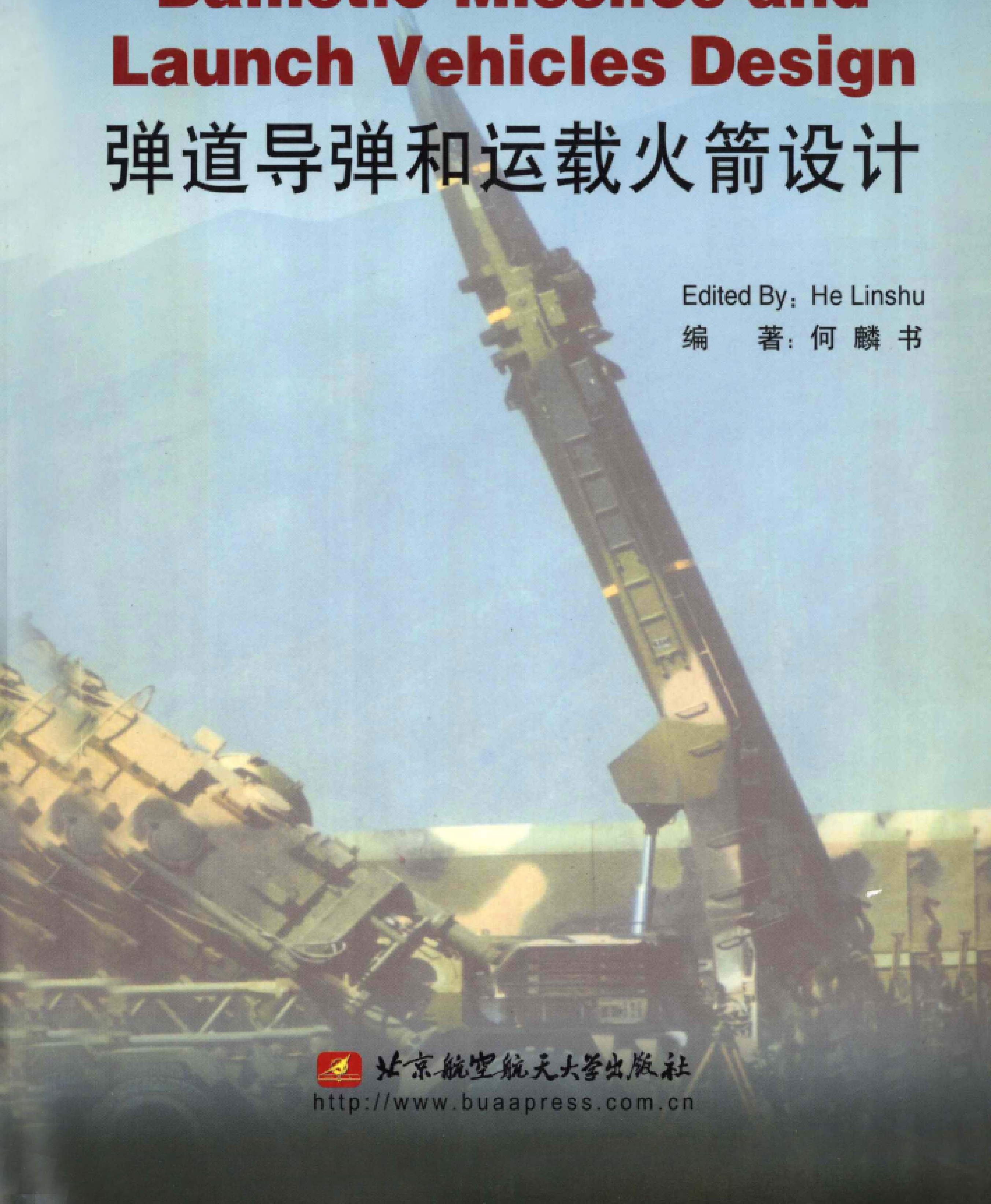
高等学校通用教材

Ballistic Missiles and Launch Vehicles Design

弹道导弹和运载火箭设计

Edited By：He Linshu

编　著：何麟书



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Abstract

This book presents and illustrates the foundations of ballistic missiles and launch vehicles conceptual design. The concept of Concurrent Engineering, determination of main design parameters, and overall configuration of schemes, as well as multistage rockets design are the principal contents of the book.

This is a text book and suitable for both postgraduate and senior undergraduate students of flight vehicle design. Practising engineers may also find it useful if they are comparatively new to this field and desire to study some professional terminologies in English.

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Preface

I have been teaching the course of Ballistic Missiles and Launch Vehicles Design for foreign postgraduate students at Beijing University of Aeronautics and Astronautics for six years. Ballistic Missiles and Launch Vehicles Design is a comprehensive course related to propulsion system, structural system, control system and launching system. I have found it difficult to find a suitable text for those students. This book is written on the base of the lecture manuscript. The book is intended to provide a reasonably comprehensive treatment for the conceptual design of ballistic missiles and launch vehicles. Conceptual design is the most important design phase in whole procedure of ballistic missiles and launch vehicles design, especially when all concerned disciplines need to be considered. The author would like to introduce some new developing ideas on conceptual design in the book.

The book contains an introductory chapter describing the system engineering and it's the newest development——Concurrent Engineering (CE), because system engineering is the foundation of the conceptual design of ballistic missiles and launch vehicles. Chapter Two gives the design missions of ballistic missiles and launch vehicles, explanation and analysis, which is of assistance to students in understanding the requirements of design tasks. Design of single stage rocket is the fundamentals of multistage rocket, so that the contents from Chapter Three to Chapter Seven include basic design methods pertinent to a single stage rocket with liquid rocket engine or solid rocket motor. Chapter Eight and Chapter Nine focus on the design approaches of multistage rocket. The provided approaches are a introduction for student's future study.

This book is intended to serve as both a classroom and a reference text. About 50 hours course might be a reasonable time to spend on the material covered in the book, however, the students need to have certain computer programming knowledge. The book has some characteristics of engineering. Some flowchart of computer programs in the book can be served as a guide for applying the basic design methods to practical system. Students may perceive a little suffering practical design process, if they do some programming assignments based on the flowcharts. This is benefit to students to experience the future design work.

The author is very greatly indebted to many people: to professor Cui Deyu for reading the manuscript and for making a number of helpful suggestion; to professor Gao Yuying for a careful reading of the book in proof, thereby eliminating some unforced errors; and finally to publishers for their assistance and cooperation in bringing the work to a state of completion. This book adopts many works written by Russian authers, American authers and Chinese authers. The author acknowledges all of the people who contributed to this book.

There must be some errors and defects due to time in a hurry, any criticism and comment will be acknowledged by the author.

He Linshu

2002. 2

List of Symbols

A	burnout point used for unpowered flight phase coordinate system
a	acceleration
a_{t}	tangential acceleration
a_{n}	normal acceleration
a_r	radial acceleration
$a_{\perp}$	vertical acceleration
C_D	coefficient of drag
$C_{D\mathrm{b}}$	coefficient of drag along the body axis
C_L	coefficient of lift
$C_{L\mathrm{b}}$	coefficient of lift vetical the body axis
C_L^{α}	derivative of C_L w. r. t. α
C_{E}	the center of the Earth
C_{m}	the center of mass
C_{p}	the center of pressure
D	drag
F	thrust
F_{s}	separating force
F_{E0}	effective thrust (ground value)
F_{EV}	effective thrust (vacuum value)
G	gravity
G_x	horizontal component of gravity
G_y	vertical component of gravity
J	moment of inertia
K	burnout point used for powered flight phase coordinate system
L	lift
L_{st}	steering force or control force
I_{sp}	specific impulse
$I_{\mathrm{sp0}}^{\mathrm{E}}$	effective specific impulse (ground value)
$I_{\mathrm{spv}}^{\mathrm{E}}$	effective specific impulse (vacuum value)
m	mass of rocket
m_{h}	mass of warhead or nose cone or upper stage

m_b	mass of body or lower stage
M	moment of rocket
M_{aero}	aerodynamic moment
M_{in}	inertial moment
$M_{ex\ damp}$	external damping moment
$M_{in\ damp}$	internal damping moment
M_{damp}	total damping moment
M_{hin}	hinge moment
M_{st}	steering or control moment
D_h	drag of warhead, nose cone, upper stage
D_b	drag of body or lower stage
θ_K	burnout velocity angle used for powered flight phase coordinate system
θ_4	burnout velocity angle used for unpowered flight phase coordinate system
α	attack angle
β	central angle of radium r
μ	mass ratio or weight ratio
ν_0	the ratio of weight to thrust
p_m	the ratio of weight to cross section area
a_E	the ratio of vacuum thrust (or I_{spv}^E) to ground thrust (or I_{sp0}^E)
ρ	density

Contents

Chapter One Introduction

1.1 System Engineering

1. What is System Engineering

From the viewpiont of flight vehicle (including ballistic missile and launch vehicle) design, the definition of system engineering can be described as follows:

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

2. The Simplified Model of a System Engineering Process During Conceptual Design

The basic idea in system engineering is to begin with a statement of system requirements and objectives, and to move in an organized way toward an optimum system(see Fig. 1 - 1).

(1) System engineering begins with the identification of a need by a potential user of the system to be developed.

① It is often the case that the user wants a system to do a given job, but he may have difficulty in stating his needs and objectives quantitatively.

② It then becomes the joint responsibility of the engineer and user to quantify system objectives so that a meaningful set of objectives may be established for the development that is to follow.

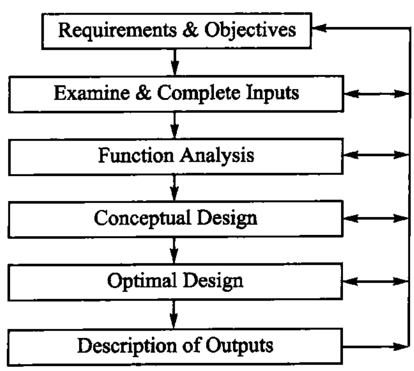


Fig. 1 - 1 A system engineering model of conceptual design

(2) Once the needs and objectives for a system are identified, it is necessary to quantitatively define functions that must be performed by the system and any subsystems that are required.

① This process is called function analysis.

② Its purpose is to pick out functions or operations that must be performed to accomplish the mission required of the system being developed.

③ These functions then become lower level objectives for the development of subsystems.

④ Identification of functions tends to be qualitative in nature.

⑤ However, once a function or operation is identified it must be described in quantitative terms.

For example, if an operation must occur quickly, the time allowed should be specified.

(3) Conceptual design, one of the most difficult functions, as its name implies, involves the identification of the concepts or basic system configurations that may meet the system objectives.

① It is desirable in this step to leave the concepts as general as possible so as not to eliminate candidate systems that might be effective.

For example, if the function to be performed is to propel a vehicle over the surface of the Earth, conceptual design might include: wheels, tracks, track vehicle (履带式车辆), legs and air cushion.

② It is important at this point in the design process to identify ranges of acceptable values of parameters describing the system.

③ For design parameters in this ranges of values, the system must be capable of performing the functions identified in the previous step.

(4) The purpose of optimal design is to choose the undetermined design parameters (or design variables) that are identified in the previous step.

① These parameters must be in the ranges defined by technological limitations and system function.

② The criterion for choosing system parameters is maximization of system worth or minimization of cost.

③ It should be emphasized that a mathematically precise optimum may be impossible to attain and may therefore serve only as a goal.

④ Methods for choosing system parameters should, however, have the nature that if an optimum does exist, then given enough patience and computer time the optimum should be approached as a limit.

(5) The final step, description of the optimum system (output), is in reality just an intermediate step.

① Unless the system design procedure has been unusually effective, the system decided upon by the engineering team will probably not satisfy the sponsor (系统工程最高负责人).

② Having the results of one pass through the system engineering process the sponsor will likely remember some constraints that be forgot to specify and which the optimum system violates.

③ In addition, the designer may also identify attractive concepts that he does not see before.

④ Much as the sponsor, he also will remember technological constraints that he forgot to specify and that the optimum system violates also.

⑤ Finally, the sponsor will undoubtedly decide that is will be all right to decrease the performance levels of the system by a small amount if it will save money.

(6) The next step in the procedure is for each member of the team to take a deep breath, sigh, and go back to work, armed with his hard-earned new knowledge.

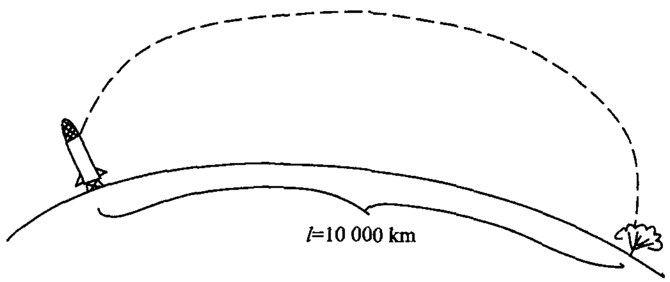
① It is for this purpose that all the feedback paths in the model of the flow chart are shown.

② This iterative procedure is continued until the sponsor decides that the system prescribed is what he really needs.

③ This will be another human decision, rather than a programmed mathematical one.

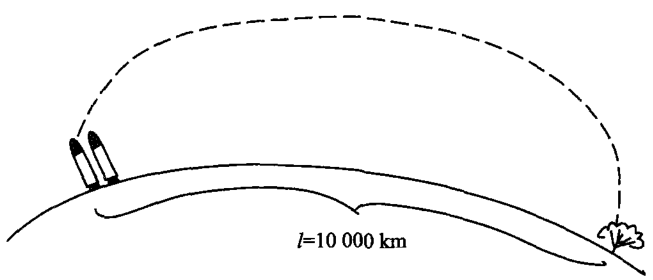
(7) Example of system engineering (see Fig. 1 - 2).

Project Ⅰ



Warhead (Nuclear Payload)	2 000 kg
Multistage Number	3
Development Period	10 years
Cost	10 million US$

Project Ⅱ



Warhead (Nuclear Payload)	1 000 kg for each, 1000 kg×2=2 000 kg have the equivalent TNT yield
Mutistage Number	2
Development Period	5 years
Cost	3 million US dollars for each, 3×2=6 million US dollars

Fig. 1 - 2　Example of system engineering

So, project Ⅱ is good, which gets the same effect, but saves time and cost. The developing period and financial support are the most important factors in armament race.

1.2　CE——Concurrent Engineering

1. Introduction

CE is termed the "modern treatment of system engineering in an integrated computer network environment."

In order to understand the definition of CE, we have to know the LC (Life Cycle) of modern flight vehicles. Fig. 1 - 3 presents the LC of a flight vehicle.

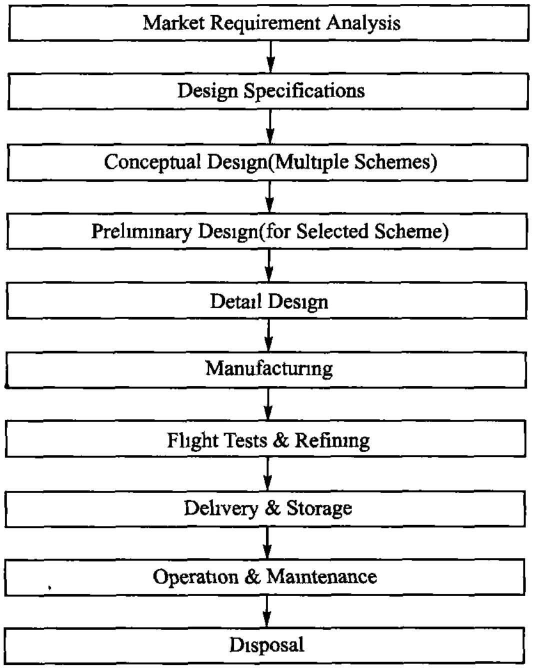


Fig. 1 - 3 Life cycle of a flight vehicle

For any flight vehicle, the life cycle always begins by market research to investigate the requirements of army and/or airlines, then, to form the TTR (Tactical and Technical Requirements) for minitary users and design specifications for civil users.

The distiction between conceptual design and preliminary design is that the former should deal with many feasible candidate schemes and the latter needs only to design various subsystems of the selected sheme. The down stream steps are easy understood. But the final step is the disposal of obsolete aircrafts or missiles which is a difficult problem to be faced by designers.

2. Definition of CE

This definition is quoted from IDA Report R - 338, 1988. The title of report is "The Role of Concurrent Engineering in Weapons System Acquisiton." IDA means Institute for Defense Analysis of DoD (Department of Defense in USA).

"CE is a systematic approach to the integrated, concurrent design of products and their related processes, 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 requirements."

IDA Report R - 338 was written by Winner, Robert I., James P. Pennel, etc., December 1988.

"并行工程是集成地、并行地设计产品及其相关的各种过程(包括制造过程和支持过程)的系统方法。这种方法要求产品开发人员在设计一开始就考虑产品在整个生命周期中从概念形成到产品报废处理的所有因素,包括质量、成本、进度计划和用户要求。"

There are two terminologys needed to explain:

Life Cycle (LC):

The distinct phases into which every system may be devided such as requirements, design, implementation, production, and maintenance.

Life Cycle Costs (LCC):

The cost of product-related activities that occur over the entire life of the product, from market research to final abandonment.

CE shares three primary objectives with TQM (Total Quality Management): increased quality, reduction in developing time, and reduction in cost. If TQM is a philosophy for flight vehicle development community, then CE is the definition of a successful implementation of the philosophy. It is an integral way of designing a complex product which defines the product as well as the processes by which it is designed, manufactured and supported.

1.3 Conceptual Design

1. LCC of a Flight Vehicle

There is a famous statistics, which can be shown in Fig. 1 - 4, created by Boeing Co. in U. S. A.. This statistics is about the LCC of flight vehicles in aeronautics and astronautics, especially, for weapon systems.

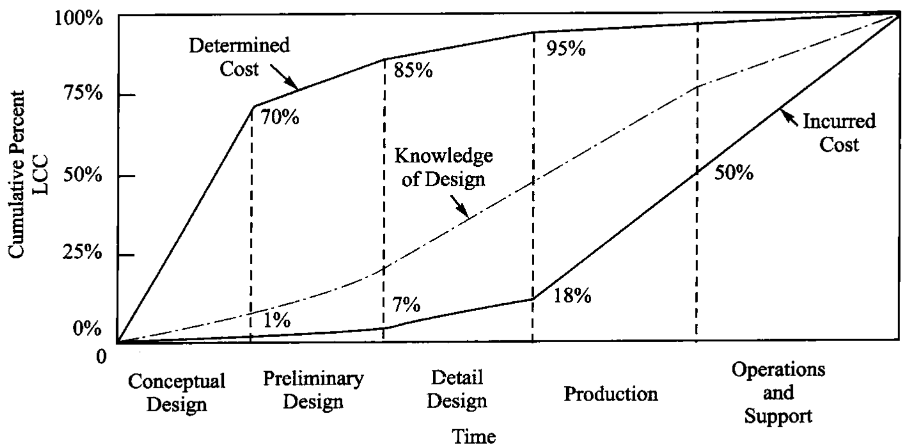


Fig. 1 - 4 LCC in different phrases for developing a new flight vehicle

Fig. 1 - 4 is a graphical illustration of the importance of the decisions made during the development of the requirement of flight vehicle design mission. The requirement is developed during the conceptual design phase. At the end of this phase more than 70% (up to now, almost 90%~96%) of the total LCC of the system will have been committed, but the actual LCC spent is only 1%~3%.

2. The Importance of Concurrent Engineering Approach

The importance of a concurrent engineering approach is clear because much of the LCC of a new weapon system is committed early in the design process, when there is little knowledge about down-stream the designers have known. CE can be utilized to close the gap between the knowledge of a complex system and the life cycle cost being committed.

3. The Conceptual Design

From Fig. 1 - 4, we should be aware of that the conceptual design is the most important phase during the development period of a new flight vehicle or a weapon system. During conceptual design approximately 70% of LCC could be determined while the incurred cost is only about 1%.

4. There are Two Terms should be Noticed

(1) Well - conditioned Scheme (良态方案)——This is a good, prospective product blank that can be modified and improved to be a "perfect" product.

(2) Ill - conditioned Scheme (病态方案)——This is a bad, congenitally defective blank that can not be improved to be a useful product. Finally, it will be abandoned.

During conceptual design, the task of designers is to do their best to obtain the well-conditioned scheme.

5. How to Engage in Conceptual Design

(1) To look at Fig. 1 - 5, we will get the enlightenment of the cartoon picture "Dream Airplanes". It is obvious that if every design group to construct the airplane according to their own desire, the airplane would not be able to fly.

(2) Compromise or Trade-off between different design group is the key skill to create a well-conditioned scheme. In fact, the different design group means different disciplinary. MDO (Multi-disciplinary Design Optimization) is the best way to deal with the compromise among several versions came from different design group or different subsystem designers.

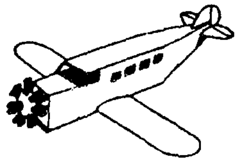
(3) Main Objective of conceptual design is to outline a scheme that can satisfy user's requirements, i. e. , high quality, low cost, and short leading time, or using the integrated standard of CE is the LCC should be minimum. At present, LCC can hardly be adopted because its relationship with various design parameters is very complicated.

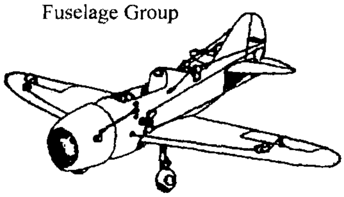
DREAM AIRPLANES

A completed airplane in many ways is a compromise of the knowledge,experience and desires of the many engineers that make up the various design and production groups of an airplane company.

It is only being human to understand why the engineers of the various groups feel that their part in the design of an airplane is of greater importance and that the headaches in design are due to the requirements of the other less important groups.

This cartoon"Dream Airplanes" by Mr.C.W.Miller,design engineer, indicates what might happen if each design or production group were allowed to take itself too seriously.


Fuselage Group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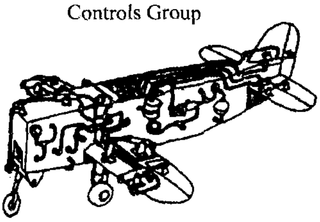
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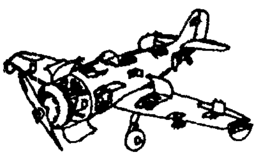
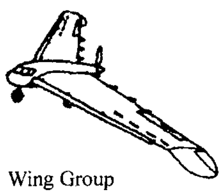

Service Group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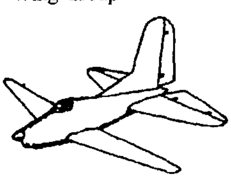
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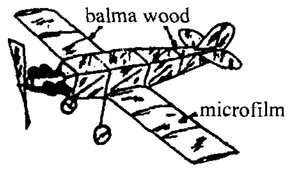
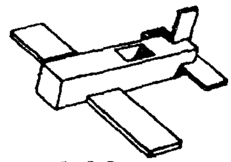
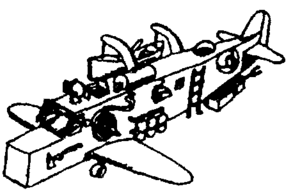


Weight Group


Loft Group


Production Engineering Group


Armament Group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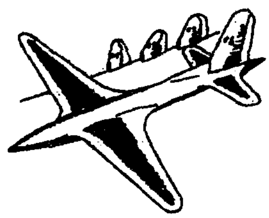
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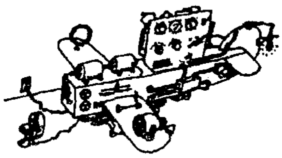
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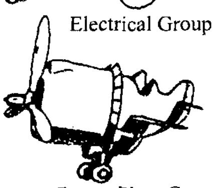
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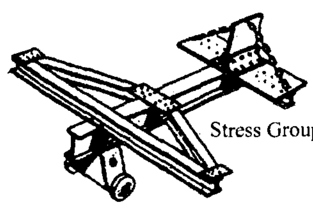
Stress Group

Fig. 1 - 5 Dream airplanes