Solid Ballistic Missiles Design
固体弹道导弹设计

Edited by：He Linshu
编　著：何麟书

北京航空航天大学出版社

Abstract

The main contents of this book include the essential principles involved in the conceptual design of solid ballistic missiles. Before the presentation of the optimization of overall design parameters, the concepts of concurrent engineering, the mass model and the trajectory model and the trajectory optimization concerned with multistage solid ballistic missiles are described. Finally, the re-entry body design which has close relationship with the usage of ballistic missiles is presented.

This book is intended for use by senioryear undergraduate and postgraduate students as well as practicing engineers who are interest in this field.

图书在版编目(CIP)数据

Solid Ballistic Missiles Design＝**固体弹道导弹设计/何麟书编著.—北京：北京航空航天大学出版社，**2004.5

ISBN 7-81077-235-X

Ⅰ.**固…** Ⅱ.**何…** Ⅲ.**固体推进剂导弹：弹道导弹—设计—英文** Ⅳ.TJ761.3

中国版本图书馆 CIP **数据核字**(2002)**第** 068182 **号**

Solid Ballistic Missiles Design
固体弹道导弹设计

何麟书　编著
责任编辑　胡　敏

*

北京航空航天大学出版社出版发行
北京市海淀区学院路 37 **号**(100083)　**发行部电话**:82317024　**传真**:82328026
http://www.buaapress.com.cn　E-mail:bhpress@263.net
涿州新华印刷有限公司印装　各地书店经销

*

开本:787×960　1/16　**印张**:8.25　**字数**:185 **千字**
2004 **年** 5 **月第** 1 **版**　2004 **年** 5 **月第** 1 **次印刷**　**印数**:2 000 **册**
ISBN 7-81077-235-X　　**定价**:19.00 **元**

Preface

The purpose of this teaching material is to present a set of applied conceptual design methods that can be used for design of solid propellant ballistic missiles. The level of the contents is suitable for postgraduate students and senior students.

Conceptual design is probably the most important design phase in whole developing process of solid ballistic missiles, especially, when all concerned disciplines need to be considered. The author would like to introduce some new developing ideas on conceptual design in this teaching material.

This teaching material is used for an about 40-hour course and the students need to have certain computer programming knowledge. It was written in a very short time, there must be some errors and defects, any criticism and comments will be acknowledged by the author.

Finally, the author acknowledges the contribution of his postgraduate students Wang Shuhe and Li Xiangqian to the task of typewriting the manuscript of this teaching material.

He Linshu
February, 2004

Contents

Chapter One Introduction

1.1 System(s) Engineering (SE) …… 1
1.2 Concurrent Engineering (CE) …… 2
1.3 Concept of (Solid) Ballistic Missile …… 4
1.4 Design Requirements of Ballistic Missile …… 8
Problems of Chapter One …… 14

Chapter Two Mass Model of Solid Ballistic Missile

2.1 Mass Equation of Solid Ballistic Missile …… 15
2.2 Calculation of the Structural Coefficient $\alpha_{\mathrm{st}i}$ of a SRM …… 19
Problems of Chapter Two …… 34

Chapter Three Trajectory Model of Solid Ballistic Missile

3.1 Coordinate Systems(Frames) …… 35
3.2 Equations of Motion in Powered Flight Phase of BM Trajectory …… 36
3.3 Equations of Motion in Free Flight Phase of a BM …… 43
Problems of Chapter Three …… 44

Chapter Four Optimization of Trajectory

4.1 Requirements for Flight Program $\varphi_{\mathrm{pro}}(t)$ …… 45
4.2 Design of Flight Program …… 47
4.3 Trajectory Optimization …… 53
Problems of Chapter Four …… 60

Chapter Five Optimization of Overall Parameters

5.1 Selection of Overall Optimization Design Parameters …… 61
5.2 Selection of Design Parameters …… 69

5.3 Mathematic Model of the Scheme Design Optimization …… 73
5.4 EPFM Method …… 76
Problems of Chapter Five …… 82

Chapter Six Example of Overall Parameters Optimization of SBM

6.1 Basic Parameters …… 83
6.2 Results of the Optimization …… 85

Chapter Seven Re-entry Body Design

7.1 Introduction …… 88
7.2 General Equation of Motion …… 91
7.3 Approximate Re-entry Trajectory …… 101
7.4 Maximum Axial Overload Coefficient …… 106
7.5 Effective Factors on Re-entry Trajectory …… 108
7.6 Re-entry Heating Problem …… 115
Problems of Chapter Seven …… 123

References

Chapter One　Introduction

1.1　System(s) Engineering (SE)

For any product, system(s) engineering can be described as follows:

"System(s) engineering is the art and science of developing an operable system capable of meeting requirements within imposed constraints including (but not instructed to) quality, cost and schedule."

Another definition of SE is:

"An approach to optimizing solutions to problems by considering the total requirements and all affected parameters."

From the viewpoint of a solid ballistic missile design, SE can be expressed as: (refer to MIL-STD-499B+GJB)

"System(s) engineering is a research field of concerning multidisciplinary. SE deals with the developing process of a product from the viewpoint of synthesis and whole life cycle so as to satisfy the requirements of users(military)."

SE includes:

(1) All disciplines and engineering concerned design, manufacture, verification, deployment, operation, maintenance and disposal;

(2) Offering equipment, software and teaching materials for training users;

(3) Establishing and maintaining the administration of the technical conditions for whole system(s);

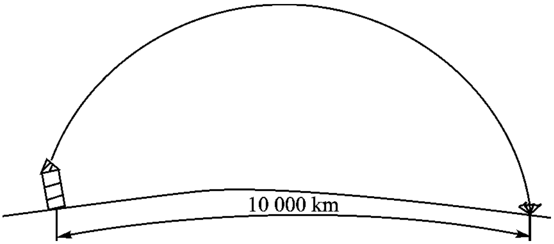
(4) Decomposing commissions and reporting work process;

(5) Providing information for decision-making.

At present, under the environment of computer network, SE has become CE (Concurrent Engineering).

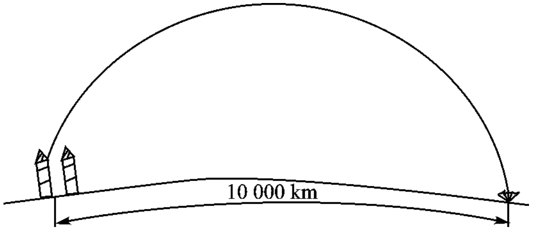
Example of SE(see Fig. 1-1):

Project Ⅰ



Warhead	1 t
Stage(s)	3
Developing period	10 years
Cost	100 million US dollars

Project Ⅱ



Warhead	0.5 t×2
Stage(s)	2
Developing period	5 years
Cost	30×2=60 Million US dollars

Fig. 1-1 Example of SE

Obviously, from the viewpoint of SE, Project Ⅱ which has the same yield of warhead is better than Project Ⅰ, because of its short leading time and less cost.

1.2 Concurrent Engineering (CE)

1. Life Cycle of a Product

Any product, which may be a weapon system, a subassembly, even a component or a part, has its Life Cycle (LC). Life Cycle of a product is shown in Fig. 1-2.

For the sake of avoiding environment pollution, disposal of outmoded product, especially for weapon system, should be noticed.

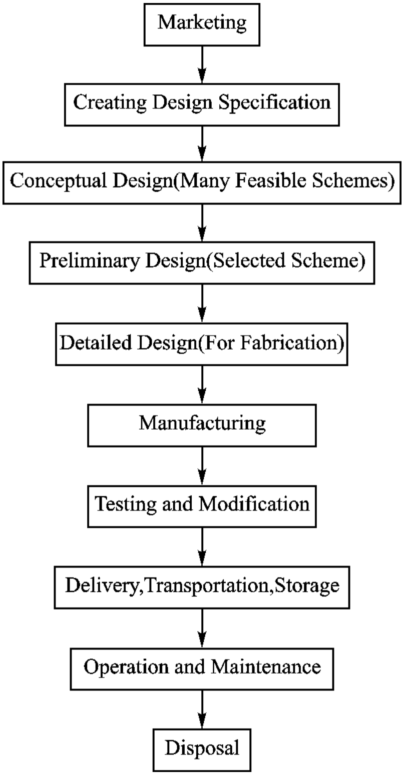


Fig. 1 - 2 Lift cycle of a product

2. Life Cycle Cost (LCC)

All expenditures during whole life cycle of a product, are called as Life Cycle Cost (LCC).

At present, LCC is one of the most important design requirements, especially, in market economy.

There was a famous statistics about LCC which created by the Boeing Co.. This statistics came from flight vehicle development in aeronautics and astronautics, especially, for weapon system.

From Fig. 1 - 3, it is obvious that the conceptual design phase is the most important period of the whole developing cycle. At the end of this phase (including conceptual design as well as verification and refinement) nearly 90% LCC will have been committed, but the real incurred LCC being only about 8%. Therefore, how to deal with the conceptual design is very important. It is difficult for designers to comprehend the potential problems in the "downstream" developing processes of the product.

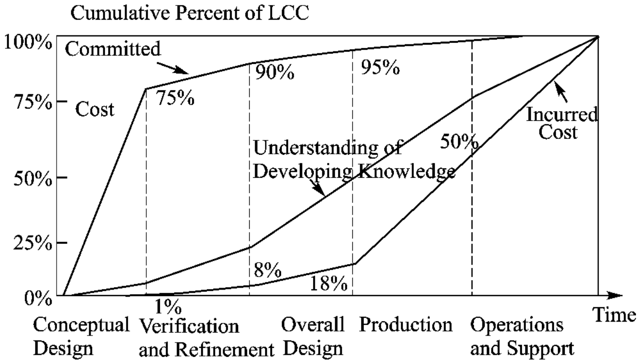


Fig. 1 – 3 LCC in different phases for developing a new flight vehicle

Nowadays, the approach to solving this problem is CE (Concurrent Engineering).

3. Definition of Concurrent Engineering (CE)

"CE is a systematic approach to the integrated, concurrent design of products and their related processed, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule and user (military) requirements."

This definition is quoted from IDA (Institute for Defense Analysis of DoD (Department of Defense in USA)) Report, R – 338, Dec. 1988, written by Winner, Robert I. ,James, P. Pennel, etc.. The title of this report is "The Role of Concurrent Engineering in Weapon System Acquisition".

The main active component in CE is conceptual design, and the crucial problem in conceptual design is MDO (Multidisciplinary Design Optimization).

1.3 Concept of (Solid) Ballistic Missile

1. The Range of Ballistic Missiles

The original definition of a ballistic missile described it as a vehicle which was designed to carry a warhead and to have a range greater than an artillery projectile and did not rely upon aerodynamic surfaces for lift.

Modern long-range ballistic missiles fall into two main categories.

IRBM—the Intermediate Range Ballistic Missile with a range of more than 1 500 nautical miles:

$$1\ 500 \times 1.852 = 2\ 778 \text{ km} \quad (\approx 3\ 000 \text{ km})$$

ICBM—the Inter-Continental Ballistic Missile which has a range greater than 5 000 nautical miles:

$$5\ 000 \times 1.852 = 9\ 260 \text{ km} \quad (\approx 10\ 000 \text{ km})$$

There are another two kinds of ballistic missiles in some papers:

FBM —the "Fleet Ballistic Missile" which is usually used by the Navy for a long-range ballistic missile. FBM can be launched from ships or submarines (e. g. Polaris).

GRBM—the Global Range Ballistic Missile with a range greater than 10 000 nautical miles:

$$10\ 000 \times 1.852 = 18\ 520 \text{ km} \quad (\approx 18\ 000 \text{ km})$$

There is an example of modern ICBN made in Russia:

$$\text{Russian Topol}-\text{M(ICBM) SS27}\left\{\begin{array}{l}\text{pc}-\text{12M1 Highway mobile}\\ \text{pc}-\text{12M2 Silo launching}\end{array}\right.$$

Range =10 500 km

m_0 =47.2 t

Mass of warhead=1.2 t

Warhead yield=550 t (TNT)

Length=22.7 m

$\phi_{\max}$ =1.86 m

Three stage SRM with upper stage boost

$$\text{CEP} \leqslant 350 \text{ m}$$

2. The Trajectory of Ballistic Missile

The purpose of a long-range ballistic missile is to transport a payload—usually a nuclear bomb (warhead)—from one point in the surface of the Earth, known as the launch point(or launch pad), to another point, also on the surface of the Earth, known as the target.

To fulfill this purpose the ballistic missile uses a propulsive system to accelerate the payload to a velocity at which it is able to follow a predetermined free flight path beyond the appreciable atmosphere. The payload moves along this free flight path without further expenditure of energy until it re-enters the Earth's atmosphere and arrives at a point close to the target, when it has been decelerated by the atmosphere, the warhead can explode within a calculated lethal distance near the target.

A typical trajectory of a long-range ballistic missile is shown in Fig. 1 – 4.

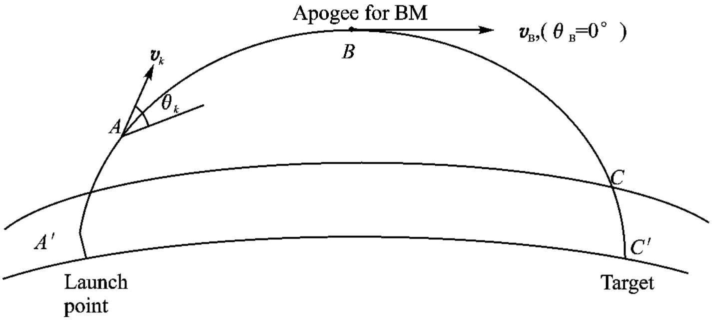


Fig. 1 – 4 A typical trajectory of a long-range ballistic missile

This trajectory is divided into three distinct sections, each section has its own characteristics.

The first section ($\widehat{A'A}$) is known as the propelled flight or powered flight. After a vertical launching the missile, which is guided by an artificial programmed turn, pitches towards the burnout point A until the direction of its velocity reaches the definite angle to the local horizontal θ_k and the value of this velocity reaches v_k. This programmed turn is known as flight program and shown in Fig. 1 – 5. It is preparatory to establishing the flight conditions for injection of the payload into the free flight or ballistic flight path which forms the second section of the typical trajectory.

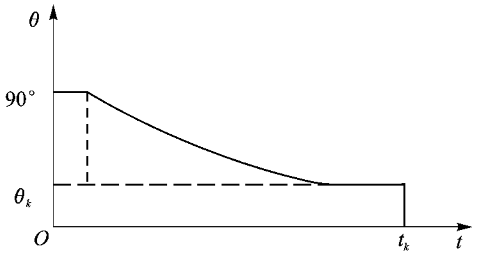


Fig. 1 – 5 Typical flight program

In Fig. 1 – 4, A is known as burnout point of the missile when the propellant is exhausted or the liquid propellant flow is cut off to cease combustion in the rocket engine or to release the pressure in the combustion chamber in the solid rocket motor. Burnout velocity v_k is the velocity of the vehicle at this time. It is close in value to the required injection velocity. Consequentially, θ_k is known as burnout angle. Another name of ($\widehat{A'A}$) is active flight phase.

The second section ($\widehat{ABC}$) is known as free flight or ballistic flight, and ($\widehat{ABC'}$) is known as unpowered flight or passive flight phase. Since the injection point (burnout point) is usually above atmosphere, the vehicle can follow the free flight path through vacuum space. During the second part of the flight the warhead can be separated from the empty body which has been used to boost the warhead to the required velocity. The warhead then follows the free flight trajectory, gradually rising through the gravitational field until it reaches the apex of its flight, a point which is known as the apogee. For a launch vehicle this point can be used for an injection point of an orbit and the perigee of an elliptical orbit. Then the warhead starts to descend towards the Earth along the downward leg of the trajectory. At the point C, it re-enters the atmosphere and is then in the third section of a typical trajectory.

The third section ($\overset{\frown}{CC'}$) is known as re-entry flight. During this re-entry phase the warhead is subjected to deceleration forces and aerodynamic heating and buffeting. The path curves rapidly at the end of the flight and the warhead may descend almost vertically on to its target. This is why the ballistic missile is still a sophisticated weapon these days.

The range of a ballistic missile is an interesting concept. The definition of range can be described as: "The range is the length of the arc section which is the part of the great circle in the plane determined by three point , launch point, target and the center of the Earth."

For a ballistic missile to have a given range from the burnout point, there are infinite combinations of burnout angles and burnout velocities, but there is an optimum burnout angle for the given range which determines the least burnout speed requirement for that range.

3. Structure of Solid Propellant Ballistic Missile

An overall block diagram of a typical two stage solid propellant ballistic missile is shown in Fig. 1-6.

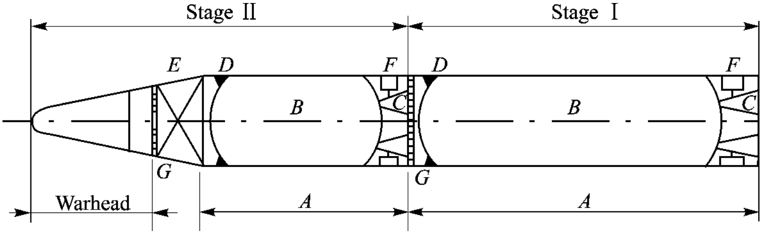


Fig. 1-6 Block diagram of a typical solid propellant two-stag ballistic missile

The first and the second stages contain a solid propellant rocket motor A. This motor consists of a solid propellant charge (grain) B and an exhaust nozzle system C. Every motor has a thrust termination system D to cut off the motor when the desired velocity has been reached for the stage. If adopting depleted shutdown, the thrust termination device D is not needed. E is instrument bay which contains navigation, guidance and control systems. The control signals are generated as a result of commands from the guidance system which determines whether or not the vehicle is on the correct path to reach its target. F is the thrust vector steering device or SERVO which can change the direction of thrust vector to produce control moment. G is the connection-separation device system to detach two stages or warhead from empty vehicle. Warhead may contain nuclear weapons or other kinds of weapons (biological or chemical) and its shell should have heating protecting coat.

1.4 Design Requirements of Ballistic Missile

1. Operational Requirement and Specification

(1) Range

The maximum range $l_{\max}$ and the minimum range $l_{\min}$ for a desired ballistic missile should be determined in advance. According to spherical triangle formula, the range can be calculated as

$$l = R_E \eta$$

where l = spherical distance.

R_E = 6 371～6 400 km(radius of the Earth).

η = range angle.

$$\cos \eta = \cos \phi_0 \cos \phi \cos(\lambda - \lambda_0) + \sin \phi_0 \sin \phi$$

where λ_0 = longitude of launch point.

ϕ_0 = latitude of launch point.

λ = longitude of target.

ϕ = latitude of target.

All parameters can be referred in Fig. 1 - 7.

There are two principles used to determine $l_{\max}$ and $l_{\min}$. One is the area between $l_{\max}$ and $l_{\min}$ should cover enemy targets as many as possible. But there is a cost consideration for $l_{\max}$. Fig. 1 - 8 (a) shows $l_{\max}$ and $l_{\min}$, $l_{\max}$ and $l_{\min}$ should cover enemy target which are comparatively neighboring. And Fig. 1 - 8(b) shows the cost curve, $l_{\max}$ has more cost and it is the suitable maximum range to match $l_{\min}$ for the desired missile.

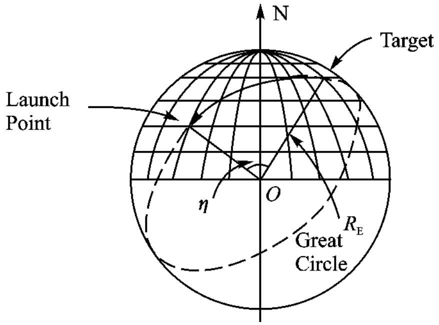
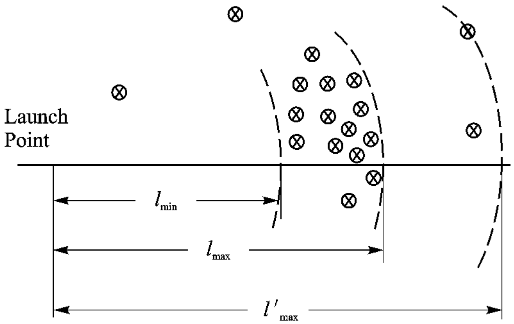
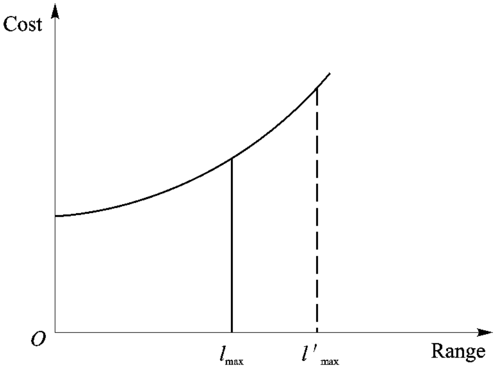


Fig. 1 – 7 The range is the length of the arc which belongs to the great circle determined by launch point, target and the center of the Earth O



(a) l_{max} and l_{min}



(b) the cost curve

Fig. 1 – 8 l_{max} and l_{min}

For two types of ballistic missile, there is an overlap or cross area which used to connect the lethal area of the two types of missiles. Fig. 1 – 9 gives the overlap area.

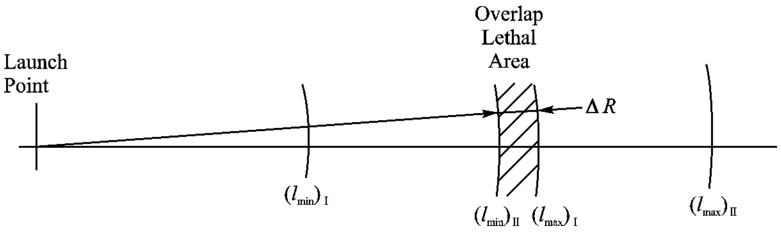


Fig. 1 - 9 $(l_{max})_{I}$ and $(l_{min})_{I}$ belong to one type of missile, $(l_{max})_{II}$ and $(l_{min})_{II}$ are of another type of missile

There is an empirical value for the overlap lethal area ΔR:

$$\Delta R = 50 \sim 100 \text{ km}$$

(2) Warhead specification

The mass of warhead is one of the most important performance indexes for design. Under the case of carrying nuclear payload, the total mass of the warhead is usually dependent upon the number of submunitions (multiple small size nuclear warhead or bomblet).

① For destroying an area target, the number of submunitions N is:

$$N = \frac{rS_m}{pS_\text{d}} \qquad \text{(Empirical Formula)}$$

where r =destroyed area part[%].

S_m =target area[km^2].

p =percentage of hit[%].

S_d =destroyed area for one submunition[km^2].

Notice:

p is dependent upon the guidance system of the missile, and S_d is dependent upon the submunition yield (how much TNT tons) (see Table 1 - 1).

Table 1 - 1 Warhead power

Yield(TNT)/($\times 10^6$ t)	0.2	1	5	10
Destroyed Radius/km	1.5	2.56	4.37	5.52
Destroyed Area/km^2	7.07	20.6	60	95.8

The destroyed area means its suffering pressure$\geqslant$4.12 N/cm^2(0.42 kgf/cm^2).

② For destroying a point target, such as missile launch silo or underground headquarter, the number of submunitions should be N (see Table 1 - 2):

$$N = \frac{\ln(1-P)}{\ln(1-Rp)} \qquad \text{(Empirical Formula)}$$

where P = the lethality probability of N submunitions[%].

R = the design reliability of one submunition[%].

p = the lethality probability of one submunition[%].

$$p = 1 - \left(\frac{1}{2}\right)^{\left(\frac{R_1}{\text{CEP}}\right)^2}$$

CEP = Circle of Equal Probability[m].

R_1 = the lethal radius[m].

Table 1 - 2 Warhead power for point target and area target

Required destroyed Pressure[kgf/cm^2]$\geqslant$		Launch silo: 7	Industrial city: 0.42
R_1/km	10×10^6t TNT	1.10	4.50
	30×10^6t TNT	1.54	6.60
	100×10^6t TNT	2.30	9.85

Notice:

Some countermeasures to ballistic missile defenses need certain extra-mass in warhead, such as: decoys, chaff, RV (Re-entry Vehicle) maneuvering, etc..

Warhead design is a special field in which many things are related to the ballistic missile design.

American 3 stages ICBM "Peacekeeper Missile" (MX), its code name is MGM-118A, has 10 × 0.48 MTNT tons yield MIRV (Multiple Independently targeted Re-entry Vehicle) submunitions. Of Course, for MIRV, it usually is matched with PBCS (Post Boost Control System).

(3) Hitting (Impact) Accuracy

CEP (Circle of Equal Probability) is usually used to express the accuracy of a ballistic missile. The definition of CEP can be described as (refer to Fig. 1-10):

CEP is a radius of a circle in which there are 50% missiles of one kind will fall down inside.

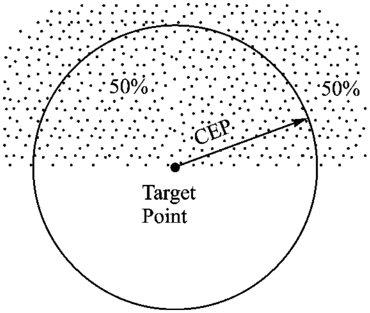


Fig. 1 - 10 CEP circle

From Fig. 1-11, it is obvious that if the accuracy of an attacking missile is improved,

e. g. its CEP can progress from about 1 km to 0.5 km, the corresponding warhead yield can be saved up to 4 times under the same lethal probability 60%. That means only one warhead with 1 Mt TNT yield is enough to destroy a "Minuteman" launch silo under the 60% lethal probability rather than 5 warheads. Where P_M is the lethal probability to the American missile "Minuteman" launch silo.

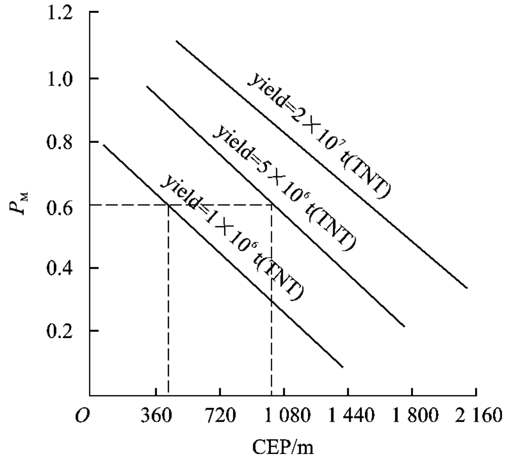


Fig. 1-11 The relationship between P_M and CEP of an attacking missile

There are two kinds of errors (deviations) which would influence the accuracy of a missile. They are guidance error and non-guidance error. The guidance error concerns the deviations of IMU (Inertial Measurement Unit) during design, manufacturing, testing, installation and the variation of their working environment. The non-guidance error has no relationship with guidance system such as gust, thrust vector misalignment, ground azimuth deviation, launch point location error, gravity anomaly, etc..

Guidance error is the primal factor for hitting accuracy which has about 70% effect on total error. Guidance error consists of two parts, method error (≈10%) and tool error (≈90%). So, the tool error (measuring error of IMU) is the main problem for using inertial guidance system.

There are some CEP values of foreign missiles in Table 1-3.