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USSR Report

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RELIABILITY OF BALLISTIC MISSILE DESIGN

Moscow NADEZHNOST' KONSTRUKTSII BALLISTICHESKIKH RAKET in Russian 1978 signed to press 19 Oct 78 pp 1-32, 255-256

[Annotation, Preface, Introduction, Chapter 1, and Table of Contents of book by A.A. Kuznetsov, Mashinostroyeniye, 3,150 copies, 256 pages]

[Text] This textbook presents the fundamentals of standardization of securement and prediction of reliability of ballistic missile design at the preliminary design stage and shows the relationship between design reliability and the safety factors employed in structural strength calculations. The author describes the methodology of reliability tests. Efficiency is adopted as a criterion of optimal reliability.

This textbook can also be of use to engineers and technicians working in the area of aircraft design.

PREFACE

The course "Efficiency and Reliability of Aircraft and Rockets" presents the principles of efficiency as a criterion for evaluation of the optimum in design of aircraft and rockets (LA) and as a criterion for comparing LA with one another. The course consists of a number of parts. One of them, namely reliability of ballistic missile design, is discussed in this textbook.

The high cost of a rocket and the limited time budgeted for developing and perfecting rockets make it impossible to perform a large number of tests for reliability, each of which should terminate with destruction of the structure being tested. Therefore in order to determine design reliability, designers employ calculations at the preliminary specifications stage and at the technical proposal and preliminary design stage -- a method of predicting reliability.

This textbook examines basic concepts of LA efficiency, theory of reliability and the essentials of failures and presents methods of calculating reliability of equipment components and systems to initial failure, methods of calculating reliability of structural components, and methods of calculating reliability of sections consisting of series, parallel or mixed connected components, dependent on or independent of one another in reliability. The textbook presents methods of calculating reliability of a rocket body, reliability of explosive devices, and reliability of mechanical components. Chapter 8 presents methods of determining reliability of an LA based on the presented material. Chapter 9 examines an interval evaluation of reliability, when fiducial probability is not designated a priori but is determined on the basis of experimental data; the reader is given an idea of optimization of reliability of design components and determination of an optimal safety factor value.

The appendix shows methods of calculating reliability of structural elements and sections based on normal distribution tables.

The author is grateful for comments by reviewers L. I. Volkov, B. G. Shcherbakov and B. A. Dmitriyev. The author is also grateful to A. A. Zolotov, V. A. Komyagin, M. I. Titov, and V. N. Yarotskiy for assistance in preparing the manuscript.

INTRODUCTION

Designing an LA is inseparably linked with optimization of its parameters. LA efficiency is the most general criterion for evaluating the degree to which a solution is optimal.

Designing a rocket involves selection of optimal design arrangements and calculation of the structure for strength. Optimal design arrangements should also be selected taking into account efficiency. At the present time selection of a design arrangement, that is, arrangement of power components in a bay or compartment, is performed by the alternative method, a method of comparing with one another on the basis of some criterion several elaborated designs of the same bay or compartment and selection of the optimal layout. Bay or compartment reliability is not considered thereby. Figuring the efficiency index and its utilization as a criterion in optimizing design parameters can alter one's ideas on optimal design arrangements and compel one to reexamine existing concepts. Comparison and evaluation of rockets are also impossible without calculating efficiency.

Efficiency of an LA as a criterion for evaluating design solutions as well as for comparing LA is of particular value at the initial stages of development of an LA, when drawings are available and only calculations are possible.

Reliability is a component part of efficiency. Without knowledge of reliability, it is important to determine the efficiency of an LA. Consequently, if one does not know how to calculate reliability it is impossible to design and evaluate an LA on a scientific basis. Failure to figure efficiency is totally impermissible when adopting computer designing. Electronic computers make it possible at early stages of LA design (at the preliminary specifications, technical proposals, and preliminary design stage) to select LA parameters based on a scientific foundation, that is, on efficiency. Inability to calculate efficiency deprives the project engineer and designer of this possibility. Of course efficiency is determined not only by reliability alone, but reliability is a complex and less studied component of efficiency.

Reliability is one of the most important operating characteristics of LA. This characteristic cannot be given to a finished product but is incorporated during the design process. Whatever magnitude of reliability can be incorporated during the design process, this magnitude can also be obtained as a result of completion work for the operation stage. In order to ensure a specified magnitude of reliability at the design stage, it is necessary to be able to determine its optimal value and to be convinced of the correctness of securing reliability. In this case calculation of reliability in no way differs from calculations for ballistics, dynamics, aerodynamics, strength, etc at the design stage.

Calculation of reliability is a way to reduce outlays on modification adjustments during testing LA. The reliability value is determined most precisely during testing. But this demands large outlays both of time and money.

A calculated estimate of reliability is less accurate than an experimental evaluation, but it is cheaper and takes less time. The less an item's reliability, the greater the cost of testing and development completion. Calculations of reliability can reduce development costs as a result of optimization of the testing program on the basis of thorough verification of less reliable components.

A calculated reliability estimate makes it possible: 1) to eliminate a given type of test if it is obvious that no great risk would be involved; 2) to reduce demands on tests both in volume and complextiy; 3) to make design changes which increase equipment reliability prior to testing, which will substantially shorten final development time and reduce the cost of testing; 4) to eliminate additional tests on that equipment reliability of which has been determined analytically with sufficient accuracy; 5) to determine all the least reliable parts and assemblies.

Taking reliability requirements into account at the initial stages of design costs hundreds of times less than subsequent correction of errors during testing and operation.

Design reliability is essentially probabilistic strength. Probabilistic strength more adequately reflects natural phenomena than determined strength (structural support capability and external loads constitute random factors). In this regard calculations of design reliability promote refinement of strength calculations performed for determined values. This refinement is especially important in connection with the observed tendency to reduce the safety factor in strength calculations aimed at increasing LA efficiency. Only design reliability calculations make it possible to determine reasonable safety factor values for calculations on determined quantities.

The project engineer and missile designer are responsible for reliability of the entire missile as a whole, but they themselves can ensure specified structural reliability of the rocket and certain parts of the pneumatic-hydraulic system. The remaining parts of the rocket (control and power supply systems, on-board cable network, motors, etc) come as finished items (component items). Engineers of other areas of specialization ensure their reliability. Therefore this book deals primarily with LA structural design reliability, selection and securement of which are primarily the task of engineers and designers. We discuss only in general terms reliability of other LA components.

CHAPTER 1. GENERAL INFORMATION

1.1. Efficiency as the Scientific Basis of Rocket Engineering and Design and Comparisons Between Rockets

1.1.1. General Information on Efficiency

Efficiency is the most important combined characteristic of any flying vehicle (LA). The efficiency of an LA is defined as its capability to correspond to its designation. Efficiency is determined by the quality of an LA and conditions of its employment (Figure 1.1).

The quality of a product is defined as the aggregate of product properties determining its ability to satisfy certain requirements in conformity with its designation (GOST 15467-70. Product quality. Terms).

A property of a product is an objective feature of the product, manifested during its construction, operation or consumption.

In a standard all terms and definitions are given applicable to a product, which may consist of finished items and (or) products. The terms and definitions which apply to the product also are applicable to the component items and products.

All properties of an LA which determine its quality (henceforth designated LA parameters) can for design purposes be represented in the form of a diagram (Figure 1.2).

Design parameters is a term meaning a minimum set of parameters which determine the countenance of an LA at the design stage. This set contains tactical, mass, power and geometric parameters.

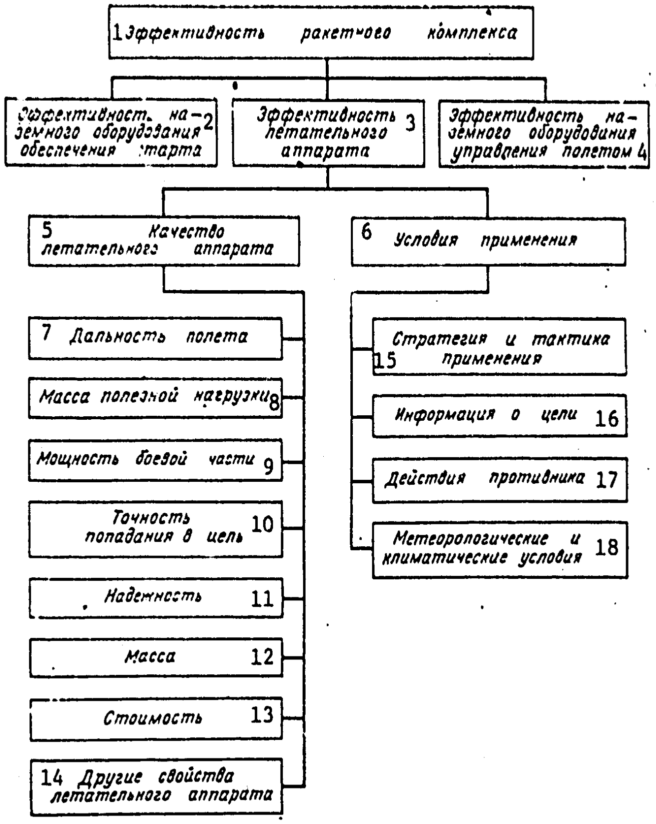

Figure 1.1. Components of Efficiency

Key:

1. Efficiency of missile system
2. Efficiency of ground launch support equipment
3. Efficiency of missile
4. Efficiency of ground flight control equipment
5. Quality of flying vehicle
6. Conditions of employment

Key to Figure 1.1 (continued)

7. Range of flight
8. Payload weight
9. Warhead yield
10. Target accuracy
11. Reliability
12. Mass
13. Cost
14. Other properties of missile
15. Strategy and tactics of employment
16. Information on targets
17. Actions by adversary
18. Weather and climatic conditions

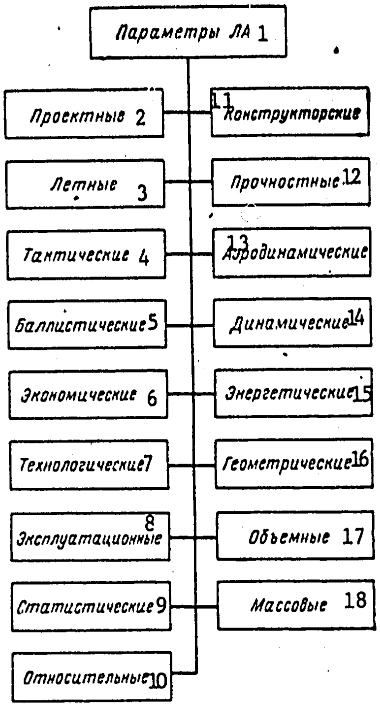

Figure 1.2. Parameters of an LA

Key:

1. Parameters of LA
2. General design
3. Flight
4. Tactical
5. Ballistic
6. Economic

Key to Figure 1.2 (continued)

7. Technological
8. Operation
9. Statistical
10. Relative
11. Specific design
12. Strength
13. Aerodynamic
14. Dynamic
15. Power
16. Geometric
17. Volumetric
18. Mass

Preliminary design specifications include flight parameters (for example, maximum range L_{max}). To these parameters one must also add specifications of the selected fuel; decision on missile body and nose cone shape, etc. We should note that some parameters can be specified during the design process (for example, mass of payload). The aggregate of parameters specified prior to preliminary design and determined in the process of designing should determine the LA in such a manner that one can begin designing the internal bays or compartments.

The conditions of employment (see Figure 1.1) are those external factors which exert substantial influence on LA efficiency: strategy and tactics of missile employment, information on the target, actions by the adversary, weather and climatic conditions of employment, etc. All conditions of employment, other than the first, are characterized by a differing degree of information uncertainty. Utilizing them in designing an LA, one must employ a game formulation in solving various design problems (take into consideration incomplete information under conditions of LA employment).

Efficiency is evaluated by numerical indices (characteristics, criteria) which reflect the designation of a weapons system: target hit probability, mathematical expectation of number of destroyed targets, probability of destroying no less than a specified portion of the target, mathematical expectation of number of destroyed elements, mathematical expectation of destroyed portion of target area, mathematical expectation of magnitude of inflicted damage, etc.

Probability of target kill as an indicator of efficiency is employed when the result of a missile launch at a target can be only target destruction or nondestruction, which applies primarily to small targets ("point" targets), which do not exceed 0.2 radius of the warhead killing zone [22].

Mathematical expectation of number of destroyed targets is applied as an indicator when missiles are fired at several targets.

The remaining efficiency indices are utilized when missiles are fired at large targets and the result of the launch may be complete or partial destruction of target elements, a given change in capability to function if targets are functioning entities, such as military-industrial installations, etc [22].

Often the designer does not fully know the strategy and tactics of employment of the missile he is designing. Sometimes tactics and strategy change or are reelaborated, depending on the efficiency obtained in tests. An efficiency index is not always specified in the preliminary specifications and performance data.

If optimization of LA parameters is performed on efficiency, one must specify the required efficiency indicator. In this case the designer is correct in selecting an efficiency indicator which should be critical to the optimized design parameters of the LA.

The efficiency index is determined by analytical methods and methods of statistical modeling. Analytical methods consist in establishing relationships between LA parameters and efficiency indices under specified conditions of employment. Statistical modeling consists in multiple reproduction of a mathematical model of the conditions of employment and in determining efficiency indices as functions of mean statistical characteristics [22].

Efficiency indices do not permit one to predict the results of individual missile firings. Only with a sufficiently large number of cases of employment of missile systems under similar conditions will the average result be close to that determined with the aid of probability criteria [22].

The term missile system is defined as the LA and all ground equipment connected with prelaunch preparations, monitoring, launch (ground launch support equipment) and control of the missile in flight (ground flight control equipment) [22].

Usually the term efficiency is employed for evaluation of an already designed LA. In this instance test results are processed in such a manner as to obtain the required efficiency indicator, and this value is compared with calculated values, thus determining the degree to which preliminary specifications have been met.

Efficiency is utilized as a scientific foundation for designing an LA when design parameters are obtained from the condition of maximum efficiency under certain disciplining conditions. Efficiency is required by designers primarily in this role.

1.1.2. Efficiency as the Scientific Basis of Missile Design

The task of designing an LA consists in elucidating, under all conditions of employment, properties of the vehicle (optimal design parameters) which would ensure maximum efficiency of the LA. Optimal design parameters can be determined for each specific set of conditions of employment, while for other conditions of employment this LA will be less efficient than it could be. If optimal design parameters are determined for certain average integral conditions of employment, taking into account the frequency of realization of each set of specific conditions, the LA will be less efficient for any concrete conditions of employment, but on the average it will be most efficient. The first statement of the problem is the simplest.

Frequently an LA is designed even without studying the concrete conditions of employment. The conditions of employment are concretized for the design engineer by the preliminary specifications, which state range (maximum), payload mass (properties of the LA), weather conditions, etc (Figure 1.3). They also ensure specific conditions of employment. Just what these conditions of employment are is determined at a higher hierarchic level of LA development.

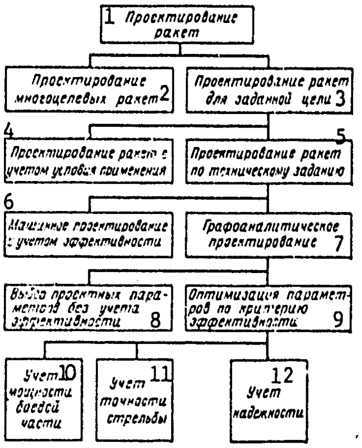

Figure 1.3. Conditions of Missile Design

Key:

1. Missile design
2. Designing of multirole missiles
3. Designing of missiles for a specified goal
4. Designing of missiles taking into account conditions of employment
5. Designing missiles on the basis of preliminary specifications
6. Computer designing, taking efficiency into account
7. Graphic-analytical designing
8. Selection of design parameters without considering efficiency
9. Optimization of parameters based on a criterion of efficiency
10. Taking into account warhead yield
11. Taking into account missile accuracy
12. Taking into account reliability

Computer designing of missiles constitutes automation of the designing process with the aid of electronic computers. With this one can immediately resolve functional relationships among the various parameters and LA efficiency and determine design parameters, maximizing efficiency. For this one must know what efficiency, reliability and other components of efficiency are. One must be able to utilize these concepts and the functional relationships between them and design parameters. One must be able to construct a design problem algorithm, to write and debug a program for calculating optimal design parameters on a computer.

Graphoanalytical missile designing. Designing of LA is presently still performed by the approximate graphoanalytical method, essentially "manually" (see Figure 1.3). Even with this method of design, however, one can utilize efficiency for further optimization of obtained parameters. To achieve this, some parameters must be altered in such a manner as to obtain a maximum LA efficiency value under certain disciplining conditions (for example, with a specified LA cost or with a specified launch weight, etc).

The method proposed in this book is designed for optimization of obtained LA parameters from the standpoint of obtaining a maximum efficiency value. To achieve this we have examined the solution of a number of problems in which it is assumed that LA parameters are already specified at the preliminary design stage. They are subsequently subjected to change for the purpose of maximizing efficiency. These changes are the following iteration during optimization of design parameters.

Formalization of the problem of optimizing design parameters for reliability with approximate graphoanalytical designing can be represented as follows:

$$
\begin{aligned}
&x_i = \text{opt}; \quad i = \overline{1, n}; \\
&3 = \min; \\
&M_{\text{п.г}} = \text{const}; \quad L_{\max} = \text{const}; \\
&x_i \geqslant 0; \ \varphi_j(x_i) = 0; \ j = \overline{1, m}; \\
&x_i = \text{opt}_{II}; \\
&H_{\text{пл}} = \text{const}.
\end{aligned}
$$

In this case optimal design parameters x_i are determined as a result of two iterations. With the first iteration design parameters are determined optimal without considering reliability, on the basis of expenditures 3 under disciplining conditions specified in the form of payload weight $M_{\text{п.г}}$ and maximum range $L_{\max}$. Here $\varphi_j(x_i)=0$ -- functional relationship between design parameters.

In the second iteration we optimize only certain of the obtained design parameters, connected with reliability of separate parts of the LA (frame, propulsion unit). Other LA components (control system, power supply system, etc) have a reliability which is in conformity with the specified payload weight. We should note that optimization on reliability of certain design parameters is performed with previously specified disciplining conditions unchanged ($M_{\text{п.г}}$=const and L_{max}=const). Specified reliability $H_{\text{ЛА}}$=const also is one of the disciplining conditions in this iteration on optimization of design parameters. Changing certain design parameters (thickness of shell sheet, cross sectional area of stringers, that is, structural mass, etc) for achieving the reliability specified in the disciplining conditions, one must also change other design parameters (engine thrust, weight of fuel, etc) determined in the first iteration in order to leave range unchanged with $M_{\text{п.г}}$=const. In this case launching weight of the LA of course changes, but with the already specified three disciplining conditions, outlays (launching weight or cost) as a criterion of optimization will be minimal.

1.1.3. Efficiency as a Scientific Basis of Specific Missile Designing

In designing a specific LA it is also essential to utilize efficiency as a scientific method of problem solving, such as for selecting an optimal safety factor value f, employed in strength calculations. Usually structural calculations for strength are performed for breaking loads N^{P}, which are determined with the formula $N^{P}=N^{Э}f$, where $N^{Э}$ is the operating load; f -- safety factor ($f \geq 1.5$). Optimizing reliability as a component part of efficiency, one can determine the optimal reliability value for structural components, and then the optimal safety factor and mass of the material receiving the external load with a given bay or compartment structural layout. Comparing design arrangements in this manner, one can determine the optimal, efficient design which ensures maximum efficiency of the LA, all other conditions being equal.

Designing missiles is inseparably linked with calculating the structural design for strength.

Methods of making structural calculations on missiles for strength boil down at the present time chiefly to methods of static determinism. Both the load and the load-carrying capability of the structure are assumed to be determined, while loads are considered to be operating for such an extended time that they can be considered static (Figure 1.4).

The following are designated in Figure 1.4: N^{P} -- external breaking load; $N^{Э}$ -- external operating load; f -- safety factor; $\sigma_{\text{пц}}$, $\sigma_{0.2}$, σ_{B} -- stresses of limit proportionality, yield point, and ultimate strength respectively; δ -- sheet thickness; S -- stringer cross sectional area; a_k -- impact strength; $W_{\text{ЛА}}$ -- LA transfer function from external loads to structure stresses; σ_{-1} -- endurance limit.

But loads change fairly rapidly in flight. Structural stresses also change rapidly. Oscillations of a flexible body filled with liquid must also be taken into account in calculating structural strength by the dynamic determinism method.

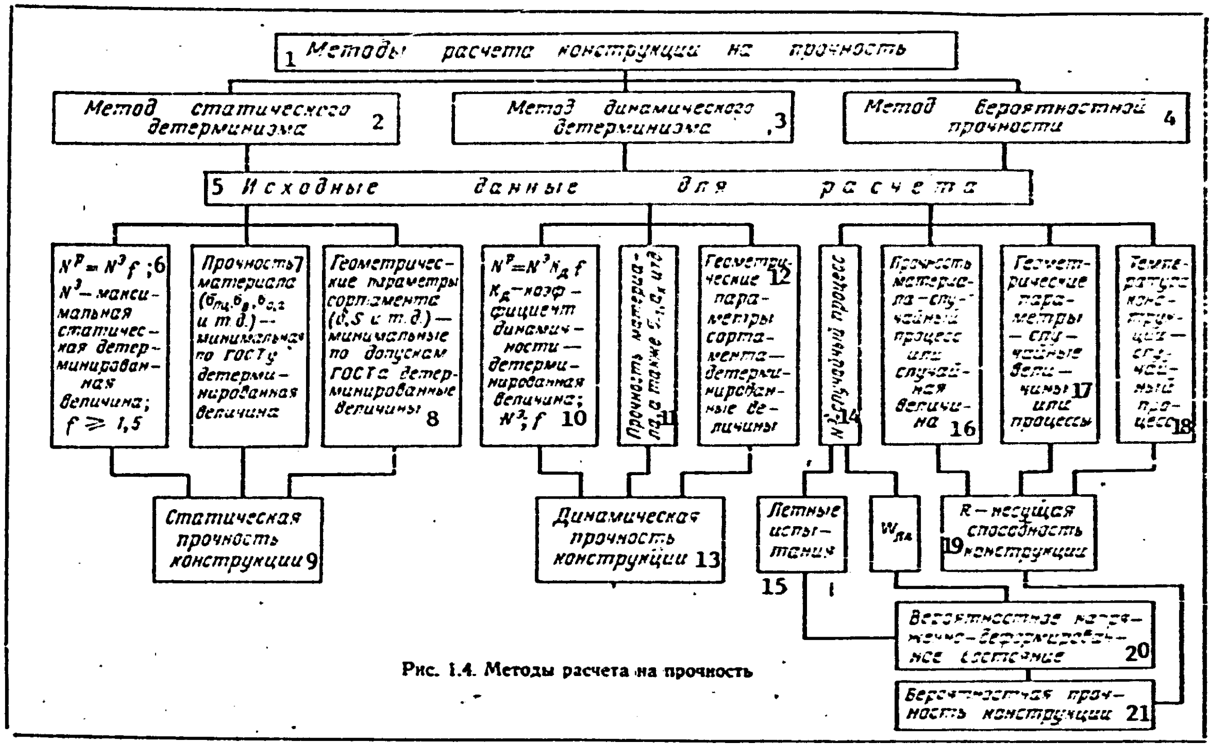

Рис. 1.4. Методы расчета на прочность

Figure 1.4. Methods of Performing Strength Calculations

Key to Figure 1.4 on preceding page:

1. Methods of performing structural strength calculations
2. Method of static determinism
3. Method of dyanmic determinism
4. Method of probability strength
5. Input data for calculation
6. Maximum static determined quantity
7. Strength of material... etc -- minimum determined quantity according to GOST
8. Geometric set parameters... etc -- minimum determined quantities according to GOST allowances
9. Static structural strength
10. -- dynamic - response factor -- determined quantity
11. Strength of material, as well as... etc
12. Geometric parameters of set -- determined quantities
13. Dynamic strength of structure
14. Random process
15. Flight tests
16. Strength of material -- random process or random quantity
17. Geometric parameters -- random quantities or processes
18. Temperature of structure -- random process
19. Load-carrying capacity of structure
20. Probability stressed-deformed state
21. Probability strength of structure

Increase in loads in comparison with the static load of the structure is considered with the aid of the dynamic-response factor ($K_{д}>1$). This factor makes it possible, at least in a static interpretation, to take into account change in external loads connected with actual missile flight.

Since methods of dynamic determinism are still far from perfection, they should be replaced by methods of probability structural strength. It is essential to reflect reality more precisely in design layout. Actual external load and the actual structural load carrying capability are probability quantities: external loads -- random processes, strength of the structural material -- a random quantity or random process (for example, if the temperature of the structure changes significantly in flight), while the geometric parameters of the employed set are random quantities.

Attaching great significance to calculations on determined quantities, one must bear in mind that calculations on random processes and quantities more adequately reflect reality.

Methods of probability strength make it possible to solve two groups of problems: with verification calculations for strength, to determine structural reliability, and with preliminary design strength calculations -- parameters of structural elements for specified reliability.

Reliability strength methods differ advantageously from methods of calculation on the basis of determined quantities in that they make it possible fundamentally to refine strength calculations and to reduce in a substantiated manner the structural mass of an LA, due to consideration of actual structural loads, the actual strength of the material, the actual geometry of the set, due to selection of an optimal reliability value.

During action of dynamic (vibration) external loads the missile body must be viewed as transfer function $W_{ЛА}$ from acting forces to a stress-deformed state of the structure. A small force applied in resonance to a structure's natural frequencies can destroy it, while at the same time a large force applied as an impact may leave the structure intact.

Measurements of stresses in a structure during flight tests make it possible to omit calculation of transfer function $W_{ЛА}$; since, however, the number of such measurements is small, one cannot avoid calculation of $W_{ЛА}$ for an LA being designed.

Dissemination of methods of probability strength is not promoted by the fact that engineers primarily with experience in designing aircraft shifted to designing rockets. Therefore the methods of static determinism employed by them in calculating aircraft structures for strength were carried over to rocket engineering. And not only the methods but also certain prevailing quantitative relationships. For example, the safety factor adopted in aircraft engineering was carried over to rocket engineering.

At that time when the designer was not firmly convinced that the rocket he was designing would get off the ground, a large safety factor was warranted, since this reduced the number of failures in rocket development connected with structural breakdown.

As experience in rocket engineering was acquired and expertise in structural design improved it became obvious that an excessively heavy structure with a large safety factor is not an advantage of an LA, since it decreases its efficiency. It became necessary to reduce the safety factor to 1.35 and even 1.25 in performing structural strength calculations.

A decrease in the safety factor leads to a decrease in LA launch mass with the same payload, but at the same time decreases structural reliability. With a safety factor of $f=1.5$ structural reliability is purely of theoretical interest, since it is large in comparison with the reliability of other LA components (control system, propulsion unit, etc), while with a safety factor of 1.25, structural reliability becomes commensurate with the reliability of the remaining parts of the rocket.

There developed an imperative necessity of calculating structural reliability at the preliminary design and structural design stage, when the safety factor is specified, as well as to specify an optimal safety factor in designing an LA, both for the entire structure and for the individual bays and bay components.

Two methods exist for solving this problem: calculation of structural reliability at the preliminary design stage, and optimization of safety factors with the aid of optimization of structural reliability at the preliminary design stage.

These methods are employed as follows. Prior to strength calculations one determines the optimal safety factor of each structural element or the entire structure at once on the basis of optimal structural reliability. Then one calculates structural strength and determines those set parameters (sheet thickness, structural section cross sectional area, etc), which determine the strength of the structure. Knowing the nominal values of the set parameters, one determines their probability characteristics.

One can calculate the structural reliability of a vehicle at the preliminary design stage. If the obtained reliability coincides in value with optimal, calculation is terminated, and if not, the set parameters are changed and the calculation is repeated.

1.2. Terminology and Basic Concepts of Theory of Reliability

Reliability is the term employed for the property of an object to perform specified functions, while retaining on a time axis the values of specified operation indices within specified limits, corresponding to specified regimes and conditions of utilization, servicing, maintenance and repairs, storage and transport (GOST 13377-75).

In a state standard all terms and definitions apply to technical objects. Object is defined as an object of a specific purpose or designation, examined during the period of design, production, operation, investigation and testing for reliability. Objects include product items, systems and their elements, and in particular structures, installations, devices, machines, apparatus, instruments and their sections, constituent units and individual components.

Operation and storage of an object are accompanied as a rule by gradual deterioration of its quality. Therefore reliability is usually a diminishing function of time. It is true that under certain conditions, when the industrial process of manufacturing an item has not yet been perfected or completely refined, reliability may also prove to be an increasing function of time, such as for reinforced concrete items at the concrete hardening stage; for objects subjected to repairs or reinforcement in the process of operation; for objects in the process of experimental development (for example, flight tests of LA).

Reliability is a combined property which, depending on the purpose of an object and the conditions of its operation, may include failure-free operation, durability, ease of maintenance, and shelf life separately or a certain combination of these properties both for the object and for its component parts.

These properties may possess differing relative significance for concrete objects and the conditions of their operation. For example, for some unrepairable objects reliability includes primarily their failure-free operation. For objects which can be repaired, one of the most important properties comprising reliability may be repairability.

Operation indices in determining reliability are defined as indicators of productivity, speed, consumption of electric power, fuel, etc.

Reliability is quantitatively characterized by reliability indices. A eliability indicator or index is a quantitative characteristic of one or everal properties comprising the reliability of an object.

A reliability indicator quantitatively characterizes to what degree specific properties determining reliability are characteristic of a concrete object. A reliability indicator may possess dimensionality (for example, hours of operation to failure), or it may not (for example, probability of failure-free operation).

In examining reliability indices one should distinguish the following: designation of indicator (for example, mean time to failure); a numerical value which can vary in relation to the conditions of operation of the object, the stage of its development or existence; a formulation of the indicator containing specifications on the methods of experimental or calculated determination of numerical value. Many reliability indices constitute parameters of distribution of random quantities (for example, mean time to failure -- parameter of distribution of a random quantity called "time to failure").

We distinguish individual and combined reliability indices.

An individual reliability indicator is a reliability indicator applying to one of the properties comprising an object's reliability. For example: time to failure (failure-free operation); gamma-percentage service life (longevity); mean restoration time (repairability); mean shelf life (shelf life).

A combined reliability indicator is a reliability indicator which applies to several properties comprising an object's reliability. For example, for an object being restored to service one employs a combined indicator -- readiness indicator, determined by the formula $K_{\Gamma}=1/(1+t_B t_0)$, where t_B is mean time of restoration to service, characterizing repairability; t_0 -- time to failure, characterizing failure-free operation capability.

In addition to the readiness factor, the following combined reliability indices can be employed: coefficient of technical utilization; coefficient of operational readiness; mean total servicing labor requirements; specific overall technical servicing labor requirements; mean total cost of servicing; specific total cost of servicing; mean total cost of repairs; specific total cost of repairs.

Failure-free operation is the property of an object continuously to maintain its operating efficiency for a specified period of time or a certain number of hours of operation.

An object possesses the property of failure-free operation both in the period of its utilization and during storage and transport.

Frequently the reliability of an item is equated with its time between failures. Time to failure and reliability are equivalent for one-time-use items which are not repaired or for individual periods of item operation (for example, for a launched one-time-use unrepairable LA). For that same LA in storage, time to failure is not equivalent to reliability but is merely one of the properties of reliability, alongside longevity, repairability, and shelf life.

Probability of failure-free operation, mean time to failure, intensity of failures, parameter of flow of failures, and time to failure are indices of trouble-free operation.

Probability of failure-free operation is the probability that an object will not fail within a specified operating time.

Mean time to failure is the mathematical expectation of an object's operating time to the first failure.

Intensity of failures is a conditional density of probability of occurrence of failure of an unrepaired object, determined for a specified moment in time under the condition that failure has not occurred for this moment in time.

Parameter of flow of failures is the density of probability of failure of a restorable object determined for a specified moment in time.

Operation to failure is the ratio of hours logged by a repairable object and the mathematical expectation of the number of failures in the course of this period of operating time.

Efficient state (efficiency) is the state of an object whereby it is capable of performing specified functions, retaining the values of specified parameters within the limits established by technical standards documentation.

The alternative of efficient state is nonefficient state (nonefficiency) -- the state of an object whereby the value of at least one specified parameter characterizing capability to perform specified functions does not correspond to the demands specified by technical standards documentation.

One should distinguish two cases of nonefficient state: a correctable state of nonefficiency and an uncorrectable state of nonefficiency. In the first instance an object's efficiency can be restored by performance of repair operations. In the second instance restoration of efficiency is technically impossible or economically inadvisable.

In addition to the terms efficiency and nonefficiency, GOST employs the terms ispravnost' [soundness, good working order] and neispravnost' [unsoundness, inoperable condition].

Operable state (good working order) is the state of an object whereby it meets all demands established by technical standards documentation. An inoperable state (inoperable condition) is the state of an object whereby it does not correspond to at least one of the demands specified by technical standards documentation.

The term "ispravnost'" is broader than the term "rabotosposobnost'" [efficiency]. An efficient object, in contrast to an operable object, meets only those demands of standards documentation which ensure its normal functioning or performance of specified functions. It may thereby not satisfy, for example, demands applying only to outward appearance. An efficient object may be inoperable, but its faults are not so substantial as to disrupt normal functioning of the object.

Longevity is the property of an object to maintain efficiency until the onset of an extreme state with the established system of servicing and maintenance.

Following are indicators of longevity: gamma-percentage service life; mean service life; designated service life; mean service life between medium (major) overhauls; mean service life to retirement; mean service life to medium (major) overhaul; gamma-percentage actual service life; mean actual service life between medium (major) overhauls; mean actual service life to medium (major) overhaul; mean actual service life to retirement.

Extreme state is the state of an object whereby its further operation should be terminated due to an uncorrectable violation of safety requirements or uncorrectable departure of given parameters beyond established limits, or an uncorrectable decrease in operational efficiency below an allowable level, or the necessity of performing medium or major repairs.

The attributes (criteria) of an extreme state are established by technical standards documentation on the given object.

An unrepairable object reaches an extreme state when failure occurs or on attainment of a prior-specified maximum allowable actual service life or total hours of operation. Maximum allowable values of service life and hours of operation are established proceeding from considerations of operational safety in connection with irreversible departure of principal parameters beyond the specified allowance and irreversible decline of the operational efficiency of an object below the allowable level, or in connection with an increase in frequency of breakdowns, expected of objects of the given type following a specified period of operation. Values of maximum actual service life or maximum total hours of operation of unrepairable objects can be determined by calculation, by experimental-statistical or combined utilization of these methods.

For repairable objects transition into an extreme state is determined by the onset of that moment when further operation is impossible or inadvisable for one or several of the following reasons: it becomes impossible to maintain safety, failure-free operation or operational efficiency of an object at an allowable level; as a result of physical wear and (or) age an object has reached a state at which repair requires excessive expenditures or fails to provide the requisite degree of restoration of efficiency and operating order.

Repairability is a property of an object consisting in capability for prevention and discovery of the reasons for malfunctions, damage, and their correction by performance of repairs and servicing operations.

Repairability indicators include probability of restoration to service within a specified time (probability of prompt restoration to service), and mean time of restoration to service. Objects can be repairable and unrepairable, capable or not capable of being restored to service.

A repairable object is an object the good working order and efficiency of which can be restored in case of breakdown or damage. An unrepairable object is an object the good working order and efficiency of which in case of breakdown or damage cannot be restored.

A restorable object is an object the efficiency of which in case of breakdown can be restored in the given situation. An unrestorable object is an object the efficiency of which in case of breakdown cannot be restored in the given situation.

Of considerable importance in formulating and solving problems of reliability, particularly in selecting the reliability indices of an object, is the decision which must be made if the object breaks down.

If in the given situation restoration of the efficiency of a given object in case of breakdown is acknowledged to be inexpedient or impossible for any reasons, in the given situation this object is unrestorable. Thus one and the same object, depending on the features or stages of operation, can be considered restorable or unrestorable. However, most frequently the property of restorability of objects is examined unambiguously applicable to the entire period of operation. For example, a light bulb is practically always an unrestorable object, while a metal-cutting machine tool is a restorable item.

The terms "unrestorable item" and "restorable item" do not replace the terms "repairable item" and "unrepairable item," since the latter characterize properties of objects (their adaptability to performance of repairs and servicing), while the former apply to conditions of restoration of efficiency of objects in a concrete situation in the process of operation. In many instances these terms coincide. For example, an unrepairable object is usually at the same time an unrestorable item, while a repairable object can be viewed as an unrestorable or as a restorable item, depending on the conditions of operation.

Shelf life is a property of an object to maintain on a continuous basis a state of efficiency and good working order during and after storage and (or) transport.

Following are indicators of shelf life: gamma-percentage period of shelf life (that shelf life period which will be achieved by an item with a specified probability gamma (γ) percent); mean shelf life (mathematical expectation of shelf life).

The shelf life of an item characterizes its ability to withstand the adverse effect of conditions of storage and transport of the item on its good working order and longevity. Since work (action, employment, direct utilization of an object for its specified purpose) is naturally the principal thing in operation of an item, of particular importance is the influence of storage and transport on the subsequent behavior of the item under working conditions.

Extended storage and transport sometimes does not have an appreciable effect on the behavior of an item while it is under these conditions, but during subsequent operation the reliability indices of such items may prove to be significantly below analogous indices of objects of the same kind but which are no in storage and have not been transported.

For example, following extended storage of chemical sources of electrical current (flashlight batteries, etc) their capacity and consequently hours of operation to failure decrease substantially, although only a relatively small number of items fail during storage. The shelf life of such items is usually characterized by a period of being in storage under specified conditions, during which a decrease in mean hours of operation to failure caused by storage is within allowable limits.

Thus shelf life cannot be equated with the time failure occurs during storage. The latter characterizes the behavior of an object (its failure-free state) only during storage and does not characterize the influence of storage on an object's failure-free operation during subsequent work.

Shelf life determines the calendar duration of storage and transport of an item under specified conditions, taking into account performance of the requisite servicing, specified in the technical standards documentation on the item.

One should distinguish shelf life on an item prior to going into operation and an item's shelf life during operation (during operation interruptions). In the latter case shelf life is a component of actual service life.

The importance of reliability as a characteristic of quality is not disputed, but its practical incorporation encounters a number of difficulties. The difficulty of incorporating reliability lies in the difficulty of its quantitative measurement. We should note that overcoming of this difficulty accompanied the adoption of all other, previously-adopted characteristics of quality. We know that for a long time we were unable quantitatively to measure precision of fabrication, and therefore drawings carried the inscription: "Fabricate Precisely," " Fabricate as Precisely as Possible." Later we learned to measure accuracy quantitatively.

The difficulty of measuring reliability is caused by a number of circumstances. Reliability is a technical characteristic, for quantitative evaluation of which it is necessary each time to determine the set of most suitable indices of reliability, to establish attributes, to determine monitored parameters, operating conditions, etc.

Measurement of reliability cannot be performed by conventional methods of measuring technical parameters. One cannot, for example, propose an instrument the dial of which would read the value of measured reliability; it is necessary to perform a large number of experiments in order to calculate reliability on the basis of experiment results. The greater the number of experiments, the more accurate calculation of reliability will be. Since the number of experiments is always finite, accuracy of calculation of reliability, even on the basis of experimental data, is always relative. This transforms measurement of reliability into an unwieldy and costly process, which can be performed only when a product has already been manufactured, which diminishes the value of the reliability figure obtained in this manner.

Prediction of reliability when an item is still on the drawing board requires input statistical data. At the present time, however, such predictive calculations are not yet sufficiently trusted.

Operation of automatic devices advances reliability to a principal position among an item's quality characteristics. This inspires the hope that difficulties connected with increase in the value of reliability will be overcome.

1.3. The Concept of Failures

The principal term in reliability theory is the term failure. Failure is an event consisting in disruption of an item's capacity to work. The attributes (criteria) of failures are established by technical standards documentation on the given item. In addition to the term "otkaz" [failure, breakdown], GOST 13377-75 introduces the term "povrezhdeniye" [damage]. Damage is an event consisting in disruption of the good working order of an item or its component parts as a consequence of the influence of external actions, exceeding levels specified in technical standards documentation on the item.

Damage can be substantial, constituting a cause for impairment of efficiency, and insignificant, whereby the items ability to operate is retained. Some insignificant damage may in time transition to the category of significant, and thus lead to failure of the item in question. Some failures do not involve damage. For example, incorrect placement of controls by an operator may lead to failure of certain devices to actuate at the proper moment (operational failure). Failures caused by violation of specified operating rules and standards are not considered in assessing an item's reliability.

Applicable to failure and damage, one examines criterion, cause, attributes (manifestations), character and consequences.

The work-capable state of an item is determined by a list of specified parameters and allowable limits to their change -- tolerances. Disruption of a work-capable state is called departure of at least one given parameter beyond the specified tolerance or allowance. Attributes which make it possible to establish the fact of disruption of a work-capable state are criteria for failure. Failure criteria are indicated in the technical standards documentation for an item.

The causes of failures may be defects occurring in the design, manufacture and repairs, violation of operating rules and regulations, various damage, as well as natural processes of wear and aging.

Indications of failure (damage) include direct or indirect effects on the sensory organs of the observer of phenomena characteristic of an inoperable state of the object or processes connected with it. For example, change in monitoring device readings, occurrence of specific noise (knocking) during engine operation, etc.

Character of failure (damage) includes concrete changes in an item connected with the occurrence of failure (damage). For example, broken wire, part deformation, etc.

Consequences of failure (damage) include phenomena, processes and events occurring after failure (damage) and in a direct causal relationship with it. For example, engine shutdown, etc. Some consequences of failure (damage) may also serve as its indications.

GOST 13377-75 lists the failure designations contained in Figure 1.5. The diagram also states the names of other failures not contained in the GOST. The designation of failures according to GOST is indicated in the diagram by the word GOST. We shall define the failures contained in the diagram.

Sudden failure is failure characterized by an abrupt change in one or several specified parameters of the item in question.

Gradual failure is characterized by a gradual change in one or several specified parameters of an item; such a parameter change practically never precedes a sudden failure.

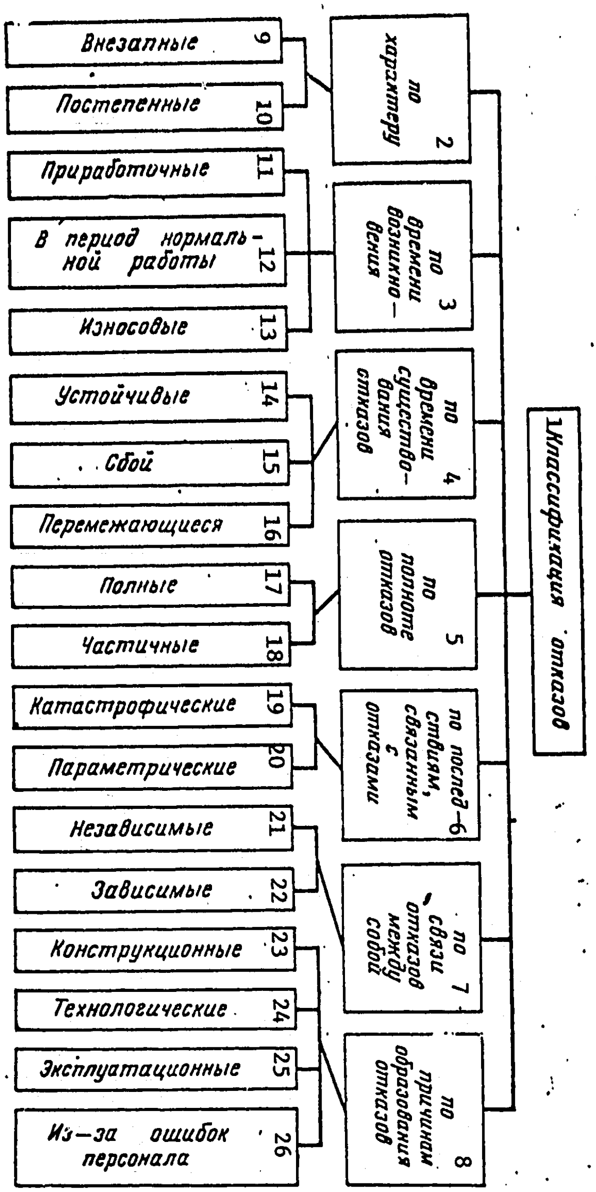

Figure 1.5. Types of Failures

Key to Figure 1.5 on preceding page:

1. Classification of failures
2. By character
3. By time of occurrence
4. By time of existence of failures
5. By completeness of failures
6. By consequences connected with failures
7. By the interrelationship of failures
8. By causes of failures
9. Sudden
10. Gradual
11. During break-in
12. During normal operation
13. Wear
14. Persistent
15. Misfiring
16. Intermittent
17. Total
18. Partial
19. Catastrophic
20. Parametric
21. Independent
22. Dependent
23. Design
24. Manufacture
25. Operation
26. Due to personnel errors

Gradual failure is an inevitable, logical result of wear and aging on any product, and therefore sooner or later it must happen, that is, its probability is equal to 1. Consequently gradual failure cannot be viewed as a random event. However, while gradual failure is not a random event, the time of onset of such a failure and the service life of an item up to gradual failure are random quantities, and therefore gradual failures are probability categories.

If one approaches an examination of failures proceeding from the time of their occurrence, it is frequently convenient to divide failures into three kinds: break-in, during the period of normal operation, and wear. This division corresponds to three clearly-marked operation periods of each item.

Break-in failures, typical of the first period of operation, are due to the presence of defective components in the product, the strength of which is considerably below the required level. If many quite diversified components are utilized in a product, even with very thorough quality control it is not always possible to eliminate the possibility that components containing various hidden production defects will reach the assembly bin. Mistakes made during assembly and mounting can also be the cause of break-in failures. Installation or mounting errors as a rule are discovered during the initial period of operation. The reliability of an item during the break-in period is entirely determined by the probability of failure of defective components. When each defective component is removed and replaced, the reliability of the product increases. But as long as even one defective component remains, the reliability of the full product cannot be greater than the reliability of this last defective component.

The break-in period is followed by the period of normal operation, during which failures are a consequence of sudden intolerable concentrations of loads on a component or a sudden change in the quality of the component itself.

For the structure of an LA such failures are a consequence not only of the vehicle entering during flight conditions not specified by determined calculations but also a consequence of natural variants of strength properties of the structural material.

All articles are subjected in time to wear and aging, which gradually leads to failure. The time of onset of such failure (service life of an item to wear failure) is a random quantity. Wear is defined as mechanical, electrical, chemical wear, etc. Mechanical wear is most obvious and as a rule is connected with change in the dimensions of items or the state of their surface, accumulation of residual deformations, etc. Electrical wear is connected with the passage of electrical current and electrochemical processes which occur thereby in the item.

Independent failure is failure of a component of an item which is not caused by damage or failures of other components of the item. Dependent failure is failure of a component caused by damage or failure of another component.

Misfire is a self-correcting failure which leads to brief disruption of efficiency. An intermittent failure is a multiply-occurring misfire-type failure of one and the same character. Persistent failure is a failure correction of which requires external intervention. This may be replacement or repair of the failed component, switching in of a backup component, or concentration in a backup component of all functions which were previously also performed by the failed component.

Design failure is a failure occurring as a result of violation of specified design rules and (or) standards. When necessary, design failures are divided into failures occurring due to violation of rules and (or) standards of designing the article, and failures occurring due to violation of rules and (or) standards in designing purchased components (parts). Production failure is a failure occurring as a result of violation of the specified process of manufacture or repair of an article. Production failures can also be subdivided into failures occurring as a consequence of violation in the process of manufacture and failures occurring as a consequence of the process of manufacture of purchased components (parts). Operational failure is a failure occurring as a result of violation of specified rules and (or) conditions of operation of the article.

Division of failures into design, production and operational is usually done for the purpose of determining the stage of existence of an article at which appropriate measures should be taken in order to correct the cause of the failure. In practice there occur failures the causes of which cannot be assigned to any one of these stages. For example, failure of a component element with observance of all the requirements of design, manufacture and operation. Such failures are figured separately in order to draw the attention of the suppliers of these components and to take measures to increase the reliability of component parts.

In many cases the following terms are employed in classifying failures: systematic failure, total failure, partial failure.

Systematic failure is defined as a multiply-repeating failure due to defects in the product design, violation of the process of its manufacture, poor quality of utilized materials, etc. Observed with total failure is complete loss of capability to operate. Partial failure is a failure after the occurrence of which an article can be utilized for its designated purpose but with less efficiency. Frequently the control system on an LA is not totally redundant, with sufficient redundancy so that if any component malfunctions the control system continues to operate, but its parameters differ from nominal, as a consequence of which there occurs, for example, only an increase in dispersion when striking the target, but not termination of the LA flight.

In examining failures, one should distinguish between failure of a component and failure of the article as a whole. The following instances are possible: failure of a component simultaneously signifies failure of the article as a whole; failure of a component does not signify failure of the article.

Parametric failure means a failure whereby any parameter goes beyond the established tolerance.

1.4. Methods of Calculating Reliability and Its Types

Various methods of calculating reliability are employed for a quantitative evaluation of reliability (Figure 1.6): mathematical (formal) methods and methods allowing for physical causes of failure.

When utilizing mathematical methods of calculating reliability one assumes that change in reliability is governed by certain statistical patterns which are determined only experimentally. One cannot elucidate thereby the causes of failures and determine possibilities of correcting them, which is a shortcoming of these methods. There exist two directions of mathematical methods: one examines reliability as a temporal category (reliability as a quality expanded in time), and the other as probability of a random event.

Mathematical methods of the first category are applied in calculating reliability of radio electronic equipment, electromechanical equipment, component parts of machinery and mechanisms, the operating capability of which is limited by the degree of wear on the components.

Mathematical methods of calculating reliability are discussed in the writings of such prominent scientists as A. I. Berg, N. G. Bruyevich, B. V. Gnedenko, V. I. Siforov, B. S. Sotskov, etc.

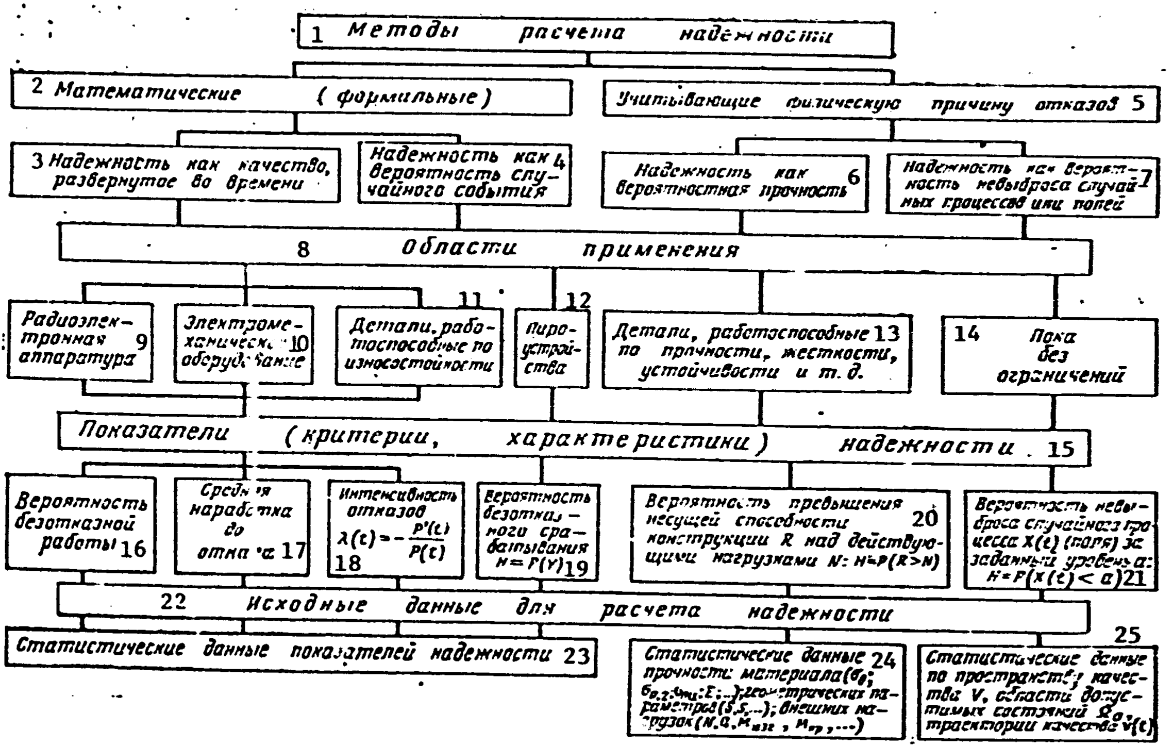

Figure 1.6. Methods of Calculating Reliability

Key to Figure 1.6. on preceding page:

1. Methods of calculating reliability
2. Mathematical (formal)
3. Reliability as a quality expanded in time
4. Reliability as probability of a random event
5. Allowing for a physical cause of failure
6. Reliability as probability strength
7. Reliability as probability of nonovershoot of random processes or fields
8. Areas of application
9. Radioelectronic equipment
10. Electromechanical equipment
11. Parts capable of operating by durability
12. Explosive devices
13. Parts capable of operating by strength, rigidity, stability, etc
14. Presently without limits
15. Indices (criteria, characteristics) of reliability
16. Probability of failure-free operations
17. Mean time to failure
18. Rate of failure
19. Probability of failure-free actuation
20. Probability of exceeding structural load capacity above operating loads
21. Probability of nonovershoot of random process... beyond specified level
22. Input data for calculating reliability
23. Statistical data of reliability indices
24. Statistical data of strength of material... geometric parameters... external loads...
25. Statistical data on space of quality V, region of allowable states..., trajectory of quality v (t)

In these studies results were obtained which agree well with experimental results. This trend in theory of reliability, which began to develop rapidly in 1950-1951 in connection with the rapid development of rocket engineering, was the leading trend for a long period of time and was accepted as a standard in many areas of technology where they were beginning to figure reliability.

Another trend in mathematical methods of calculating reliability applies to explosive devices and devices actuating instantly and one time. In this case it is essentially impossible to employ temporal reliability characteristics, and reliability is determined by experimentation as the probability of realization of a random event Y.

There also exist two types of methods which consider the physical causes of failures: one of them examines reliability as probability strength, operating with random quantities, and the other -- as probability of nonovershoot of a random process (field) beyond a specified level.

The method of calculating reliability as probability structural strength was elaborated in 1926-1929 by N. F. Khotsialov and M. Mayer, but it did not develop strongly. The first studies in this area did not win wide approval, were not applied in practice and did not go beyond the boundaries of debate.

Subsequent studies by N. S. Streletskiy, A. R. Rzhanitsin, Ya. B. Shor and other scientists began gradually developing practical applications for this method.

The indicator of reliability in this method of calculation is probability of structural load-bearing capacity exceeding actual loads. Both the load-carrying capacity of the structure and actual loads are viewed as random quantities.

Statistical data are also input data for calculation in this case, but not reliability characteristics proper but rather strength characteristics of the structural material ($\sigma_{\text{В}}$, $\sigma_{0.2}$, $\sigma_{\text{пц}}$, E), geometric parameters of the set (δ, S), external loads acting on the structure (tensile stress N, shearing force Q, bending moment $M_{\text{изг}}$, and torque M_{kp}).

These methods consider the reasons leading to failure of structural components, since they examine external loads acting on the structure, and the load-bearing capacity of the structure, but they do not consider the time factor, which narrows the limits of application of this method in calculating reliability.

The most general method of reliability theory, based on theory of sets, was developed by V. V. Bolotin. According to this method, a certain system quality space V is introduced, a region of allowable system states Ω_0 and trajectory v(t) of change in system quality on a time axis. Departure of trajectory v(t) from the region of admissible states is viewed as system failure. The first study of this method was published by V. V. Bolotin in 1959. In studies in 1969 the theory was presented systematically, with various examples of its application [4, 5].

Characteristics of structural reliability according to this method include probability of nonovershoot of a random field or process beyond a specified level. Also essential here for calculating reliability are input statistical data pertaining to the parameters of random fields or random processes. It is much more difficult to obtain such data from experiments than input data for methods of calculating reliability as probability strength.

Obviously when calculating reliability of different parts of an LA (control system, explosive devices, body structure, etc) one should utilize that method which is most acceptable for calculations.

Development of reliability as a science evoked the appearance of a large number of terms in this area, sometimes interpreted differently by each author. In order to eliminate ambiguity in the interpretation of certain terms in the area of types of reliability, we shall introduce some explanations, applying primarily to LA design reliability (Figure 1.7).

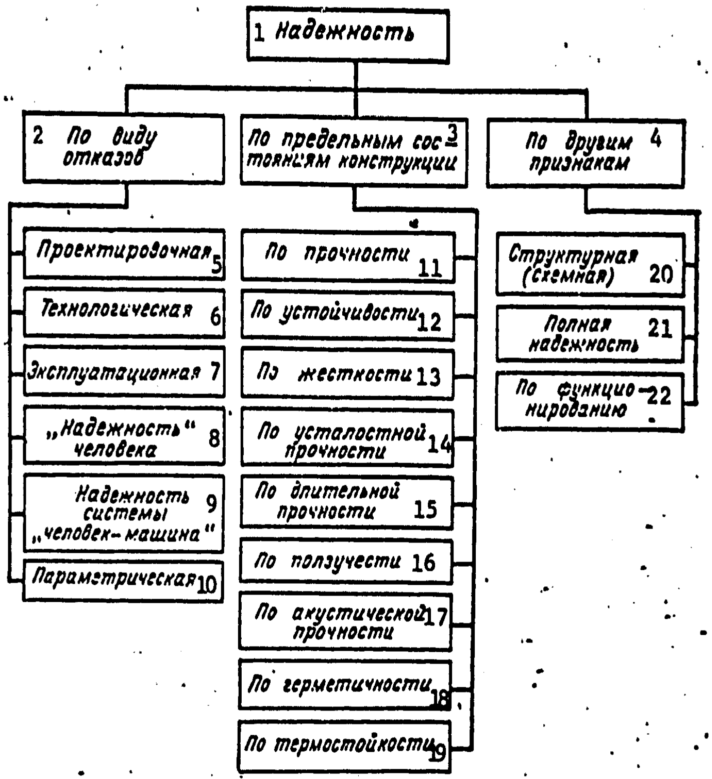

Figure 1.7. Types of Reliability

Key:
1. Reliability
2. By type of failure
3. By extreme structural states
4. By other indicators
5. Design
6. Manufacture
7. Operation
8. "Reliability" of man
9. Reliability of "man-machine" system
10. Parametric
11. Strength
12. Stability
13. Rigidity
14. Fatigue strength
15. Prolonged strength
16. Creep
17. Acoustic strength
18. Airtightness
19. Thermal stability
20. Structural (circuitry)
21. Total reliability
22. Functioning

Often reliability is designated by types of failures: design reliability, manufacturing and operation reliability, human "reliability," reliability of the "man-machine" system, parametric reliability, etc.

Sometimes reliability is designated according to those extreme states in which a structure may find itself: reliability according to strength, stability, rigidity, fatigue strength, long-time strength, creep, acoustic strength, airtightness, etc.

Sometimes the following terms are also encountered: structural reliability, total reliability, etc.

Design reliability is reliability which is determined by calculation at the LA design stage. In calculating design reliability one takes into consideration the physical picture of operation of the structure, the process of its manufacture, operation, etc, but only in the form of models, which substitute for actual phenomena in calculations. Actual phenomena are always more complex than models.

Some statistical factors at the design stage must be determined on the basis of materials of past similar LA. This inevitably leads to errors in calculations.

We must note that design reliability is calculated when an LA is represented primarily in drawings. In this instance only on the basis of theory which takes into account the physical causes of failures can one determine methods of calculating reliability. The opinion that without statistical experiments reliability cannot be determined is also correct in this case. At the design stage as well one utilizes statistical data for calculating reliability, which have been obtained totally separate from connection with the designed vehicle. One utilizes statistical data of the strength properties of the structural material employed in the designed vehicle, the geometric parameters of the mix (sheets, sections, tubing, etc), which is not dependent on the concrete LA, and which are manufactured at metalworking plants in conformity with current GOSTs. They should merely be selected and utilized in calculations.

External loads on a structure which are essential for calculating reliability are determined from flight experiments on previous rockets, and from theoretical calculations on the vehicle being designed.

Design reliability is calculated by the designer with that degree of accuracy which is in conformity with all design calculations. Verifying calculations of structural reliability can be performed by a reliability team; verifying calculation for structural strength is performed by a strength team, and design calculation for strength is performed by the bay or unit designer.

Manufacturing reliability differs from design reliability in that here one considers the disparity between the actual and planned manufacturing process, difference between actual probability characteristics of the mix and calculated characteristics and actual dimensions of components from those specified in the drawings, etc.

In calculating design reliability these distinctions are taken into account both theoretically and by means of a statistical factor calculated from past products. If everything planned during the design process is carried out during manufacture, manufacturing reliability coincides with design reliability.

Operational reliability differs both from design and manufacturing, since the conditions of operation may not coincide with those which were assumed in making computations (the most difficult conditions are assumed as a rule); the design may be subjected to modification, periods of storage may not correspond to calculated periods, etc. Operational conditions are determined from data on previous LA in calculating the design reliability of a vehicle. But more accurate data can be obtained only during operation (at least partial) of the vechicle being designed.

"Reliability" of man can be defined as the probability of man's error-free performance of functions in a "man-machine" system. As practical experience has shown, many equipment failures are connected with human errors during preparation for operation and during operation proper.

In calculating reliability of a "man-machine" system it is essential to consider not only design reliability but also human errors in preparation for operation and operation of an LA, leading to structural failure. The number of errors made by a human operator depends on the complexity of the design. Human errors are also affected by conditions of operation, qualifications, a person's training, etc.

In calculating design reliability, human errors are figured in by certain statistical factors on the basis of previous equipment, but only operation (at least partial) of series-built LA of the target type can give the most accurate figure.

Parametric reliability is reliability connected with fulfillment of conditions pertaining to certain parameters (acceleration, velocity, angle, target accuracy, exceeding stresses equal to limit of proportionality, etc).

Probability of breaking of the airtightness of rocket bays led to the term "airtightness reliability."

Structural (or circuit) reliability is reliability of a system consisting of elements connected in series, in parallel or combined, and dependent on or independent of one another.

Sometimes one employs the term total reliability, although there is no term "partial reliability." Total reliability is defined as reliability of a structure which may be in various extreme states. In this instance total design reliability is a function of design reliability in each extreme state.

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CAPABILITIES OF SOVIET ARMED FORCES DISCUSSED

Hamburg STERN in German No 24, 7 Jun 79 pp 20-30, 272-273

[Report by Wolf Perdelwitz: "SALT II: How Dangerous Are the Russians?"]

[Text] As dawn was breaking, one could hear the blast of the first fire among the hills. In the morning mist, it was hardly possible to recognize the attackers. The defenders had dug in on the top of the city--a miserable collection of soldiers, full of lice, wrapped in rags and shoes torn. Ammunition was scarce, armament outdated. As the sun went down, they were holding fast. The next day, they chased the enemy away.

The skirmish made history. It was (on 23 February 1918 before the gates of the capital, Petrograd, today's Leningrad) the first engagement of the "Red Workers and Peasants Army" of Soviet Russia, precursor of the "Union of Socialist Soviet Republics, USSR." It was also its first victory.

Not quite 20 years later, there was a blast of fire again. Again at dawn. Joseph Stalin, Soviet dictator, was consolidating his power. The old army command was in the way. Tens of thousands of his fighting comrades from the days of the revolution fell victim to the "purges." Half of all the officers died within 12 months. In the middle of peace, it was the greatest defeat of the Red Army.

On 22 June 1941, there was the blast of fire again, and again at dawn. Hitler's attack against the Soviet Union had begun. It brought the Red Army to the brink of annihilation. But 4 years later, at the end of the "Great Fatherland War" proclaimed by Stalin, the tanks with a red star on their turrets stood on the eastern bank of the Elbe, in the center of Germany. It was its greatest victory so far.

They are still standing east of the Elbe and in the center of Germany--advance guard of the "Russian steamroller" with its more than 3 million men under arms, with 52,000 tanks and 40,000 pieces of artillery, with 10,000 fighter planes and 2,570 atomic missiles.

Between the Bavarian Forest and the Pacific, between the Arctic Sea and the 8,000-kilometer border with China, the Red Army dominates Europe and

Asia. On the oceans, more ships are sailing under its flag than constituted the onetime world-dominating British navy in its prime--243 capital ships and 235 submarines, almost half of them atom powered.

The fearful in Western Europe and the United States see the red flag, with its golden hammer-and-sickle emblem, fly on the Rhine as early as tomorrow. According to widespread opinion, only the U.S. atom shield prevents the Soviets and their allies in the Warsaw Pact* from overrunning Western Europe and NATO** within 48 hours.

And in fact the Red Army, the core of the armed forces of the Warsaw Pact, appears to be overwhelmingly powerful. Systematically strengthened and modernized since World War II, it is today the strongest ground force ever maintained by a single country on earth.

Increasingly, its war concept has been switched decidedly to attack; if a war does turn out to be inevitable, let it at least not be fought any longer in one's own country. But nothing in Soviet military doctrine indicates that the Red Army would ever without provocation begin of its own an attack on Western Europe. Only once in its history has the Red Army attacked a country--Finland, the former Russian grand duchy turned independent in 1917, in the year 1939.

It has been spared any traumatic experience, such as the Vietnam war was for the U.S. Army. "Heroic deeds for the homeland," according to Soviet Minister of Defense Dimitriy Ustinov, "determine the attitude of the Soviet soldiers in battle."

Heroes are held in high regard--even when they are already dead. In some crack divisions, a flower-adorned bed is left vacant in the barracks quarters--the bunk of a particularly death-defying fighter who fell in World War II. There is not a single general's speech which fails to extol heroism. Nevertheless, George F. Kennan, who for many years was U.S. ambassador in Moscow, says mockingly: "The Russian soldiers, after all, are not all 2 1/2 meters tall."

They certainly are not. And the army is doing a lot to make them even smaller. Defectors and letters smuggled to the West report unanimously that the 2 years'--in the navy even 3 years'--compulsory military service can be hell. Veteran soldiers and noncommissioned officers mercilessly

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*Members of the Warsaw Pact, established in 1955, are: The Soviet Union, Poland, the GDR, Czechoslovakia, Hungary, Romania and Bulgaria.

**Members of NATO, founded in 1949, are: The United States, Canada, Norway, Iceland, Denmark, the FRG, the Netherlands, Belgium, Luxembourg, Great Britain, Portugal, Italy, Greece and Turkey.

harass their young comrades in many units. Though prohibited, flogging is customary--when "comrades' courts" assemble in barracks quarters at night. The armed forces stationed in the interior of the Soviet Union are sent to help with the harvest every summer. In the spring they repair frost damage to roads, canals and railroads. And in the fall and winter, owing to the shortage of labor, they have to help out in industry.

The Main Enemy in the West: the FRG and the United States

There is therefore little military training. Even crack divisions of the Red Army cannot keep step with the highly trained NATO forces. Combat readiness of the Soviet forces suffers anyway from the fact that recruits are immediately assigned to combat formations. In NATO, on the other hand, these are assigned to special training centers, with the result that the combat forces are fully ready for action at any time.

Ideological training is all the more intensive, with 18 hours a week devoted to political instruction. In the indoctrination, the United States and the FRG are portrayed as the main adversaries, only their "imperialist cravings for aggression" constituting a "danger to peace." In addition, the 90 minutes' leisure time to which every soldier is entitled in the evening is often enriched with political drill and "voluntary" service. In the Moscow Military District, it even happened during pauses in combat during a maneuver that regiments were assembled around hurriedly installed loudspeakers to hear explanations of the decisions of the latest party congress.

The ultimate in gung ho was accomplished one Sunday by the political officer on board of a destroyer in the Black Sea. To "strengthen anti-imperialist consciousness" he organized a competition obligatory for all sailors. The winner was the one who could take apart and reassemble a machinegun the fastest blindfolded. The navy journal quite seriously voiced its enthusiasm, calling it "exemplary."

The daily schedule in force since the end of 1975 would lead to collective refusal of orders in Western armies:

0600	Reveille
0610	Early-morning gymnastics and cleaning of accommodations Washing, dressing, making of beds
0650	Political information
0725	Breakfast
0800	First to sixth training hour
1400	Lunch
1440	After-lunch rest period
1510	Maintenance of personal weapon and equipment

1530 Political training Mondays and Thursdays
Weapon and equipment servicing Tuesdays and Fridays
Sports Wednesdays and Saturdays
1830 Private study (party assembly)
1940 Supper
2010 Leisure time
2140 Evening walk-through and roll call
2200 Retreat

Intelligence officer defector Aleksey Myagkov told STERN: "The ordinary soldier lives a miserable life in the Soviet Army. During his military service he is strictly prohibited from leaving the station of his unit. His whole day is filled with duty down to the last minute; he is engaged in drill almost the entire time. Only very few sometimes get furloughs to visit their families at home--a rare reward for the best."

When he drops into bed dead tired after 16 hours' work and drill, the soldier on compulsory military service still does not get any rest. His bed stands in a hall with 70 or 100 other beds. The crowding and smell are downright intolerable, the generally old barracks being hopelessly overcrowded. There is no locker for one's few private belongings.

Despite the fact that all alcohol is banned from Soviet barracks, soldiers and officers in some units drink like fish. And among the troops on the Chinese border, Western intelligence services noted to their amazement that a marihuana-like drug, "anakha," has come into use in addition to alcohol. The flight, by the divisions, into narcotics becomes explicable when one looks at a poll published in a Soviet military journal which came up with frightful data 3 years ago: three-quarters of those doing compulsory military service were repelled by the tedious drill. In the meantime, the flight into narcotics is not all. At the 20th Guard Army, 73 young soldiers committed suicide within a period of 3 years.

According to the NATO intelligence services, the number of deserters too is exceptionally high. With embarrassing consequences for Soviet armament: so far defectors have enabled the Americans to place every single new "miracle plane" of the Soviets on their own runways. In November 1975 they even very nearly got hold of a modern guided-missile destroyer. After a mutiny on the Baltic Sea, the crew of the "Storoshevoy" had taken over the ship and headed for Sweden. The Soviet Naval Command stopped the flight attempt with fighter planes and other destroyers in the last minute. A total of 50 mutineers died in the process.

NATO experts conclude from such incidents that large parts of the Soviet armed forces (the estimate is more than half) are unfit for an offensive war--particularly the troops stationed deep in the interior of the country and on the Chinese border. Great fighting strength and high level of training is being certified only to the forces of the Red Army directly confronting the NATO forces, the 32 divisions stationed by the Soviet Union in the "fraternal countries" of the Warsaw Pact and the 7 airborne divisions in western Russia--the elite of the Red Army. These "advance area divisions" are the only ones among the 167 Soviet combat divisions up to combat strength and immediately ready for action.

The strongest contingent is the 10 armored and the 10 armored infantry divisions (motorized infantry) and the artillery division in the GDR. Maneuvers observed by Western intelligences services have shown that these can leave their barracks ready for combat within 4 hours. After another 8 or 10 days they can be reinforced by the 30 divisions, with 375,000 men, stationed in the 3 western military districts of the Soviet Union--in the Baltic, Belorussia and the Carpathian mountains.

Without this reinforcement, an attack on Western Europe would be suicide, because Soviet soldiers serve in "throwaway divisions" without reserves of their own. With their 10,000 men they are not quite half as strong as divisions of the Bundeswehr [FRG Armed Forces] with their up to 17,500 men. The Soviet divisions are worn out in an offensive and right away replaced by new formations. The allied troops of the Warsaw Pact, however, appear to be hardly suited for this. According to a new U.S. study, "it is doubtful whether the non-Soviet armies would remain politically reliable in a massive offensive action."

Life in the crack units, almost all of which bear the title of "guard," is hard. By contrast, despite all the harassment, service on the Chinese border and in the interior of the country, is a bit slovenly, and whoever handles himself astutely can somehow scrape through. Among the occupation forces in the Warsaw Pact states, the drill is taken seriously--like the draconian drill of ill repute in the old Prussian army. Discipline is rigorous.

Even the noncommissioned officers have 87 different types of punishment with which they can bully the soldiers, ranging from punitive duties to solitary arrest in a dark cell with only bread and water. The soldiers in these crack divisions are trained only for combat. They are spared work in the fields or in roadbuilding. They can go out but seldom, and then only in groups under the command of the one most senior in service.

Even with the "fraternal" forces of their host countries, contact is limited to the official level, and there is no cordiality. Thus, among the GDR soldiers of the National People's Army [NVA], the Soviets are merely circumscribed as the "unit next door." They are unloved, and the constant appeals by the SED leadership "to learn from the Soviet brothers" get on the nerves of the NVA officers, who have become independent-minded.

The voluntary isolation of the Soviets has its reasons: the soldiers should not be exposed to a culture shock. Some are anyway. Soviet Army drivers have a hard time finding their way in the--by Soviet standards--rapid and dense GDR road traffic. There are frequent accidents, and, frightened by the traffic, the Red Guardists prefer to go ahead and drive their cars into the ditch. Nor do the Soviet divisions ever stay in the GDR more than a year. They are then exchanged and sent to the Baltic for moral rearmament.

The 21 Soviet divisions in the GDR and the additional 11 in the other Warsaw Pact states get preferential treatment in the supply of new armament. But the latest NATO investigations have shown that the East enjoys only an insignificant superiority with its modern combat tanks--11,000 compared with 9,500 in Western Europe. The threatening "Russian steamroller"--estimated at 19,000 to 60,000 tanks, depending on one's political point of view--consists two-thirds of venerable veterans.

The Austrian expert on the East Dr Friedrich Wiener states: "These old vehicles, worn out in 15- to 20-year use by the troops, are parked in large camps. It cannot be assumed that in times of tension new formations can be established from these supplies." No wonder; batteries and copper wiring of many of these veterans have long since been sold on the black market by the guard crews, as shown by constantly reported trials.

But this armored junk has still a twofold political value. The Warsaw Pact can introduce it as a quid pro quo in the negotiations about troop reductions in central Europe, and the NATO command can put pressure on Western governments for greater armament expenditures by pointing to enormous Eastern tank stocks.

The most important Western defense politicians all agree that such an increase is not necessary, for alone the immense quantity of the Soviet firing equipment worries many NATO generals. According to calculations of the U.S. CIA intelligence service, the Soviet Union spent the equivalent of 270 billion dollars on its armed services last year. The intelligence service of the Chinese People's Republic added up the expenditures of their disliked red brothers to as much as 350 billion dollars--as much as the whole Second World War cost the German Reich.

In a Europe of detente such enormous armament seems absurd, for the USSR needs detente on its western border just as urgently as NATO. The situation on the Chinese border is so tense that even now large parts of the Red Army are standing on the Ussuri. Therefore not quite half can be marshaled for a war against the West. Despite increasing hostility in the Far East, the Soviet Union cannot risk withdrawing troops for instance from the GDR, because these units insure the survival of the communist regime.

Table 1. NATO and USSR Weapons

	NATO	USSR
Tanks	9,500	21,000
Combat aircraft	2,000	3,500
Capital ships	274	404
Submarines	241	248

Table 2. NATO and Warsaw Pact Ground Forces

United States	982,000	Soviet Union	2,000,000
Great Britain	188,000	Bulgaria	115,000
Canada	34,000	GDR	105,000
FRG	327,000	Poland	220,000
Belgium	66,000	Romania	140,000
Netherlands	82,000	Czechoslovakia	135,000
Luxembourg	550	Hungary	83,000
Denmark	27,000		
Norway	18,000		
Italy	223,000		
Greece	120,000		
Turkey	360,000		
Iceland	-		
Portugal	180,000		
Total	2,607,550		2,798,000

Table 3. Weapon Totals and SALT II

	USA	Permitted under SALT II	USSR
Total of Strategic Nuclear Weapons	2,060	2,250	2,570
Missiles with multiple warheads	1,046	1,320	795
Submarines and long-range missiles with multiple warheads	1,046	1,200	725
Intercontinental missiles with multiple warheads	550	820	600
Heavy intercontinental missiles with multiple warheads	0	*	308

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*Frozen at present volume

Millions for Armament In Order To Be Taken Seriously

Moreover armament costs--worldwide a million dollars every minute--are getting to be too much for all sides. While, in the experience of NATO, each new weapon costs five times as much as its predecessor, it is worth only twice as much.

Nevertheless the huge military expenditures, hindering the progress of the country, make sense from the point of view of the Kremlin: only because of its war equipment is the developing country of the Soviet Union taken seriously by the world and by the countries of the West as a big power with claims to global domination.

For the Soviet Union, after all, is not only the country of sputniks and leaders in sports, of revolution and missiles; it is above all an extremely poor country, at the technological level of the early fifties and with a backward agriculture that cannot give the populace enough to eat.

It is only to the military that the Soviet Union owes its standing in the world, and the military is therefore treated gently. One-seventh of the yearly national income is devoured by armament. Such a demonstration of devotion is important for the Soviet leadership--particularly for its own survival--because armament makes it easier for the marshals and generals, all personal privileges notwithstanding, to have a quite limited say in government. Of the three pillars of the USSR--the party, intelligence and the army--the military has the least influence on politics.

Instead they are allowed to live well. In the "classless society" the officers corps has become a class of its own. In an army which did not even have any ranks 60 years ago, there are now up to five different messes, and the 4,200 calories that every member of the Red Army has been entitled to since 1972 can vary a great deal depending on whether a recruit or a colonel gets them.

Officers of the rank of major and up earn a good deal more than the government bureaucrats, are given servants and a car, live inexpensively in houses away from barracks, and in officers' stores for little money buy the kind of things their civilian fellow citizens can only dream about.

The Communist Party has a firm hold on the armed forces. Up to 90 percent of the officers are party members. Each unit, in addition to a commanding officer, is ruled by a Communist Party functionary, enjoying equal rank, as "representative for political matters." Moreover the party sees to it that most of the higher commanders do not get their posts until they are almost old men, because there is no such thing as a Napoleon at the age of 65 (someone that old no longer thinks about a coup).

The KGB secret service too has drawn its own net of command and espionage over the armed forces. KGB officers--both overt and covert--have infiltrated the forces. The most feared are the secret snoopers: while they know everyone and everything about him, no one knows them.

The interest of the party and secret service in the armed forces is understandable. Just as [the armed forces] in Germany in Kaiser Wilhelm's times, the Red Army in the Soviet Union of today is the school of the nation--as the Communist Party sees it. And it is the most important Russian racist stronghold in the multipeople state of the Soviet Union. While the proportion of Russians is visibly shrinking below the 50-percent mark, they are holding on to their rule in the state. Whoever wants to get somewhere as a soldier has to be Russian.

With the Army, the Russians Rule in the Multipeople State

The language of command is Russian, and with a few exceptions the officers corps is Russian. The aim of being a crucible of society in the multipeople state, however, has not yet been reached by the Red Army. The contrasts between Georgians and Mongols, Ukrainians and Kirgizians are noticeable.

The armament of the Soviet Union primarily has domestic political and alliance-political reasons--to preserve what has been accomplished in the country and in central Europe. Just as at one time the U.S. Cavalry with its massacres of Indians and Mexicans created the superiority of the present U.S. leading stratum, so the Red Army today is insuring the domination of the Russian party over the greater part of Europe and one-third of the Asian Continent. The Soviet generals are convinced that "once our tanks are stationed somewhere, communism is firmly anchored there." And if it happens that things don't work out, as for example in Hungary in 1956 or in the CSSR in 1968, you just put more tanks in motion.

In international affairs, on the other hand, the Red Army has as yet not been very useful to the Communist Party leaders. But, in the estimate of Western intelligence services, this will soon change. Whereas the United States--for decades "world gendarme No 1"--since World War II has interfered 215 times in foreign conflicts and wars, the Soviet Union dared do so only 115 times, albeit increasingly so since the mid-sixties.

For, since not quite 10 years ago, the pure land power has also risen to be a sea power. The Russian "bear" has learned to swim. Owing to increased expansion of its Red Fleet, the Soviet Union today can operate worldwide. Through the buildup of air transport power--something only the Americans had previously--it has gained additional global mobility.

The results have already been felt by the West. When civil war broke out 3 years ago in the former Portuguese colony of Angola, the United States no longer could risk the previously customary employment of marine infantry. In a constant operation, the Soviets flew thousands of Cuban soldiers in long-range transport aircraft across the Atlantic to Africa and thus decided the civil war.

The Chinese too, who in the first war between two communist states attacked Vietnam at the beginning of this year, came to feel this new mobility.

With an aerial bridge for thousands of tons of armament goods, the Soviets flew to the aid of their harassed friends in Vietnam.

Alone its potential for worldwide military interventions will enable the Soviet leadership in the future to lend more effective support to the revolutionary movements in the Third World than heretofore. It thus will be able to conduct a pincer movement against the West, dependent on raw materials. For the eighties, therefore, NATO intelligence experts predict an increasing number of "substitute wars."

On the other hand, the Red Army will not be able to afford for decades such things as a lightning attack against central Europe and the FRG. The latest defense white paper of the FRG Government therefore for the first time no longer contains the term "threat." And rightly so.

A U.S. study about the armament configuration completed at the end of 1978 shows that it is not the West but the East that is lagging. Even the feared Soviet medium-range SS 20 atomic missiles, just directed against targets in Western Europe by the Soviet Union, so far are rather something like a paper tiger. Not 600 missiles have been installed, as cold warriors in the West were lamenting, but--as of end of March--only 57.

PHOTO CAPTIONS

1. p 21. Photograph of rows of soldiers stripped to the waist. "Early-morning gymnastics for Red Guardists, the elite of Soviet forces. Their daily routine is tough; every minute is filled with drill. But the overwhelming majority of the Red Army does not consist of crack divisions. Training and discipline are poor, and soldiers often are dispatched to help with the harvest or to build roads."

2. pp 22-23. Photo of countryside being overflown by missiles. "With the Stalin organ, the fear of the Germans against the Soviets began. Since World War II the Red Army has developed more and more new rockets--from salvo guns for the field artillery to intercontinental missiles threatening every point on earth. In their strategic missile forces serve 350,000 men--not combat soldiers but highly qualified technicians. This very month Washington and Moscow plan to sign the new SALT agreement for limiting armament. It compels the Soviets to junk some of their atomic missiles."

3. pp 24-25. Photograph of parading tanks. "Tanks on Red Square. The impressive posture conceals the fact that the 'Russian steamroller' to a large part consists of poorly trained soldiers with antiquated arms."

4. p 25. Photograph of soldiers presenting arms. "Heroes are in high regard. The picture of the heroic Red Army is deceiving. Only the occupation forces in the western 'fraternal countries' such as the GDR can get ready for combat within a few hours."

5. pp 28-29. Photograph of soldiers hoisting Red Flag. "First on the brink of annihilation, then victory. After a bloody 4-year struggle against Hitler Germany, Sgts Milton Kentariya and Mikhail Yegorov on 30 April 1945 hoist the flag of the USSR on the Reichstag [parliament] building in Berlin. The invasion of the Soviets fomented a traumatic fear of the Russians among the Germans which persists to this day."

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