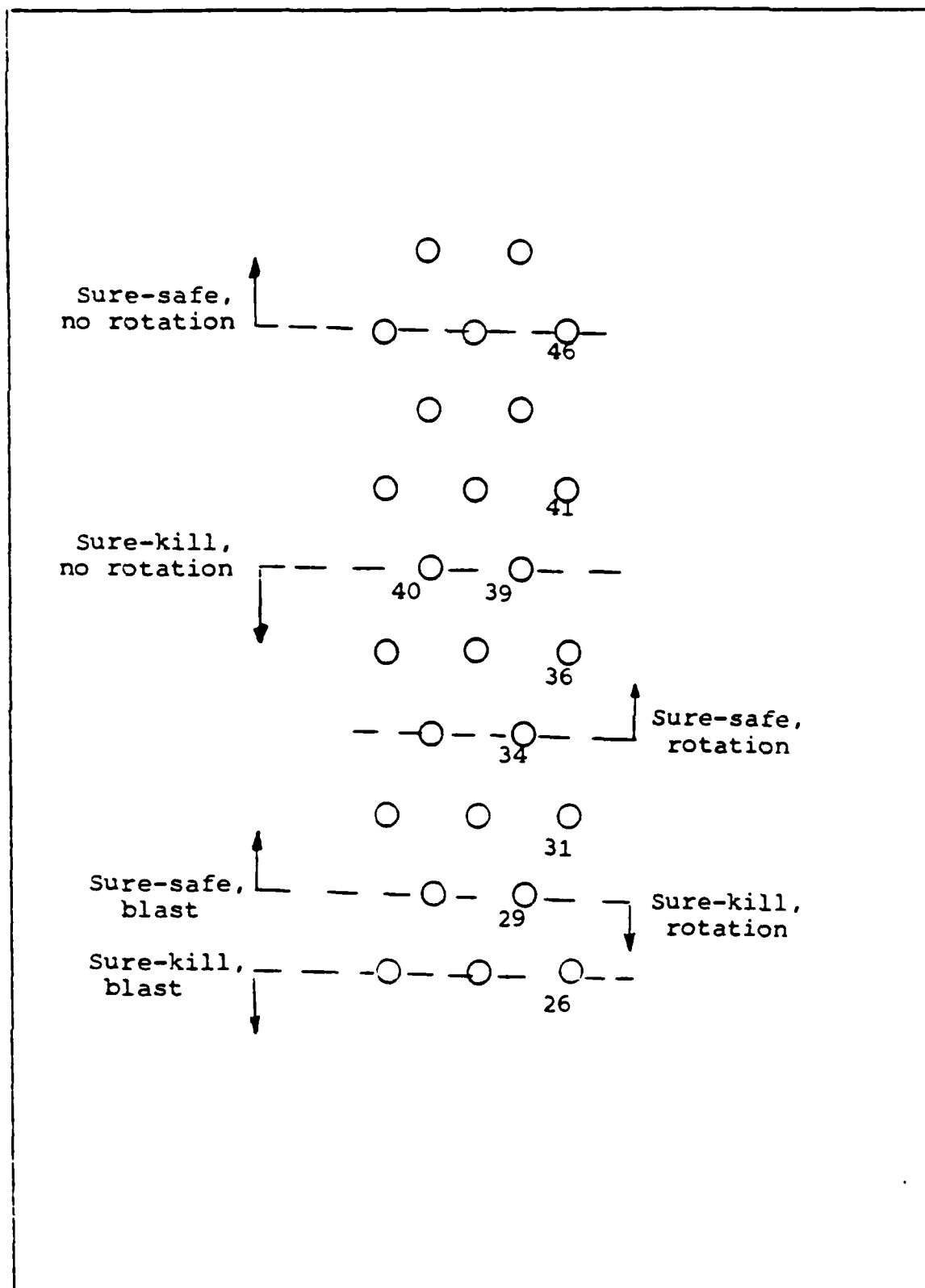


Fig. 11. Location of Sure-kill and Sure-Safe Regions

from a walk attack, where the bursts progress in an orderly fashion (for example, south to north). In the 4-on-1 attack, the missile was subjected to four bursts. The burst locations, relative to the launching missile, were such that the missile was radiated from all sides. The intent was to determine if the optimum rotation rate was scenario dependent. Each burst occurred every two seconds, and fell in a counterclockwise manner about the launching missile.

Figure 12 shows the probability of survival vs. rotation rate for a missile under a 4-on-1 attack. The probability of survival initially goes down, reaching a minimum at approximately .7 radians/sec. This occurs because the missile rotation rate, and the burst explosion rate are approximately the same. In otherwords, the missile was rotating into the thermal pulse as each weapon exploded. However, as the rotation rate increased, the probability of survival also increased. Thus, at the higher rotation rates, the thermal energy was effectively distributed on the missile surface, decreasing the maximum temperature, and increasing the probability of survival. Several other 4-on-1 scenarios were examined, and in all cases, the maximum rotation rate was the most effective.

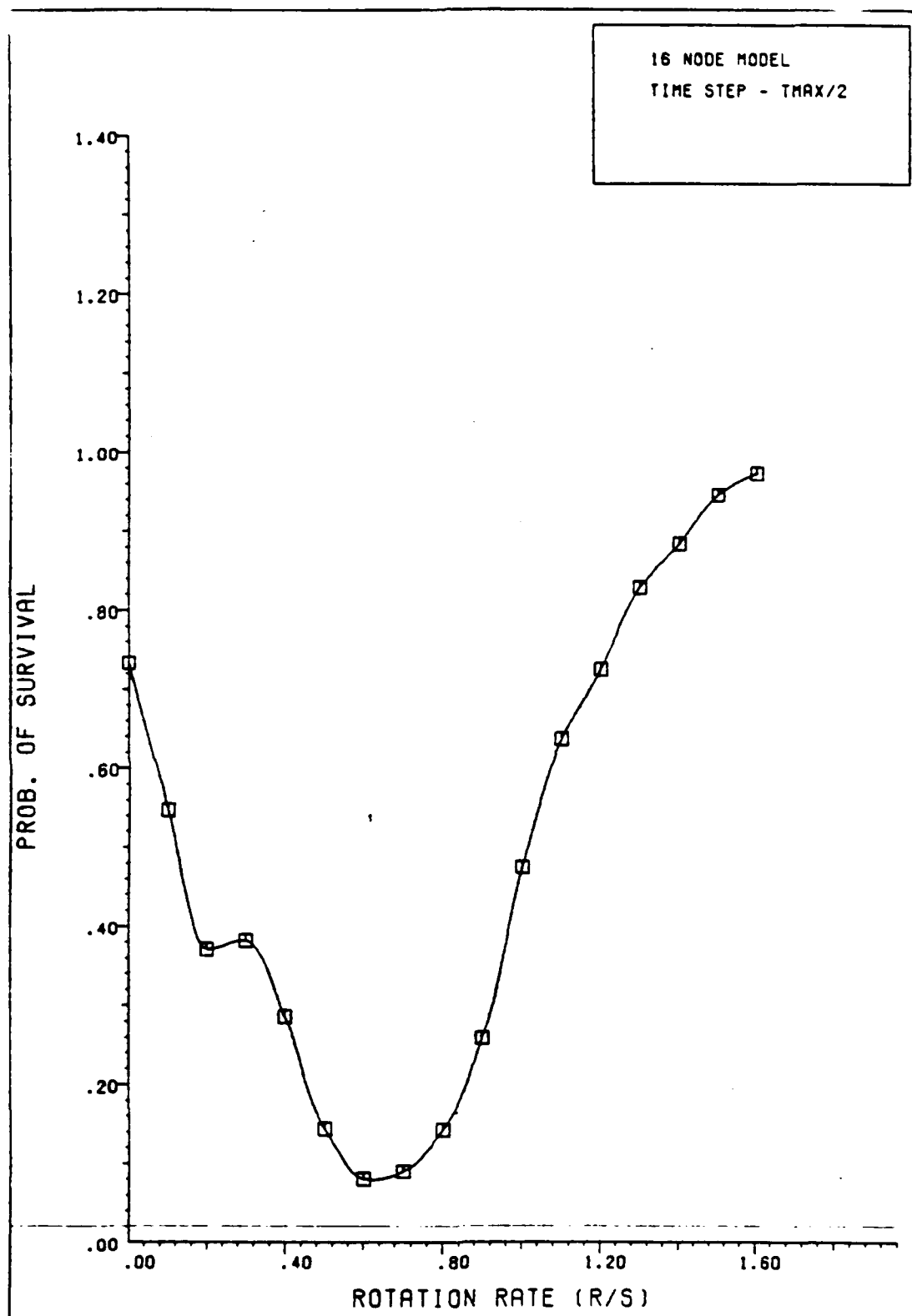


Fig. 12. Random Attack - Ps. vs. Rotation Rate

Effect of Rotation on Temperature for the Laser Threat

Figure 13 shows the maximum temperature versus rotation rate for the missile surface subjected to a laser pulse. The laser spot radius on target was 10 cm, with an intensity of $2000 \text{ J/cm}^2\text{-s}$.

The effect of rotation on maximum temperature is clearly shown for this scenario. As the rotation rate increases, the maximum temperature decreases to a minimum. The high temperatures at the low rotation rates are a result of the laser spot overlapping on the missile surface during the iteration process. As the rotation rate increases, the spot overlaps less until for each time step, the laser spot moves an entire spot width, and no overlapping occurs. As the rotation rate increases, and the temperature decreases, the probability of survival increases accordingly. Thus, for this limited scenario, rotation significantly increases the probability of survival. However, spot size drastically changes the rotation rate at which the minimum temperatures are reached.

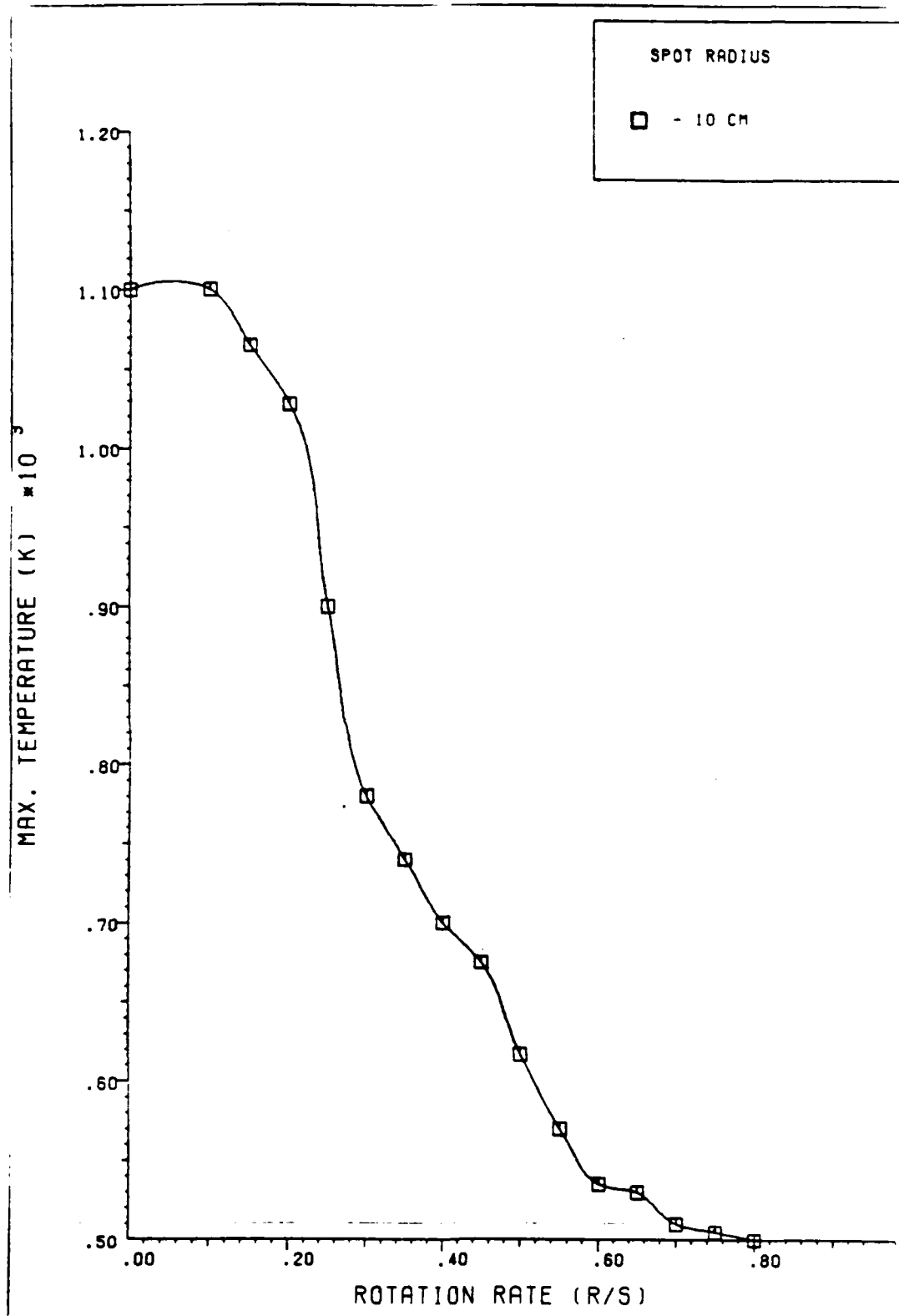


Fig. 13. Max Temperature vs. Rotation Rate - Laser

Comparison of Spot Size
to Probability of Survival

Figure 14 shows the probability of survival versus rotation rate for a missile subjected to a one second laser pulse with an intensity of $2000 \text{ J/cm}^2\text{-s}$. The four curves are for the four spot sizes considered: 10, 20, 30, and 40 cm radius. The most obvious characteristic of the illustration is that as the spot size increases, the rotation rate required to cause an increase in survival also increases. This seems logical since a larger spot would require a higher rotation rate to reduce the spot overlap. For rotation rates restricted to 1.6 radians per second, a large spot could not be moved quickly enough to reduce the missile skin temperature. In that event, rotation would have little effect on the probability of survival for the missile.

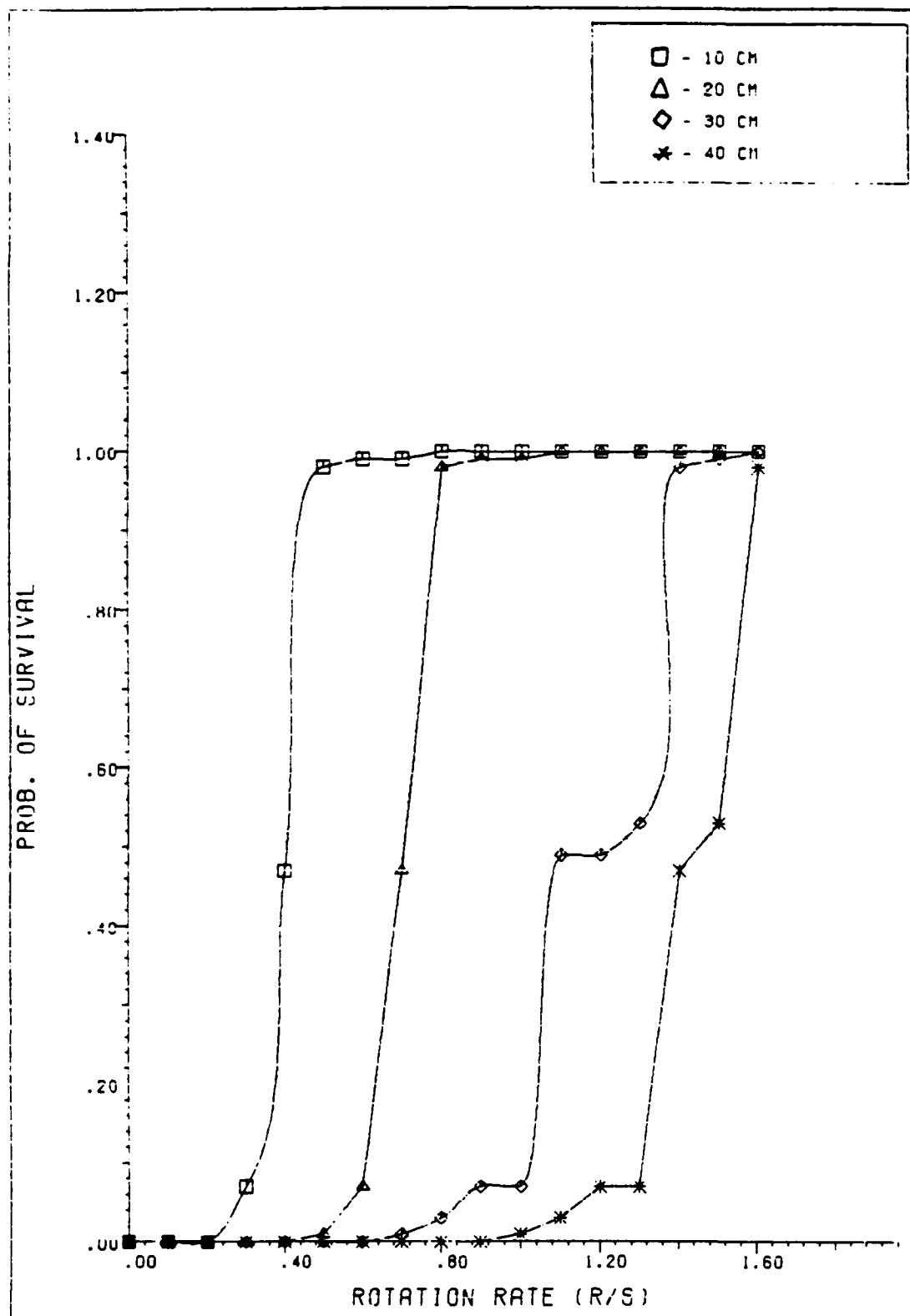


Fig. 14. Spot Comparison - Ps. vs. Rotation Rate

Chapter V. Conclusions and Recommendations

Conclusions

From the results given in Chapter IV, the following conclusions are made:

1. The maximum skin temperature for a missile exposed to thermal radiation can be decreased if the missile rotates. The most effective rotation rate depends on the scenario. However, in general, the faster the rotation rate, the greater decrease in skin temperature. Therefore, rotation is an effective defense against the thermal threat.

2. In a scenario such as a walk attack, where the attack progresses from one quadrant (i.e. south to north), rotation can have dramatic effects. In particular, a relatively low optimum rotation rate of .8 radians/sec was observed. Using this optimum rotation rate, the sure-kill region for the cumulative thermal threat can be significantly decreased. Specifically, for the walk attack scenario, 10 more missiles survive, and the sure-kill region is reduced by approximately 2000 m.

3. For the 4-on-1 attack, where four bursts surround a launching missile, rotation still significantly decreases the maximum skin temperature. However, the most effective rotation rate for this type

of attack was the maximum rate of 1.6 radians/sec.

4. As stated before, the cumulative thermal effect is more lethal than the noncumulative blast effect. However, when rotation is considered, the dominance of the thermal threat is decreased to a point where the sure-kill regions for the blast effect and the thermal effect are approximately the same.

5. Rotation is an effective defense against the laser energy threat. For the scenarios considered, the 1.6 radian/sec rotation rate was adequate to keep the missile skin maximum temperature below the sure-kill level. However, rotation as a defense against the laser threat does have certain limitations. A sufficiently powerful laser, with a large spot size could kill a missile before rotation could remove the missile surface from the spot. Therefore, for rotation to be effective, the threat against the missile must be known.

Recommendations

Based on the assumptions presented in Chapter I, as well as the observations made during the study, the following recommendations are made:

1. Since the effectiveness of rotation is scenario dependent, a more thorough investigation should be made into different scenario types.

2. A study should be made using the more accurate

cylindrical geometry between the missile surface and laser spot. This is especially true as the laser spot size increases to a point where the entire diameter of the missile is covered by the spot.

3. As recommended in a previous study by Hall, the synergistic effects of thermal heat and blast should be studied (Hall, 1985:66). This study did not investigate the mechanical stresses imposed on a rotating body. However, the increased load factor caused by rotation, coupled with the heat and blast from a nuclear explosion, may exceed the structural limits of the missile.

Appendix A. Calculating the Rotation Correction Factor

This appendix outlines the method used to calculate the rotation correction factor (RF). This correction factor accounts for the cylindrical shape of the missile. A correction factor was needed to determine the amount of thermal radiation that falls incident perpendicular to the missile skin's surface. An 8 node model will be used for this illustration.

The Rotation Correction Factor

The RF was found by considering the geometry between the burst point and the 8 nodes that make up the missile's cylindrical shape. For this study, the RV's were assumed to land directly on their targets, with no aiming error. Thus, the burst locations are known exactly. The next step was to find the exact location of the 8 nodes.

Using a standard polar coordinate system, the location of the 8 nodes was known for each time step by their position vector, r , and angular displacement, θ . Since the missile radius is very small compared to the distance between the burst and missile, only the angular displacement was used. The next step was to find the relative position where the thermal radiation is perpendicular to the missile surface. This

position will also be identified by a relative angular displacement, called thetaprime. In order to find thetaprime, the burst-missile geometry must be known. Figure A-1 shows a burst-missile encounter. Since the missile flies straight north, it is convenient to define the angle beta as:

$$\text{Beta} = \arctangent\left[\frac{(Y_{\text{burst}} - Y_{\text{missile}})}{X_{\text{burst}} - X_{\text{missile}}}\right] \quad (\text{A.1})$$

where

Y_{missile} = missile's Y position, does not change
 X_{missile} = missile's X position
 Y_{burst} = burst's Y position
 X_{burst} = burst's X position

If the missile is north of the burst, the angle thetaprime can be found using the equation:

$$\text{Thetaprime} = (1.5 * \pi) - \text{Beta} \quad (\text{A.2})$$

If the missile is south of the burst, the angle is found using the equation:

$$\text{Thetaprime} = (\pi / 2) - \text{Beta} \quad (\text{A.3})$$

Thus, thetaprime is the relative angular location where the thermal radiation is perpendicular to the missile's skin. With the two angles theta, and

Missile Position

$x_{\text{missile}}, y_{\text{missile}}$

X (North)

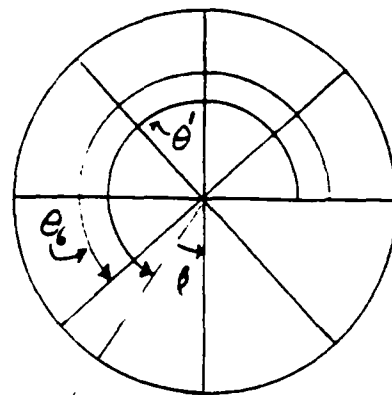
Y

Burst Position

$x_{\text{burst}}, y_{\text{burst}}$

(not to scale)

Figure A.1 Sample Burst-Missile Encounter



thetaprime, the rotation correction factor for each node can easily be determined. First, recognizing that the cosine of the difference between thetaprime and the angle theta for each node is the measure of the fraction of the thermal radiation perpendicular to that node, the RF for any node can be found using the following equation:

$$RF(n) = \text{Cos}(\text{Thetaprime} - \text{theta}(n)) \quad (A.4)$$

where

thetaprime = location on missile surface where
radiation is perpendicular

theta(n) = location of node (n = 1,2,...8)

RF(n) = correction factor for node, n

For each time step, theta(n) changes, which in turn changes the value of the correction factor RF(n). When the difference between the two angles is greater than 90 degrees, the cosine becomes negative. This means the radiation is shielded from the node, and therefore, the RF(n) is set to zero. This of course assumes perfect shielding, and does not account for scattering of the radiation. However, radiation scattering was not modelled in this study.

Appendix B. Skin Depth, and Absorption Coefficient

This appendix shows sample calculations of skin depth and absorption coefficient for laser radiation on aluminum. The laser is assumed to be a chemical laser with an operating wavelength of $4.0 * 10^{-6}$ m. Further examples can be found in Bailey (Bailey, 1985: 42-44).

Skin Depth

Whenever electromagnetic radiation strikes a good conductor, like aluminum, it can be absorbed or reflected. In either case, the electromagnetic wave must penetrate the material in order to interact with the material's electrons. The depth of penetration can be found from:

$$= \left[\frac{\epsilon * c * \lambda}{\pi \sigma} \right]^{.5} \quad (B.1)$$

where

$$\sigma = 3 * 10^7 \text{ mho/m}$$

$$\lambda = 4 * 10^{-6} \text{ m}$$

$$\epsilon = 9 * 10^{-12} \text{ C}^2/\text{J-m}$$

$$c = 3 * 10^8 \text{ m/sec}$$

Substituting into equation (B.1), skin depth is approximately $1.1 * 10^{-8}$ m. Thus, the heating is confined to the surface of the aluminum skin.

Absorption Coefficient

The fraction of energy actually absorbed by a material is known as the absorption coefficient. For good conductors, it is found using the equation:

$$\alpha = \left[\frac{4 * \pi \delta}{\lambda} \right] \quad (B.2)$$

Substituting into this equation, alpha is approximately .03. However, this calculation is based on an ideal material surface. The actual value is expected to be higher, because the missile surface has impurities, oxidation, and defects which would increase the energy coupling to the surface. Ready suggests a value of .1 (Ready, 1971:49). Therefore, for this study, the absorption coefficient is .1 for all laser calculations.

Appendix C. Calculation of Minimum Energy Density

The minimum energy density required to achieve a thermal kill is calculated using the thin skin approximation. Specifically, the amount of absorbed thermal energy required to raise the missile skin temperature above the sure-kill level of 809 degrees in one second, is determined. Also, this calculation was checked by two other methods. However, only the results of these methods are presented, along with appropriate references.

Calculating Minimum Energy Density

As explained in chapter II, the missile skin temperature can be found using the thin skin approximation. The derivation leads to equation (2.2) which is:

$$T_2 = \frac{[T_1(a - \frac{h \cdot \Delta T}{2}) + h \cdot T_{air} + \alpha \Delta Q]}{(a + \frac{h \cdot T}{2})} \quad (C.1)$$

where

T_2 = temperature at end of jth time step
(K)

T_1 = temperature at beginning of jth time
step (K)

ΔT = time step, 1 second

T_{air} = temperature of ambient air (K)

$a = C_p \rho d$ (J/m^2-K)

h = convective heat transfer coefficient
(J/m^2-s-K)

Q = absorbed thermal energy (J/m^2)

The missile's velocity and altitude are extremely high as it comes within range of the space based laser (Bailey, 1985). Under these conditions, the local convective heat transfer coefficient, h , will be very small. Using a procedure explained by Hall, h , can be calculated (Hall, 1985:85-87). For example, at 100 km altitude, and 3000 m/s velocity, h is approximately .04 J/m^2-s-K . Then using equation (C.1), and substituting in the appropriate values, the radiation absorption term, ΔQ , is approximately $1.5 * 10^6 J/m^2$.

This value was checked by two separate methods. The first was taken from notes on laser weapons by Bailey (Bailey, 1985:45-46). This analysis determined the amount of energy needed to melt, or remove a depth of surface in a given amount of time. Neglecting loss process, and assuming all the energy goes into melting

the material, the absorption term is approximately $3.0 * 10^6 \text{ J/m}^2$. The second method was taken from Raedy, and involves a two dimensional heat flow equation to calculate the temperature at any point and time in the laser spot (Raedy, 1971:75-85). This analysis also involved melting the material, and the calculated absorption term was approximately $2.75 * 10^6 \text{ J/m}^2$. Since complete melt through is not required to insure a kill, these two estimates are considered high. However, some melting surely occurs prior to failure, so for this study, the minimum absorbed energy density was assumed to be $2.0 * 10^6 \text{ J/m}^2$.

Appendix D. Data for Figures in Chapter IV

This appendix contains tables of data used to plot figures 7, 8, 12 and 14.

TABLE D-I

DATA USED TO PLOT FIGURE 7, MODEL COMPARISON
OF 8, 16, AND 32 MODELS
PROBABILITY OF SURVIVAL VS. ROTATION RATE

Omega (r/s)	Model (nodes)		
	8	16	32
0.0	.495	.495	.495
0.1	.728	.635	.618
0.2	.897	.897	.868
0.3	.994	.993	.991
0.4	.999	.999	.999
0.5	.999	.999	.999

Missile #41

Launch time: 0 sec

Time of first burst: 0 sec

TABLE D-II
DATA USED TO PLOT FIGURE 8

Omega (r/s)	MaxT (K)	Omega (r/s)	MaxT (K)
0.0	708	0.9	467
0.1	691	1.0	477
0.2	651	1.1	472
0.3	603	1.2	473
0.4	555	1.3	474
0.5	513	1.4	465
0.6	487	1.5	452
0.7	465	1.6	446
0.8	457		

Missile #41
Launch time: 0 sec
Time of first burst: 0 sec
Fireball rise considered

TABLE D-III
DATA FOR FIGURE 12
4-ON-1 RANDOM ATTACK

Omega (r/s)	Ps	Omega (r/s)	Ps
0.0	.733	0.9	.259
0.1	.547	1.0	.475
0.2	.371	1.1	.637
0.3	.382	1.2	.725
0.4	.286	1.3	.829
0.5	.144	1.4	.884
0.6	.080	1.5	.946
0.7	.090	1.6	.973
0.8	.143		

Missile #41
Launch time: 0 sec
Time of first burst: 0 sec

TABLE D-IV
DATA FOR FIGURE 14, SPOT SIZE COMPARISON
2000 J/CM², 10, 20, 30 AND 40 CM RADII

Omega (r/s)	Spot Size (cm)			
	10	20	30	40
0.0	0.00	0.00	0.00	0.00
0.1	0.00	0.00	0.00	0.00
0.2	0.00	0.00	0.00	0.00
0.3	0.07	0.00	0.00	0.00
0.4	0.47	0.00	0.00	0.00
0.5	0.98	0.01	0.00	0.00
0.6	0.99	0.07	0.00	0.00
0.7	0.99	0.47	0.01	0.00
0.8	1.00	0.98	0.03	0.00
0.9	1.00	0.99	0.07	0.01
1.0	1.00	0.99	0.07	0.03
1.1	1.00	1.00	0.49	0.07
1.2	1.00	1.00	0.53	0.07
1.3	1.00	1.00	0.98	0.27
1.4	1.00	1.00	0.99	0.47
1.5	1.00	1.00	1.00	0.53
1.6	1.00	1.00	1.00	0.98

Appendix E. Computer Program

This program is a modified version of a program called "Therm", written as part of a master's thesis by Lt. Barbara A. Hall. The program, Therm, was written in Fortran 77, and required a mainframe computer for effective operation. However, several simplifying conclusions were made by Lt. Hall, and incorporated in this program. Consequently, the following program is written in BASICA, an IBM, and Z-100 compatible Basic language. The program was run on Z-150 personal computer.

```

10 *****
20 *****
30 Cumulative Effect - With Rotation *****
40 Test Version #2, 16 node, T=TMAX/2 *****
45 Program called 'T162' *****
50 *****
60 *****
70 *****
80 *****
90 *
100 DECLARE PROGRAM CONSTANTS *
110 *
120 *****
130 *****
140 PI=3.14159: REM Radians
150 R=116.84: REM Radius of missile (cm)
160 THTA=0: REM Initial angular displacement
170 HOB=0: REM Height of burst (km)
180 ISS=619: REM Intensity Sure-Safe (Kelvin)
190 ISK=809: REM Intensity Sure-Kill (Kelvin)
200 CEP=200: REM Circular Error Probable (m)
210 *****
220 *****
230 *****
240 *****
250 *
260 DECLARE MISSILE SKIN CONSTANTS *
270 *
280 *****
290 *****
300 ALFA=.5: REM Absorptivity of Aluminum
310 CV=900: REM Specific Heat Capacity (J/Kg-K)
320 D=.001: REM Skin Thickness (m)
330 RHO=2700: REM Density of Aluminum (kg/m**3)
340 *****
350 *****
360 *****
370 *****
380 *
390 DIMENSIONALIZE STORAGE ARRAYS FOR PROGRAM CALCULATION *
400 *
410 *****
420 *****
430 DIM VDATA(52),ZDATA(52),XDATA(52),ANGDATA(72),SX(100),SY(100)
440 DIM DCT(6,32),HFB(6,32),VEL(32),ALT(32),DRD(32),ANG(32),H(32),TEMP(32)
450 DIM T2(16),DQ(16),RF(16),THETA(16),T1(16)
460 *****
470 *****
480 *
490 INITIALIZE ARRAYS WITH MISSILE FLIGHT DATA *
500 *
510 *****
520 *****
530 *****
540 *****

```

GOSUB 4490

```

550  *****
560  *
570  *          INPUT ATTACK/WEAPON PARAMETERS
580  *
590  *****
600
610  FOR MN=41 TO 41
620  BLUE=0
630  INPUT "ENTER MISSILE NUMBER";MN
640  INPUT "ENTER DESIGNATED LAUNCH TIME";LT
650  INPUT "ENTER NUMBER OF WEAPON BURSTS AFFECTING MISSILE";MAXB
660  INPUT "ENTER TIME OF FIRST BURST ( >= launch time and even)";TB1
670  INPUT "ENTER YIELD (kt)";Y
680  INPUT "ENTER 1 IF YOU WANT FIREBALL RISE, 0 IF NOT";RISE
690  INPUT "ENTER ROTATION RATE OF MISSILE (in radians)";OMEGA
700  GOSUB 5300
710  OMEGA=BLUE/20
720  *****
730
740  *****
750  *
760  *          PRELIMINARY PROBABILITY DENSITY FUNCTION CALCULATIONS
770  *
780  *****
790
800  BETA=(1!/4.108)*LOG(ISK/ISS)
810  ALPHA=.5*LOG(ISS*ISK)
820  *****
830  *****
840
850  *****
860  *
870  *          PRELIMINARY MATH CALCULATIONS FOR THIS ITERATION
880  *
890  *****
900
910  A=CV*RHO*D          :REM  (J/M**2-K)
920  TF=.18              :REM  Thermal fraction
                           (surface burst)
930  XM=5.5              :REM  Critical point along
                           missile length (m)
940  THAX=.0417*Y*.44    :REM  Thermal Maximum
950
960  *****
970  *****
980  *
990  *          BEGIN CALCULATIONS FOR THE MAXIMUM TEMPERATURE
1000 *
1010 *****
1020 *
1030 *          CALCULATE INITIAL MISSILE CHARACTERISTICS
1040 *
1050 *****
1060
1070 GOSUB 2340
1080
1090 *****

```

```

1100 *
1110 *
1120 *          CALCULATE FIREBALL CHARACTERISTICS
1130 *
1140 *
1150 *          W=Y/1000
1160 *          GOSUB 2620
1170 *
1180 *
1190 *
1200 *
1210 *          INITIALIZE MAX AND MIN TEMPERATURES FOR CALCULATIONS
1220 *
1230 *
1240 *
1250 *          LOWT=1000000!: HIT=0!: SUMPD=0!
1260 *
1270 *
1280 *
1290 *
1300 *          BEGIN ITERATION PROCESS FOR MAX TEMPERATURE
1310 *
1320 *
1330 *
1340 *          GOSUB 1630
1350 *
1360 *
1370 *
1380 *
1390 *          PRINT THE RESULTS
1400 *
1410 *
1420 *
1430 LPRINT:PRINT
1440 LPRINT "MAX TEMPERATURE (kelvin)";MAXT
1450 LPRINT "MISSILE NUMBER";MN
1460 LPRINT "ROTATION RATE (radians)";OMEGA
1470 LPRINT "PROBABILITY OF SURVIVAL (Ps)";1-SUMPD
1480 *
1490 *
1500 *
1510 *
1520 *          TRY ANOTHER MISSILE/BURST SCENARIO OR QUIT
1530 *
1540 *
1550 BLUE=BLUE+1
1560 *          INPUT "WOULD YOU LIKE TO TRY ANOTHER SCENARIO (YES OR NO)?";TRY$
1570 IF BLUE <= 32 THEN GOTO 700 ELSE GOTO 1590
1580 *          IF TRY$="YES" THEN GOTO 600 ELSE END
1590 NEXT MN
1600 END
1610 *
1620 *
1630 *
1640 *
1650 *          SUBROUTINE: TCALC
1660 *
1670 *

```

```

1680 '
1690 '
1700 NB=1
1710 J=0
1720 T1=TEMP(J)
1730 T2=T1+1!
1740 '
1742 FOR L=0 TO 15: T1(L)=TEMP(J): NEXT L
1750 '
1760 IF (T2 >= T1 AND J <= 20) THEN GOTO 1770 ELSE GOTO 2170
1770 J=J+1
1780 COUNTER=J
1790 IF (NB < MAXB AND J*TMAX/2 >= 2*NB) THEN GOTO 1800 ELSE GOTO 1330
1800 NB=NB+1
1810 NEWBST=1
1820 GOTO 1860
1830 NEWBST=0
1840 ' END IF
1850 '
1860 FOR L=0 TO 15: DQ(L)=0: NEXT L
1870 '
1880 FOR K=1 TO NB
1890 TB=TB1+2*(K-1)
1900 SB=(TB+2)/2
1910 '
1920 '
1930 IF (NEWBST=1 AND K=NB) THEN GOTO 1940 ELSE GOTO 1990
1940 T=TB1-LT+J*TMAX/2-(TB1+J*TMAX/2-TB)/2
1950 GOSUB 3620
1960 VEL=V:ALT=Z:DRD=X:ANG=PHI
1970 GOSUB 3510
1980 GOTO 2020
1990 ' END IF
2000 '
2010 GOSUB 3960
2020 '
2030 FOR L=0 TO 15
2040 DQ(L)=DQ(L)+DCT(K,J)*TF*Y*TAU*CF*RF(L)*4.186E+12/(4!*PI*(SR^2))
2050 '
2060 '
2070 T2(L)=(T1(L)*(A-H(J)*TMAX/4)+H(J)*TMAX/2*TEMP(J)+ALFA*DQ(L))/(A+H(J)*TMAX/4)
2080 '
2090 NEXT L
2100 GOSUB 5120
2110 NEXT K
2120 FOR L=0 TO 15
2130 IF T2(L) > T1(L) THEN T1(L)=T2(L)
2140 NEXT L
2150 T1=T2
2160 GOTO 1760
2170 MAXT=T1
2180 IF (MAXT < LOWT) THEN LOWT=MAXT
2190 IF (MAXT > HIT) THEN HIT=MAXT
2200 '

```

```

2210 Z=(LOG(MAXT)-ALPHA)/BETA
2220 ZP=ABS(Z)
2230 PZ=1!-1!/(2!*(1!+.196854*ZP+.115194*ZP^2+.000344*ZP^3+.019527*ZP^4)^4)
2240 '
2250 IF (Z >= 0!) THEN PDI=PZ ELSE PDI=1-PZ
2260 '
2270 '
2280 '
2290 SUMPD=SUMPD+PDI
2300 '
2310 '
2320 RETURN
2330 '*****
2340 ' *****
2350 ' *
2360 ' * SUBROUTINE: INITCHAR *
2370 ' *
2380 ' *****
2390 J=0
2400 TO=TB1-LT
2410 T=TO
2420 GOSUB 3620
2430 VEL(J)=V: ALT(J)=Z: DRD(J)=X: ANG(J)=PHI
2440 '
2450 '
2460 GOSUB 4160
2470 H(J)=H: TEMP(J)=TA
2480 '
2490 'Calculate missile characteristics,h, and Temp for midpoint
2500 'of each time step
2510 '
2520 FOR J=1 TO 31
2530 TM=TO+(J-.5)*TMAX/2
2540 T=TM
2550 GOSUB 3620
2560 VEL(J)=V: ALT(J)=Z: DRD(J)=X: ANG(J)=PHI
2570 GOSUB 4160
2580 H(J)=H: TEMP(J)=TA
2590 '
2600 NEXT J
2610 RETURN
2620 '*****
2630 ' *
2

```

```

640 ' * SUBROUTINE: FIREBALLCALC *
2660 ' *
2670 ' *****
2680 FOR K=1 TO 4
2690     FOR J=1 TO 11
2700         DCT(K,J)=0!
2710         HFB(K,J)=0!
2720     NEXT J
2730 NEXT K
2740 J=0
2750 K=0
2760 NB=1
2770 '
2780 'FOR EACH TIME STEP J, FIND DIFFERENTIAL FLUENCE AND FIREBALL HEIGHT
2790 '
2800 FOR J=1 TO 31
2810     IF (NB < NMAX AND J*TMAX/2 >= 2*NB) THEN GOTO 2820 ELSE GOTO 2850
2820         NB=NB+1
2830         NEWBST=1
2840     GOTO 2860
2850         NEWBST=0
2860 '
2870 '
2880 '
2890 'FOR EACH BURST K THAT HAS OCCURED, FIND THE THERMAL FLUENCE
2900 '
2910 FOR K=1 TO NB
2920     TB=TB1+2*(K-1)
2930     TP=(TB1+J*TMAX/2-TB)/TMAX
2940     IF (TP <= 10) THEN GOTO 2950 ELSE GOTO 3070
2950         GOSUB 3240: CTU=CT
2960         TP=TP-.5
2970 '
2980     IF (TP > 0) THEN GOTO 2990 ELSE GOTO 3020
2990         GOSUB 3240: CTD=CT
3000 '
3010     GOTO 3050
3020         CTD=0!
3030 '
3040 '
3050 DCT(K,J)=CTU-CTD
3060 '
3070 '
3080 'Find fireball rise for burst k at time t
3090 '
3100 IF (RISE = 1) THEN GOTO 3110 ELSE GOTO 3200
3110     IF (NEWBST=1 AND K=NB) THEN GOTO 3120 ELSE GOTO 3140
3120         T=(TB1+J*TMAX/2-TB)/2!
3130     GOTO 3170
3140         T=TB1+(J-.5)*TMAX/2-TB
3150 '
3160 '
3170 HFB(K,J)=21640.8*(W^.177)*(1!-(1!-T/240!)^2)

```

```

3199 '
3200 NEXT K
3210 NEXT J
3220 '
3230 RETURN
3240 '*****
3250 '
3260 '          SUBROUTINE: THERMCOEF          *
3270 '          *                               *
3280 '          *****
3290 '
3300 IF (TP <= .75) THEN CT=-.02*TP+.24*(TP^2)
3310 '
3320 IF (TP > .75 AND TP <= 1.5) THEN CT=.32*TP-.12
3330 '
3340 IF (TP > 1.5 AND TP <= 2.5) THEN CT=-.257219+.556415*TP-.0969029*(TP^2)
3350 '
3360 IF (TP > 2.5 AND TP < 10) THEN CT=.335808+.0949904*TP-4.94514E-03*(TP^2)
3370 '
3380 IF TP>=10 THEN CT=.8
3390 '
3400 '
3410 RETURN
3420 '*****
3430 '
3440 '          SUBROUTINE: ALTMISSEPOS:      *
3450 '          *                               *
3460 '          *      Used if burst occurs during time step, and new missile      *
3470 '          *      position characteristics required. If not, gosub 5760.      *
3480 '          *****
3490 '
3500 '
3510 DELTAZ=ALT-HFB(K,J)
3520 XB=SX(SB): YB=SY(SB)
3530 GR=SQR((SY(MN)-YB)^2+(DRD-XB)^2)
3540 SR=SQR(GR^2+DELTAZ^2): SRX=DRD-XB: SRZ=DELTAZ
3550 IF VEL=0 THEN GOTO 3560 ELSE GOTO 3570
3560 CF=1: GOTO 3590
3570 COSPHI=(SRX*VEL*COS(PHI)+SRZ*VEL*SIN(PHI))/(SR*VEL)
3580 CF=SQR(1!-COSPHI^2)
3590 TAU=EXP(-.02455-6.439E-05*SR-1.407E-09*SR^2+1.792E-14*SR^3)
3600 GOSUB 4860:COUNTER=COUNTER+1
3610 RETURN
3620 '*****

```

```

3630 ' *
3640 ' * SUBROUTINE: MISSILECALC *
3650 ' *
3660 ' *****
3670 '
3680 TD=INT(T): TU=TD+1: REM UPPER AND LOWER INTEGER VALUE OF T
3690 '
3700 IF T>50 THEN GOTO 3710 ELSE GOTO 3780
3710 '
3720 V=105!*T-1350
3730 Z=2460!*T-65000!
3740 X=3700!*T-127000!
3750 '
3760 GOTO 3820
3770 '
3780 V=(T-TD)*(VDATA(TU+1)-VDATA(TD+1))+VDATA(TD+1)
3790 Z=(T-TD)*(ZDATA(TU+1)-ZDATA(TD+1))+ZDATA(TD+1)
3800 X=(T-TD)*(XDATA(TU+1)-XDATA(TD+1))+XDATA(TD+1)
3810 '
3820 '
3830 IF (T > 70) THEN GOTO 3840 ELSE GOTO 3860
3840 PHI=30.6-.1*(T-70)
3850 GOTO 3880
3860 PHI=(T-TD)*(ANGDATA(TU+1)-ANGDATA(TD+1))+ANGDATA(TD+1)
3870 '
3880 V=V*.3048
3890 Z=Z*.3048
3900 X=X*.3048+SK(MN)
3910 PHI=PHI*PI/180
3920 RETURN
3930 '
3940 ' *****
3950 ' *
3960 ' * SUBROUTINE: MISSPOSM *
3970 ' *
3980 ' *****
3990 '
4000 DELTAZ=ALT(J)-HFB(K,J)
4010 XB=SX(SB): YB=SY(SB)
4020 GR=SQR((SY(MN)-YB)^2+(DRD(J)-XB)^2)
4030 SR=SQR(GR^2+DELTAZ^2): SRX=DRD(J)-XB: SRZ=DELTAZ
4040 '
4050 IF VEL(J)=0 THEN GOTO 4060 ELSE GOTO 4070
4060 CF=1: GOTO 4090
4070 COSPHI=(SRX*VEL(J)*COS(ANG(J))+SRZ*VEL(J)*SIN(ANG(J)))/(SR*VEL(J))
4080 CF=SQR(1!-COSPHI^2)
4090 TAU=EXP(-.02455-6.439E-05*SR-1.407E-09*SR^2+1.792E-14*SR^3)
4100 DRD=DRD(J): GOSUB 4860: COUNTER=COUNTER+1
4110 RETURN
4120 ' *****
4130 '
4140 '
4150 ' *****
4160 ' *
4170 ' * SUBROUTINE: HEATCALC (heat transfer coefficient h (j/m2-s-k) *

```

```

4100 ' *
4110 ' *****
4200 '
4210       Z=ALT(J): GOSUB 4310: REM Find ambient air parameters
4220       CP=240*4.184
4230       RE=RHOA*VEL(J)*XM/NU
4240       PR=NU*CP/KA
4250       IF RE<=500000! THEN NU=.332*PR*.333*RE*.5 ELSE NU=.0296*PR*.333*RE*.8
4260       H=NU*KA/XM
4270 RETURN
4280 '
4290 ' *****
4300 ' *
4310 ' *           SUBROUTINE: U.S. Standard Atmospheres ( 47 km )
4320 ' *
4330 ' *****
4340 '
4350 IF Z<11000 THEN LK=-.006545: PK=101300!: TK=288.15: ZK=0!
4360 IF Z>=11000 AND Z<20000 THEN LK=0!: PK=22690!: TK=216.65: ZK=11000
4370 IF Z>=20000 AND Z<32000 THEN LK=.001: PK=5528!: TK=216.65: ZK=20000
4380 IF Z>=32000 AND Z<47000! THEN LK=.0028: PK=888.8: TK=223.65: ZK=32000
4390 IF Z>47000! THEN PRINT" Consult NOAA for values"
4400 IF LK=0 THEN GOTO 4410 ELSE GOTO 4420
4410       P=PK*EXP(-.034164*(Z-ZK)/TK): TA=TK: GOTO 4430
4420       TA=TK+LK*(Z-ZK): P=PK*(TK/TA)^(.034164/LK): GOTO 4430
4430 RHOA=.003484*P/TA
4440 NU=(1.458E-06*TA^1.5)/(TA+110.4): REM (kg/m-s)
4450 KA=(2.64638E-03*TA^1.5)/(TA+245.4*10^(-12!/TA)): REM (j/m-s-k)
4460 '
4470 RETURN
4480 '
4490 ' *****
4500 ' *
4510 ' *           SUBROUTINE: INITIAL DATA INPUT
4520 ' *
4530 ' *****
4540 '
4550 OPEN "I",#1,"veldata.txt"
4560 FOR I=1 TO 51: INPUT #1,VDATA(I): NEXT I : CLOSE #1
4570 OPEN "I",#1,"altdata.txt"
4580 FOR I=1 TO 51: INPUT #1,ZDATA(I): NEXT I : CLOSE #1
4590 OPEN "I",#3,"drddata.txt"
4600 FOR I=1 TO 51: INPUT #3,XDATA(I): NEXT I : CLOSE #3
4610 OPEN "I",#1,"degdata.txt"
4620 FOR I=1 TO 71: INPUT #1,ANGDATA(I): NEXT I:CLOSE #1
4630 'OPEN "I",#1,"MLO.txt"
4640 'FOR I=1 TO 100: INPUT #1,MLT(I): NEXT I : CLOSE #1
4650 '
4660 ' *****
4670 ' *
4680 ' *           SILO POSITIONS (X & Y COORDINATES)
4690 ' *
4700 ' *****

```

```

4710 '
4720 DX=519.62 : DY=300
4730 FOR I=0 TO 95 STEP 5
4740     SY(I+1)=0: SY(I+2)=2*DY: SY(I+3)=4*DY: SY(I+4)=DY: SY(I+5)=3*DY
4750 NEXT I
4760 '
4770 J=0
4780 FOR I=0 TO 38 STEP 2
4790     SX(J+1)=I*DX: SX(J+2)=I*DX: SX(J+3)=I*DX: SX(J+4)=(I+1)*DX: SX(J+5)=(I+1)*DX
4800     J=J+5
4810 NEXT I
4820 RETURN
4830 ' *****
4840 ' *****
4850 ' *
4860 ' * ROTATION FACTOR CALCULATIONS
4870 ' *
4880 ' *****
4890 '
4900 IF J=COUNTER THEN GOTO 4910 ELSE GOTO 4960
4910 THETA(0)=THETA+THETA(0)
4920 FOR I=1 TO 15
4930     THETA(I)=THETA(I-1)+PI*.125
4940 NEXT I
4950 '
4960     BOTTOM=DRD-XB: TOP=SY(MN)-YB
4970     IF BOTTOM=0 THEN GAMMA=0 ELSE GAMMA=ATN(TOP/BOTTOM)
4980 '
4990 '
5000 FOR I=0 TO 15
5010 '
5020 IF DRD(J) > XB THEN THETAPRIME=(1.5*PI)+GAMMA
5022 IF DRD(J) <= XB THEN THETAPRIME=(.5*PI)+GAMMA
5030     ZPRIME=ABS(THETAPRIME-THETA(I))
5040     RF(I)=COS(ZPRIME)
5050     IF RF(I)<.25 THEN RF(I)=.25
5060     THETA=OMEGA*TMAX/2
5070 NEXT I
5080 '
5090 RETURN
5100 ' *
5110 ' *****

```

```

5120 ' *
5130 ' *
5140 ' *
5150 ' *****
5160 ' *
5170 'LPRINT "TIME STEP";J, "BURST NUMBER";K,"T/TMAX";((J-.5)*TMAX/2)/TMAX
5180 'LPRINT "NODE      TEMP      THETA      ROTATE-FACTOR      GAMMA"
5190 FOR I=0 TO 15
5200 '
5210 IF T2(I) > T2 THEN T2=T2(I)
5220 'LPRINT USING "###";I+1,
5230 'LPRINT USING "  ####.##";T2(I),
5240 'LPRINT USING "          ###.###";THETA(I)*180/PI,
5250 'LPRINT USING "      ##.####";RF(I),
5260 'LPRINT USING "          ###.###";GAMMA*180/PI
5270 NEXT I
5280 '
5290 RETURN
5300 '
5310 LT=0
5320 TB1=0: MAXB=4
5330 Y=2000: RISE=1
5340 THTA=0
5350 FOR I=0 TO 15: THETA(I)=0: NEXT I
5360 RETURN

```

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Vita

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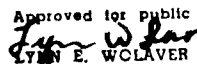
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Survivability studies have shown that intercontinental ballistic missiles are vulnerable to thermal effects. In particular, the cumulative thermal effect from a multiburst attack, and laser thermal energy can seriously damage or destroy a missile. One possible defense against the thermal threat is rotation of the missile. The purpose of this thesis was to determine if rotation decreased the maximum skin temperature of the missile, increasing the missile's probability of survival.

The study investigated several different scenarios. The first scenario was the Peacekeeper Dense Pack missile system. The missile field was subjected to a walk attack of 2 MT weapons, with the incoming RV's exploding every two seconds. The second scenario was a 4-on-1 attack of a missile launching system. More specifically, one missile was subjected to four bursts located in various positions surrounding the missile. The intent was to determine if rotating a missile, even when surrounded by thermal radiation, would increase the probability of survival. Finally, the missile is attacked by a space-based laser with a maximum absolute power of 10 megawatts. In all cases, the rotation rate was limited to a maximum of 1.6 radians/second, as established by studies at the Air Force Institute of Technology. Using computer programs, the maximum skin temperature was calculated, with the resultant probability of damage determined using a cumulative log-normal distribution function. Comparisons were made between the rotating and nonrotating missiles to determine if rotation did increase the probability of survival for the missile system.

In all scenarios studied, rotation significantly decreased the maximum skin temperature, increasing the probability of survival for the missile. The decrease was most dramatic for the walk attack, where an optimum rotation rate of .8 radians/second was established. For the 4-on-1 attack, rotation was effective, but required the maximum 1.6 radians/second rotation rate for best results. Finally, for the laser threat, rotation was effective for the scenarios studied, with the maximum rotation rate providing the greatest amount of protection. As a consequence, even at these relatively low rotation rates, rotation is an effective defense against the thermal threat.

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