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# FOREIGN TECHNOLOGY DIVISION

SOLID ROCKET PROPELLANTS

By

A. I. Silant'yev

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SOLID ROCKET PROPELLANTS

By: A. I. Silant'yev

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A. I. Silant'yev

# TVERDYYE RAKETNYYE TOPLIVA

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ABSTRACT: Of all the rocket fuels used at present or proposed for the future, solid rocket fuels or, as they were called earlier, rocket powders, are the most ancient. In the first primitive rockets which appeared long ago, black gun powder — solid rocket fuel — was burned. At present, new compositions of solid fuels which approximate liquid fuels with respect to their energy properties have been discovered. The servicing of rockets with solid propellant engines is considerable simpler than for liquid propellant rockets. All this has caused renewed interest among rocket builders in solid rocket fuels. This book is devoted to a description of the compositions of rocket fuels, their energy and service properties. The book is written from material of the domestic and foreign open press and is intended for soldiers, sergeants, students in military schools, and for a broad audience of readers interest ' in rocket technology. English translation; 59 pages.

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## U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

| Block | Italic | Transliteration | Block | Italic | Transliteration |
|---|---|---|---|---|---|
| А а | *А а* | A, a | Р р | *Р р* | R, r |
| Б б | *Б б* | B, b | С с | *С с* | S, s |
| В в | *В в* | V, v | Т т | *Т т* | T, t |
| Г г | *Г г* | G, g | У у | *У у* | U, u |
| Д д | *Д д* | D, d | Ф ф | *Ф ф* | F, f |
| Е е | *Е е* | Ye, ye; E, e* | Х х | *Х х* | Kh, kh |
| Ж ж | *Ж ж* | Zh, zh | Ц ц | *Ц ц* | Ts, ts |
| З з | *З з* | Z, z | Ч ч | *Ч ч* | Ch, ch |
| И и | *И и* | I, i | Ш ш | *Ш ш* | Sh, sh |
| Й й | *Й й* | Y, y | Щ щ | *Щ щ* | Shch, shch |
| К к | *К к* | K, k | Ъ ъ | *Ъ ъ* | " |
| Л л | *Л л* | L, l | Ы ы | *Ы ы* | Y, y |
| М м | *М м* | M, m | Ь ь | *Ь ь* | ' |
| Н н | *Н н* | N, n | Э э | *Э э* | E, e |
| О о | *О о* | O, o | Ю ю | *Ю ю* | Yu, yu |
| П п | *П п* | P, p | Я я | *Я я* | Ya, ya |

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

## Solid Rocket Propellants

Of all the rocket propellants applied at the present or proposed by technical progress for the future, solid rocket propellants, or, as they were earlier called, rocket powders, are the most ancient. The first primitive rockets that appeared in the distant past burned black (smoky) powder, i.e., solid rocket propellant.

New compositions of solid propellants are presently being invented with energy characteristics similar to liquid propellants. The maintenance of rockets with solid-propellant engines is considerably simpler than that of rockets with liquid-propellant engines. All this again aroused the interest of rocket builders toward solid rocket propellants.

This pamphlet is devoted to a description of the compositions of rocket propellants, their energy [power] characteristics, and operational properties.

The pamphlet was written on the basis of domestic and foreign open-source materials and is intended for enlisted men, NCO's, students of military schools, and also for a wide variety of readers interested in rocket technology.

Anatoliy Ivanovich Silant'yev
Engineer-Colonel

## INTRODUCTION

Contemporary rocket engines are heat machines. The work of any heat machine requires a source of thermal energy, i.e., fuel.

The fuels applied in rocket engines are called propellants.

Contemporary rocket propellants are chemical substances which give off thermal energy as a result of chemical reactions (burning); therefore, they are called chemical propellants in distinction, for instance, from intranuclear and electrical sources of energy.

In general, rocket propellants consist of a fuel and an oxidizer. Depending upon the physical state of the fuel and oxidizer, rocket propellants, as a rule, occur in two forms, i.e., liquid propellants [LP] (ЖРТ) and solid propellants [SP] (ТТТ). In accordance with these forms of propellants, corresponding rocket engines have been developed: liquid-propellant rocket engines [LPRE] (ЖРД) and solid-propellant rocket engines [SPRE] (РДТТ).

Solid propellants similar to contemporary black powder were the first sources of energy of rocket engines and were applied for the first time in China and India in the beginning of our chronoglogy. Black powder later remained only as a propellant for rocket engines.

Prior to invention of the smokeless powder and artillery weapons with rifled barrels, rockets with SPRE were widely applied in military operations and were included in the armament of the armies of many countries.

However, the comparatively small reserve of energy in black powder and the small quantity of gases formed during its burning did not make it possible to develop operational rockets which could compete with rifled cannon-type artillery.

As the cannon-type artillery improved, and its power, closeness of firing pattern, and rate of fire increased, the ineffective operational rockets were almost completely withdrawn from the armament of armies.

Before the Second World War, are especially in the course of it, [illegible] SPRE of mainly tactical assignment again obtained an important [illegible] appeared in the armament of the fighting armies.

Soviet scientists, considerably earlier than the others, reached successes in the area of creating contemporary rockets with SPRE. Already in 1939 rocket missiles were part of the aviation armament and in 1941 at Moscow our famous "Katyusha's" [rocket launchers] brought panic and terror to the [illegible] ite soldiers.

During the Second World War, rockets with SPRE obtained the widest application and in many cases the impact of its influence exceeded that of cannon-type artillery.

The successes in the creation of rockets with SPRE became possible due to the use of new nitrocellulose propellants (rocket powders).

The postwar period of the development of rocket technology was characterized by outstanding achievements in the area of the development of guided rockets with LPRE. The high effectiveness of liquid-propellant rockets and the well-developed propulsion systems and flight control systems in a short period of time made it possible to attain huge successes in the task of the conquest of space. Many rockets with LPRE of various range also were developed for the needs of the army and navy.

The appearance of new solid-propellant mixtures and the improvement of the operating characteristics of nitrocellulose propellants made it possible to develop new, more improved rockets with SPRE.

Thus, for instance, the United States is replacing rockets with LPRE (Corporal and Redstone) with rockets with SPRE (Sergeant and Pershing). Simultaneously, intercontinental, antiaircraft, and research solid-propellant rockets are being developed (Polaris, Minuteman, Scout, and others). Superpowerful SPRE's with thrust up to thousands of tons and a service life up to nearly one minute also are being designed. The propellant charges of these engines will weigh hundreds of tons and will have a diameter of up to five meters and a length of up to twenty meters.

Table 1 gives data on rockets with SPRE according to the development of new propellants and more improved engine designs. From a comparison of the data given

Table 3. Comparative Data of Rockets with SPRE

| Year of application | Rockets | Propellant | Gross weight of rocket, kg | Range, km |
|---|---|---|---|---|
| 1799 | Indian rockets | Black powder | 6 | – |
| 1800-1807 | British rockets | The same | 3-11 | 1.8-2.7 |
| 1815-1870 | Russian incendiary and fragmentation-demolition rockets | The same | – | 2.4-3.5 |
| 1939-1945 | Soviet rockets | Nitrocellulose | 8<br>42.5<br>127 | 5.5<br>7.9-8.5<br>4.5 |
| 1941-1944 | German turbojet missiles | The same | 34<br>127 | 6.9<br>4.5 |
| 1944-1945 | American rockets | The same | 19.3<br>27.6 | 4.75<br>0.20 |
| 1945-1951 | Rockets of different capitalistic countries adopted for service: | | | |
| From 1951 – and later | – antipersonnel | The same | 200-400 | 18-10 |
| | – tactical | The same | 2000-2700 | 32-50<br>160-200 |
| | – operational-tactical | Nitrocellulose and hybrid | 9000-11,000 | 1600-2400 |
| | – medium radius of action | Hybrid | 13,000 | 8000 |
| Being developed | – intercontinental | The same | Up to 36,000 | |
| Projects | – space | The same | Over 300,000 | For satellite launching |

in Table 1, one may see that considerable successes in the creation of rockets with SPRE have been made in the last decade.

Solid propellants are finding wide application in the engines of guided antitank missiles [GATM] (НТУРС), guided and unguided aircraft rockets, in the rocket weapons of the navy, and also as boosters and assisted-takeoff engines for rockets and aircraft (Fig. 1). In addition, solid propellants are being used successfully to drive the various accessories on rockets, aircraft, and earth satellites.

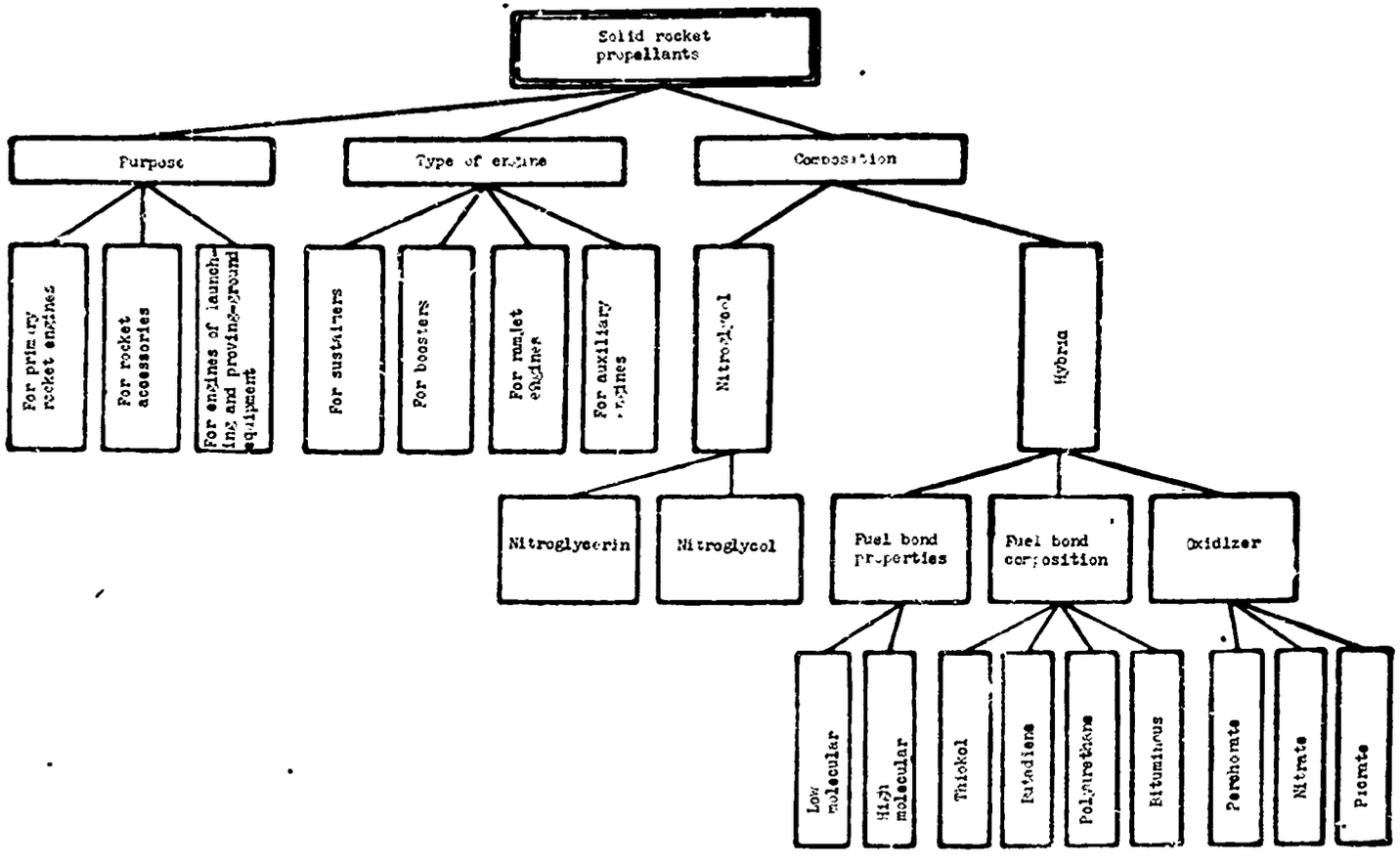


Fig. 1. Classification of solid rocket propellants.

The various areas of application of solid propellants impose on them diversified requirements which are not always possible to satisfy; therefore solid rocket propellants cannot completely replace liquid propellants. Both propellants are applied in rocket technology where they can be used with the greatest effectiveness.

# CHAPTER I

## GENERAL INFORMATION

### § 1. Rocket Propellants — Sources of Energy of Rocket Motion

All sources of energy which can be used for rocket motion are subdivided into two large groups: chemical and nonchemical.

The nonchemical sources of energy include sources of electrical energy and the energy of nuclear fission (atomic or nuclear energy); when nonchemical energy sources are used in rocket engines, the rocket must have, in addition to the propellant, a substance that directly accomplishes work, i.e., a working substance. Nonchemical sources of energy have not yet found much application in rocket technology.

Chemical sources of energy include all form of chemical substances (fuels) which can burn rapidly in an engine chamber with the release of a large quantity of heat and combustion products.

In national-economic power engineering, fuels are defined only as combustible substances (peat, coal, oil, natural gases) which burn in an atmosphere (in atmospheric oxygen). On board a rocket which moves both in an atmosphere and in a vacuum it is necessary to have both a fuel and an oxidizer or such complicated chemical substances which would have fuels and oxidizing elements in their composition.

As we already mentioned, rocket propellants are subdivided into two basic forms according to their physical aggregate state: liquid and solid.

Liquid propellants, as a rule, consist of two components: an oxidizer and a fuel, which are stored separately. They are combined in the combustion chamber



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and only there do they become the actual propellant.

In distinction from liquid propellants, solid propellants are monopropellants (complex) which contain both fuels and oxidizing elements in their composition. Solid propellants are manufactured in factories from various solid and liquid substances in the form of grains in a specific geometric shape and are used in engines in this form.

The physical properties of the propellant determine the engine design.

If we compare the diagrams of the [LPRE] (ЖРД) and the [SPRE] (РДТТ) (Fig. 2), it is possible to note their essential distinction: the propellant components in the LPRE are located in different tanks of the feed system and are pumped into the combustion chamber; the combustion chamber in the SPRE is simultaneously the propellant container ("magazine"); this is one of the advantages of rocket engines that operation on solid propellant.

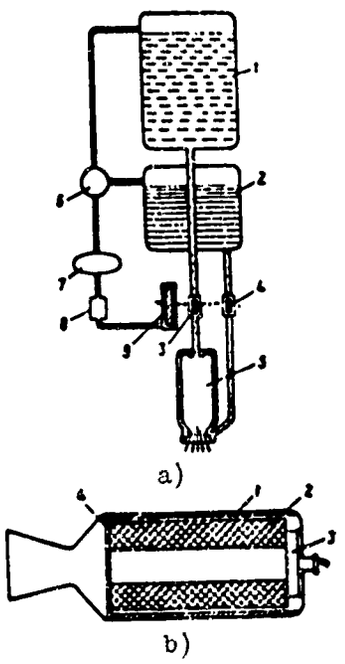



Fig. 2. Diagrams of rocket engines: a) diagram of LPRE with turbopump feed system: 1 — oxidizer tank; 2 — fuel tank; 3 — oxidizer pump; 4 — fuel pump; 5 — combustion chamber; 6 — bottle of compressed gas; 7 — bottle with hydrogen peroxide; 8 — steam-gas generator; 9 — turbine; b) diagram of SPRE: 1 — engine chamber with thermal insulation; 2 — solid-propellant charge; 3 — igniter; 4 — grid (diaphragm).

Both liquid and solid rocket propellants must possess a large reserve of energy and form a large quantity of gaseous products while burning.

However, solid propellants have a large number of special requirements.

In general, these requirements amount to the following:

a) the ready propellant should be chemically and physically stable, i.e., it should not change its properties during storage due to the influence of external conditions, in particular temperature and atmospheric humidity;

b) the propellant grains must possess certain mechanical properties: they must not be destroyed during transportation and during rocket launching, and must not essentially change their mechanical properties when the temperature changes;

c) the propellants must ignite easily, burn completely and stably in the engines at rather low and high pressures, and insignificantly change

their burning rate depending upon the change of the external temperature.

For use in specific rockets, the propellants are presented with a number of additional special requirements.

Knowing the requirements imposed on solid rocket propellants, it is possible to define them: solid rocket propellants are compact, unitary, complex chemical systems that possess a reserve of energy and have the necessary physical and mechanical properties which permit their use in rocket engines.

The necessary properties are given to solid rocket propellants in process of their manufacture by selecting the necessary chemicals.

Solid rocket propellants can burn rapidly with the release of a considerable energy content and combustion products which pickup this energy and serve as the working substance of a jet engine.

## § 2. Classification of Solid Rocket Propellants

Solid rocket propellants can be classified according to purpose, engine type, and the nature of the substances in their composition (see Fig. 1).

With respect to purpose, solid propellants are divided into primary-purpose propellants (for primary rocket engines) and secondary-purpose propellants (for driving rocket accessories, e.g., pumps, control mechanisms, and for launching and boosting trolleys.

With respect to engine type, solid propellants divide into propellants for rocket sustainers, for rocket boosters, for ramjet engines [RJE] (ПВРД), and for auxiliary engines.

With respect to the nature of the substances in their composition and the methods of their manufacture, solid rocket propellants are subdivided into nitrocellulose solid rocket propellants (rocket powders) and hybrid solid rocket propellants.

Nitrocellulose solid rocket propellants are, as a rule, complex systems whose energy and physico-mechanical properties determine the cellulose nitrates which are dissolved and plasticized by low-volatile solvents.

Nitrocellulose propellants, depending upon the nature of the low-volatile solvent, are subdivided into:

— nitroglycerin nitrocellulose propellants, where the solvent of the cellulose nitrates is nitroglycerin (glyceryl trinitrate);

— nitroglycol nitrocellulose propellants, where the solvent of the cellulose

nitrates is nitrodiglycol (diethylene glycol dinitrate).

Mixed solid rocket propellants are mechanical mixtures of mineral oxidizers, fuels, and binders.

In many cases the fuel also is simultaneously the binder, and conversely therefore, they frequently are combined into one category, i.e., fuel binders.

Depending upon the properties of the fuel binders, mixed solid rocket propellants can be:

– propellants on a low-molecular fuel base (black powder, RJE propellants, etc.);

– propellants on a high-molecular fuel-binder base.

Mixed solid rocket propellants can differ with regard to the nature of the oxidizer and the nature of the high-molecular fuel binder.

With respect to the nature of the fuel binder, they can be: thiokol, butadiene, polyurethane, bituminous, etc. With regard to the nature of the oxidizer: perchlorate (on an ammonium perchlorate or potassium perchlorate base), nitrate (on an ammonium nitrate base with a mixture of it and potassium nitrate), and picrate (on an ammonium picrate base).

The primary-purpose propellants used most often in rocket engines are various compositions of nitrocellulose and mixed (on a high-molecular fuel-binder base) solid rocket propellants.

They will be considered subsequently in more detail.

## CHAPTER II

## SOLID PROPELLANT COMPOSITIONS

### § 3. Nitrocellulose Propellants

There are many varieties of nitrocellulose propellants which differ in composition and component weight ratio. However, the weight ratio of the base substances — cellulose nitrates and solvent — varies insignificantly. As a rule, the composition of nitrocellulose propellants (with regard to weight) can vary within the following limits:

| | |
|---|---|
| Cellulose nitrates | 54-60% |
| Solvents-plasticizers (nitroglycerin or nitrodiglycol) | 25-43% |
| Additional plasticizers and substances which regulate the energy characteristics of the propellants | 8-11% |
| Chemical stabilizers | Up to 1-5% |
| Substances which facilitate propellant manufacture (technological additives) | Up to 2% |
| Substances which improve the rate of propellant burning (catalysis and burning stabilizers) | Up to 5% |

Table 2 gives the composition of typical nitrocellulose propellants.

One may see from Table 2 that nitrocellulose propellant are very complicated, multicomponent systems in which each substance has its own role in accordance with its properties.

Cellulose nitrates [CN] (HII) are the energy bases of propellants, i.e., they release a maximum quantity of heat upon combustion. They also simultaneously determine the physico-mechanical properties of propellants.

Cellulose nitrates are obtained by treating cellulose materials (cotton, paper) with nitric acid in the presence of sulfuric acid. This process is called nitration.

Table 2. Composition of Nitrocellulose Propellants

| Substance | Quantity of substances (by weight) % | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | USSR | | USA | | | | | | Former gray army | | |
| | H | HM -2 | M-8 | M-13 | T-3 | T-5 | T-6 | T-8 | Digl 10.2 | Digl 8.9 | R-61 |
| Cellulose nitrates with nitrogen content in % — 12 | 57 | 54 | – | – | – | – | – | – | – | – | – |
| 12.2 | – | – | – | – | 56 | – | 55.5 | – | – | – | – |
| 12.5 | – | – | – | – | – | | – | – | – | 59.8 | 61.5 |
| 13.15 | – | – | 52.2 | 57.3 | – | 57.4 | – | 58 | 60.2 | – | – |
| Nitroglycerin. . . . | 28 | 27 | 43.0 | 40.0 | 27 | 39.2 | 27.5 | 22.5 | – | – | – |
| Nitrodiglycol. . . . | – | – | – | – | – | – | – | – | 39.0 | 35.3 | 34.0 |
| Dinitrotoluene . . . | 11 | 15 | – | – | 9.3 | – | 10.5 | 10.5 | – | – | – |
| Diethyl phthalate. . | – | – | 3 | – | – | – | – | – | – | – | – |
| Chemical stabilizers | 3 | – | 0.6 | 1.2 | 7.2 | 1.7 | 4.0 | 8.0 | 0.7 | 2.5 | 3.5 |
| Graphite or carbon . | – | – | – | 0.1 | – | 0.1 | 0.5 | – | – | – | – |
| Magnesium oxide. . . | – | 2 | – | – | – | – | – | – | 0.1 | 0.3 | 0.5 |
| Technological additives. . . . . | 1 | 2 | – | – | – | 0.1 | 0.5 | 0.5 | – | – | – |
| Other substances . . | – | – | 1.2 | 1.4 | 0.5 | 1.5 | 1.5 | 0.5 | – | 2.1 | 0.5 |

Sulfuric acid is added during nitration in order to bind the water released in the course of the reaction.

In simple form the reaction of nitration may be represented as follows:

$$C_6H_7O_2(OH)_3 + nHNO_3 \xrightarrow{H_2SO_4} C_6H_7O_2(OH)_{3-n}(ONO_2)_n + nH_2O.$$

Inasmuch as in the process of nitration it is not possible to completely replace the OH groups in cellulose with $ONO_2$ groups, cellulose nitrates, with regard to their chemical composition, are very heterogeneous, high-molecular compounds that consist of various fractions which contain a various quantity of $ONO_2$ groups (n varies from zero to three). In view of this, the technical forms of cellulose nitrates are distinguished first of all by their nitrogen content and solubility in an ether-alcohol mixture.

With regard to nitrogen content, cellulose nitrates are divided on pyroxylin (with a nitrogen content from 12.0 to 13.5%) and collodion (with a nitrogen content less than 12%).

The nitrogen content also determines many properties of cellulose nitrates. Thus, the higher the nitrogen content, the lower their solubility in low-volatile solvents, but the higher their energy characteristics and burning temperature, and the lower the specific volume of gases.

Cellulose nitrates ignite easily from an open flame and even a small spark.

Their burning occurs due to the active oxygen that is contained in the $ONO_2$ groups and does not require an external oxygen supply. The combustion products are $CO_2$, CO, $H_2O$, $H_2$, and $N_2$ gases.

The heat of combustion of pyroxylin is 800-900 kcal/kg, gas volume is 880-890 liter/kg, and its burning temperature is up to 3000°K; the heat of combustion of collodion is 800-900 kcal/kg, gas volume is 920-930 liter/kg, and its combustion temperature is 2500°K.

Cellulose nitrates are solid fibrous substances with a specific gravity of 1.66-1.67 g/cm$^3$. They are hygroscopic, i.e., they can absorb and retain a comparatively large amount (1.5-2.5%) of moisture. Their hygroscopicity is less, the greater the nitrogen content.

With regard to their reserve of energy, cellulose nitrates could be used directly as a propellant since they contain combustible elements (carbon and hydrogen) and active oxygen. However, the direct use of cellulose nitrates as solid propellants is impossible inasmuch as solid, progressive-burning grains cannot be manufactured from them. Even if they are very intensely pressed in grains, they will have pores. The burning of these grains in an engine will occur with an explosion and will cause the destruction of the engine.

In order to manufacture compact, mechanically strong grains, cellulose nitrates are treated with solvents and plasticizers. In the process of treatment, at comparatively high temperatures and pressures, solid solutions or plasticized cellulose nitrates are obtained. In order not to lower the energy reserve of the propellant, the solvents and certain plasticizers are selected from those which actually contain active oxygen and have a large energy reserve. The most convenient for these purposes turned out to be nitroglycerin and nitrodiglycol. Nitroglycerin and nitrodiglycol also are the energy bases of nitrocellulose propellants and simultaneously ensure the manufacture of a homogeneous, physically uniform, propellant mass.

Thus, nitrocellulose propellants include, as a rule, two substances that are the basic sources of energy in the propellant (cellulose nitrates and nitroglycerin or nitrodiglycol), and they are still called <u>double-base</u> propellants.

<u>Nitroglycerin</u> is a complete ester of triatomic glycerin alcohol and nitric acid. It is easily formed by the interaction of nitric acid and glycerin in the

presence of sulfuric acid according to the following reaction:

$$\begin{array}{l} CH_2-OH + HNO_3 \\ | \\ CH-OH + HNO_3 \\ | \\ CH_2-OH + HNO_3 \end{array} \xrightarrow{H_2SO_4} \begin{array}{l} CH_2-O-NO_2 \\ | \\ CH-O-NO_2 + 3H_2O. \\ | \\ CH_2-O-NO_2 \end{array}$$

Nitroglycerin is one of the most powerful explosives. It is very sensitive to shocks and friction.

Nitroglycerin also burns due to the active oxygen that is contained in the $ONO_2$ groups. The total oxygen content in nitroglycerin is retained with an excess for complete oxidation of the combustible elements – hydrogen and carbon. Therefore, the combustion products of nitroglycerin are $CO_2$, $H_2O$, $N_2$, and a slight amount of oxygen $O_2$.

Burning is accompanied by the release of 1465 kcal/kg of heat with the formation of 715 liter/kg of gases at a temperature of up to 4400°K.

With respect to its energy reserve, it exceeds cellulose nitrates and is a very important component part of propellants.

Under normal conditions, nitroglycerin is a transparent, odorless liquid with a specific gravity of 1.6 g/cm$^3$. At a temperature of 13.2°C it crystallizes into rhombic crystals. Pure (without an acid admixture) nitroglycerin is a more chemically stable substance than cellulose nitrate. It intensely evaporates at a temperature of 50°C.

Various ratios of cellulose nitrates and nitroglycerine are the double bases of contemporary nitrocellulose rocket propellants.

<u>Nitrodiglycol</u> is a complete ester of nitric acid and diethylene glycol. It is obtained in approximately the same way as nitroglycerin:

$$\begin{array}{l} CH_2-CH_2OH + HNO_3 \\ | \\ O \\ | \\ CH_2-CH_2OH + HNO_3 \end{array} \xrightarrow{H_2SO_4} \begin{array}{l} CH_2-CH_2-O-NO_2 \\ | \\ O \\ | \\ CH_2-CH_2-O-NO_2 \end{array} + 2H_2O.$$

Nitrodiglycol also is an explosive; it is less sensitive to mechanical influences than nitroglycerin.

There is less active oxygen in nitrodiglycol. The combustion products of nitrodiglycol are $CO_2$, CO, $H_2O$, $H_2$, and $N_2$ gases. Burning is accompanied by a release of about 1030 kcal/kg of heat and the formation of 1020 liter/kg of gases with a temperature of up to 2800°K.

Under normal conditions, nitrodiglycol is a colorless, sometimes yellowish, odorless liquid with a specific gravity of 1.39 g/cm$^3$. It solidifies at a temperature of -11.3°C.

Nitrodiglycol dissolves and plasticizes cellulose nitrates better than nitroglycerin. However, because it is impossible to vary the energy properties of double-base compositions of nitrodiglycol and cellulose nitrates in wide limits, nitrodiglycol is used less often than nitroglycerin, for the manufacture of nitrocellulose propellants.

Nitroglycerin in combination with cellulose nitrates, depending upon their relationship in the bipropellant system, provide wide limits of the energy capabilities of these propellants. The greater the content of nitroglycerin in the propellant, the greater the reserve of energy. But with a very large content of nitroglycerin (more than 40-45%), the physico-mechanical properties of the double systems are sharply lowered; they simply become jelly-like (viscous) and it is impossible to make grains from them. In addition, double systems do not always correspond to the requirements imposed upon solid rocket propellants and a number of other properties; therefore, several other substances are introduced into cellulose nitrate-nitroglycerin (nitrodiglycol) double systems.

Additional plasticizers and substances which regulate the energy properties of nitrocellulose propellants. They include dinitrotoluene [DNT] (ДНТ), dibutyl phthalate [DBP] (ДБФ), and diethyl phthalate [DEP] (ДЭФ).

Dinitrotoluene $C_6H_3CH_3(NO_2)_2$ is a dark-yellow crystal substance with a specific gravity of 1.52 g/cm$^3$ and a melting point of 70.5°C. For the manufacture of propellants, it is applied in melted form.

Dibutyl phthalate $C_6H_4(COOC_4H_9)_2$ and diethyl phthalate $C_6H_4(COOC_2H_4)_2$ are colorless liquids which well plasticize cellulose nitrates.

The substances of this group, which are organic compounds, combine well with low-volatile solvents. They do not contain at all or contain very little (dinitrotoluene) active oxygen; therefore, in the oxidation (burning) of the carbon and hydrogen atoms which they contain, part of the active oxygen of nitroglycerin and cellulose nitrates is expended. The relative amount of oxygen in the propellant is lowered, which leads to a lowering of its energy characteristics.

Chemical stabilizers are introduced into the propellant to prevent the rapid

chemical decomposition of the chemically unstable cellulose nitrates and nitroglycerin during propellant manufacture and storage.

As noted above, cellulose nitrates and nitroglycerin are chemically unstable compounds which are inclined towards spontaneous decomposition with the [illegible] of nitrogen oxides. The process of decomposition is greatly accelerated at raised temperatures and may cause self-ignition of the propellants, especially in the process of their manufacture.

Chemical stabilizers do not eliminate nitrate decomposition, but, after being combined with the liberated nitrogen oxides, neutralize them and thereby prevent the acceleration of decomposition.

The chemical stabilizers applied are complex organic compounds — centralites and acardites.

For instance, centralite No. 1 (diethyldiphenylurea) $C_6H_5C_2H_5 \cdot \cdot - CO - N = - C_2H_5C_6H_5$ is a white crystalline substance with a specific gravity of 1.3 g/cm$^3$ and a melting point of 79°C. At raised temperature, centralite No. 1 (just as other stabilizers) can plasticize collodion.

Centralites are introduced into the propellant as chemical stabilizers in small quantities of no more than 3%. They are introduced in larger quantities as collodion plasticizers and as substances which lower the energy characteristics of propellants (fuel T-3, T-6, T-8, see Table 2).

Substances that improve propellant burning are usually mineral compounds: e.g., salts or oxides ($SnO_2$, MgO, ZnO, $Cr_2O_3$), and also carbon black or graphite. Their action shows up only during propellant burning and leads either to acceleration or deceleration of the burning process, or to its stabilization in the engine chamber.

Technological additives are intorduced into a propellant for the most critical technological operations — rolling and molding (pressing) the propellant mass — to lower machine loads and friction. They play the role of a lubricant both inside the propellant mass and also between the propellant mass and the tool. The following technological additives are used: vaseline oil (vaseline), lead stearate, graphite, and others. They are introduced in small quantities.

The propellant compositions given in Table 2 were developed basically by means of experimental selection of component substances. At present there is theoretical research being conducted on the purposeful composition of new

propellant mixtures. However, the possibilities of nitrocellulose propellants are limited. In addition, the higher the energy characteristics of nitrocellulose propellants, the more difficult and, essentially, the more dangerous the production. In particular, propellants of the type M-8 and M-13 cannot be manufactured by contemporary production methods in the form of grains of more than 280 mm in diameter, which to a considerable extent limits the application of nitrocellulose propellants for large engines.

Nitrocellulose propellants are manufactured according to a comparatively complicated system with the use of high temperatures and pressure.

The production task is to manufacture solid, physically compact, propellant grains suitable for use in engines from a large quantity of chemical substances which differ in their properties and physical state.

The production of nitrocellulose propellants is shown schematically in Fig. 3 and consists of the following.

All substances that are preliminarily prepared for production are mixed in an aqueous medium in a mixer. Here, nitroglycerin (nitrodiglycol) and other liquid plasticizers that are slightly soluble in water impregnate cellulose nitrates, partially dissolving them. No chemical reactions occur, and only physical processes take place.

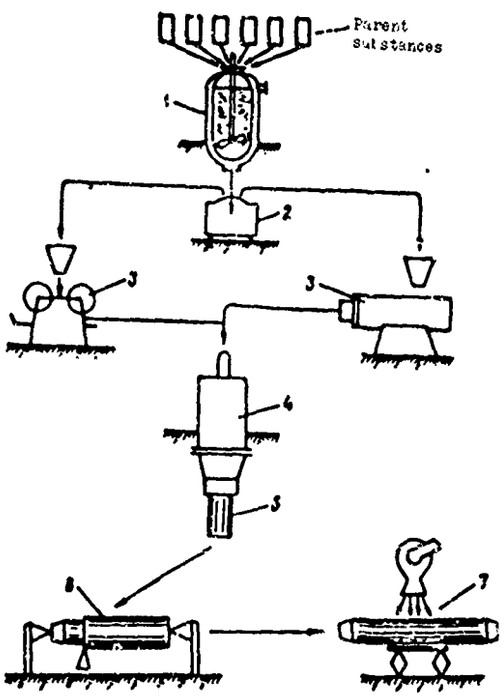



Fig. 3. Fundamental diagram of the production of nitrocellulose propellants. 1 — heated mixer; 2 — centrifuge; 3 — heated rollers and machine for plasticization under pressure; 4 — press or injection machine; 5 — billet; 6 — machining of billet; 7 — check for uniformity of grain.

The ready mixture of substances on centrifuges 2 is removed from the water and directed to hot rollers 3, where, at raised temperature and under cylinder pressure, there occur accelerated processes of dissolution and plasticization of the cellulose nitrates and removal of excess water.

The finished propellant emerges from the rollers in the form of a soft sheet and is then molded on presses 4 in the form of grains or billets 5. The billets are machined

to a specified shape 6, checked, and can be assembled with an engine.

Most industrial operations for manufacture of propellants are dangerous in the sense of fire and explosion, and they are controlled at a distance (remotely).

## § 4. Hybrid Propellants

Hybrid solid rocket propellants, in distinction from nitrocellulose propellants, are mechanical mixtures of mineral oxidizers and fuel binders.

The oxidizers used for the manufacture of hybrid propellant are exclusively the salts of mineral acids which, during thermal decomposition, can liberate free oxygen.

The fuel binders employed in contemporary hybrid propellants are high-molecular compounds, e.g., monomers, which are polymerized or consolidated into polymers during the manufacturing process.

If the oxidizer basically determines the energy capabilities of hybrid propellants, their chemical and physico-mechanical properties then depend on the fuel binders.

Depending upon the fuel binder employed, propellants can be thermoactive (thermoplastic), i.e., just as nitrocellulose propellants, which are softened under the influence of high temperature, and thermoreactive (rubber-like), i.e., which are not softened under the influence of high temperature.

In spite of the variety of existing compositions and those being developed in foreign laboratories, hybrid fuels, as a rule, contain the following substances (by weight):

| | |
|---|---|
| Oxidizers (potassium perchlorate, ammonium perchlorate, ammonium nitrate) | 60-80% |
| Fuel binders (rubber, polyurethane) | 25-15% |
| Aluminum (in powder form) | 10-5% |
| Catalysts and other special substances | Up to 5% |

Typical compositions of hybrid propellants are given in Table 3.

By comparing hybrid propellants with nitrocellulose propellants, it is possible to see that hybrid propellants are simpler with regard to composition and quantity of substances. They contain two or three (rarely four) substances, which ensures the simplicity of their manufacture.

Table 3. Composition of Hybrid Propellants

| Substance | Quantity of substances (by weight), % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ALT-161 | Thiocol | | EIA | AN | Polyurethane | | Styrene | FP |
| Potassium perchlorate | 76 | – | 60 | – | – | – | – | – | – |
| Ammonium perchlorate | – | 75 | – | 45 | – | 60 | 60 | 72 | 80 |
| Potassium nitrate | – | – | – | 45 | – | – | – | – | – |
| Ammonium nitrate | – | – | – | – | 80 | – | – | – | – |
| Bitumens | 17 | – | – | – | – | – | – | – | – |
| Petroleum oils | 7 | – | – | – | – | – | – | – | – |
| Thiocol | – | 25 | 20 | – | – | – | – | – | – |
| Polyurethane | – | – | – | – | – | 25 | 40 | – | – |
| Aluminum (powder) | – | – | – | – | – | 15 | | – | – |
| Synthetic resins | – | – | – | 10 | 18 | – | | 10 | 20 |
| Catalysts | – | – | – | – | 2 | – | | – | – |
| Toluene | – | – | 20 | – | – | – | – | – | – |
| Polystyrene | – | – | – | – | – | – | – | 18 | – |

## Hybrid Propellant Oxidizers

The oxidizers in hybrid solid rocket propellants can be solid, chemically stable, inert to combustible substances, chemical compounds, upon thermal disintegration of which the liberation of excess free oxygen is possible.

Inasmuch as all solid oxidizers also have other, frequently combustible, elements in their composition, the free oxygen of an oxidizer is usually thought of as that amount of it which remains after the complete oxidation of the combustible elements of the oxidizer itself.

For instance, in ammonium nitrate $NH_4NO_3$, the combustible element is hydrogen, which oxidizes to water upon thermal disintegration according to the following reaction:

$$NH_4NO_3 \rightarrow 2H_2O + N_2 + 0{,}5O_2.$$

If $M_{O_2}$ is the molecular weight of oxygen, and $M_{NH_4NO_3}$ is the molecular weight of ammonium nitrate, the free oxygen in ammonium nitrate in percents will be

$$\frac{0{,}5M_{O_2}}{M_{NH_4NO_3}}100 = \frac{0{,}5\times 32}{80{,}0}100 = 20\%.$$

With respect to its reserve of free oxygen, ammonium nitrate is almost the same oxidizer as air.

The quantity of free oxygen is a very important characteristic since it determines not only the energy characteristics of the propellants, but also the possibility of manufacturing a propellant with a given fuel binder.

For instance, in order to completely burn 1 kg of kerosene, it is necessary to have 14 kg of air and a total of 2.5 kg of oxygen. To completely burn 1 kg of bitumen (its composition is similar to that of kerosene), it is necessary to have about 15 kg of ammonium nitrate. If we tried to manufacture such a solid propellant, it would be necessary to have up to 97% ammonium nitrate and a total of 3% bitumen. This propellant, due to the small quantity of the fuel binder, will not possess the necessary properties. Therefore, the greater the amount of free oxygen in the oxidizer, the better it will be.

Other requirements for oxidizers are involved with the conditions of manufacture and subsequent storage of the propellants. In accordance with these requirements, oxidizers must not interact chemically with their fuel binder, must not be hygroscopic, and must not decompose at high temperatures, and also, must not liberate solid products during propellant burning as much as possible.

Table 4 lists some typical oxidizers and their properties are described below.

Table 4. Properties of Oxidizers for Hybrid Propellants

| Oxidizer | Formula | Molecular weight | Specific gravity, $g/cm^3$ | Melting point, °C | Heat of combustion, kcal/kg | Reaction of high-temperature disintegration | Quantity of free oxygen, % |
|---|---|---|---|---|---|---|---|
| Potassium perchlorate | $KClO_4$ | 138.5 | 2.5 | 600 (decomposes) | 775 | $KClO_4 \rightarrow KCl + 2O_2$ | 46 |
| Lithium perchlorate | $LiClO_4$ | 106.4 | 2.43 | | 940 | $LiClO_4 \rightarrow LiCl + 2O_2$ | 60 |
| Ammonium perchlorate | $NH_4ClO_4$ | 117.5 | 1.88 | 150 (decomposes) | 591 | $2NH_4ClO_4 \rightarrow 3H_2O + 2HCl + N_2 + 2{,}5O_2$ | 34 |
| Potassium nitrate | $KNO_3$ | 101.1 | 2.10 | 333 | 1160 | $2KNO_3 \rightarrow K_2O + N_2 + 2{,}5O_2$ | 40 |
| Ammonium nitrate | $NH_4NO_3$ | 80.05 | 1.70 | 169 | 1090 | $NH_4NO_3 \rightarrow 2H_2O + 0{,}5O_2 + N_2$ | 20 |

Ammonium perchlorate $NH_4ClO_4$ is a white crystalline powder with a specific gravity of 1.88 $g/cm^3$. It decomposes upon heating to a temperature about 150°C. It absorbs an insignificant amount of moisture in the air. It is sensitive to shocks and friction, especially when it contains combustibel admixtures. It can burn and explode. Upon burning, it does not release solid products, but its combustion products contain an aggressive and poisonous gas, i.e., hydrogen chloride HCl.

Potassium perchlorate $KClO_4$ is a white crystalline powder with a specific gravity of 2.5 g/cm$^3$. It decomposes upon being heated above 600°C. It does not absorb moisture in the air. It is less sensitive to shocks and friction than ammonium perchlorate. It does not burn and does not explode. Upon burning in propellants, it releases a solid product, i.e., potassium chloride KCl, which creates a dense smoke cloud.

Ammonium nitrate (Norway saltpeter) $NH_4NO_3$ is a white crystalline powder with a specific gravity of 1.7 g/cm$^3$. It decomposes upon being heated above 170°C. It is very hygroscopic. It can burn and explode. Upon burning, it liberates only a large quantity of gaseous products.

Potassium nitrate (niter) $KNO_3$ is a white crystalline powder with a specific gravity of 2.1 g/cm$^3$. It decomposes upon being heated above 330°C; it is less hygroscopic than ammonium nitrate. It does not burn and does not explode. Upon burning in propellants, it releases a solid product, i.e., potassium oxide $K_2O$.

There is obviously much more to the nature of solid mineral oxidizers than indicated in Table 4. However, either due to an insignificant quantity of free oxygen, or because of their physcial properties, they cannot be used practically for the manufacture of solid propellants.

Moreover, even from the five oxidizers given in Table 4, not all oxidizers satisfy the requirements imposed on them.

Thus, lithium perchlorate, which has a maximum reserve of free oxygen, greedily absorbs moisture from the air and loses its properties. Therefore, it is not applied for the manufacture of propellants.

Potassium and ammonium nitrate also are very hygroscopic and, in addition, have a very low heat of formation, which does not permit the manufacture of a propellant even with a medium reserve of energy. Moreover, potassium nitrate thermally disintegrates with the formation of solid potassium oxide, what lowers its qualities as an oxidizer. Therefore, potassium and ammonium nitrate are applied very rarely.

Potassium perchlorate's properties are of interest with regard to oxidizers. However, it possesses one essential deficiency: the potassium chloride that is formed during its thermal disintegration evaporates at propellant-burning temperatures and strongly lowers the thermal properties of the combustion products. It is sometimes applied either as the primary oxidizer or as an additive in nitrocellulose

propellants.

The only oxidizer which to some extent satisfies all the requirements is considered to be ammonium perchlorate, but it also is not an ideal oxidizer since it has a comparatively small reserve of free oxygen and releases aggressive hydrogen chloride upon burning, which turns into hydrochloric acid in the presence of moisture. Ammonium perchlorate at present is the only oxidizer on the basis of which hybrid solid rocket propellants are manufactured abroad.

## Fuel Binders of Hybrid Propellants

As shown above, the manufacture large grains from nitrocellulose propellants with high energy characteristics is very complicated and dangerous.

Hybrid solid propellants do not yield to nitrocellulose propellants and even essentially exceed them with respect to their energy characteristics, and make it possible to manufacture propellant grains of practically any size.

To manufacture grains of hybrid propellant, a mobile mixture of oxidizer and fuel binder is made, and then it is poured into molds or directly into the engine chamber and solidifies there. In this method of production, the mechanical operations are reduced to a minimum and are applied only in the less dangerous technological processes.

This method of propellant production required new chemicals. The most suitable ones turned out to be high-molecular compounds, or polymers.

High-molecular, or polymer compounds are those substances whose molecules consist of numerous elementary members are bound together by intramolecular bonds into long chains of linear or bifurcated structure and, in accordance with their structure, form elastic or rigid space lattices.

The primary chain of organic polymers consists of carbon atoms, sometimes with the alternation of hydrogen, oxygen, nitrogen sulfur, or phosphorus atoms.

The properties of polymers depend on the chemical structure of the elementary sections, their number, and relative positions. The following designation has been adopted for polymers of linear structure:

$$(-M-)_n,$$

where M is an elementary structural link of the chain; n is the number of link or the degree of polymerization.

For instance, polyethylene can be designated as

$$(-CH_2-CH_2-)_n.$$

Polymer compounds are not individual chemical compounds; they usually are a mixture of polymerhomologs, i.e., compounds with various numbers of members.

Many polymers are obtained in solid form from liquid low-molecular compounds, i.e., monomers, the length of whose chain consists of a small number of links or only one link.

Monomers can be spontaneously united into long chains, i.e., polymers. Special substances called initiators or solidifiers are employed to accelerate the process of polymerization or solidification.

Many high-molecular compounds can be mixed well and bonded with inert fillers (powders), and then solidified into a monolithic mass.

Upon heating, certain polymers are softened and become viscous or plastic, and in this state they can be mixed with fillers and durably held together. They can be poured into molds and propellant grains of a specific shape can be obtained.

The ability of certain polymers to be bonded with oxidizers and to possess high physico-mechanical properties following solidification made it possible to develop and manufacture various solid hybrid propellants. Inasmuch as polymers execute the role of a fuel and a binder, they are called fuel binders.

Fuel binders are presented with the following requirements:

— they must be able to take as large a quantity of oxidizer as possible and be strongly bonded with it;

— they must be chemically and physically stable compounds, especially under the influence of external temperature and atmosphere;

— upon solidifying, they should release fewer reaction products and should not shrink;

— it is desirable have as many hydrogen atoms and as few oxygen, carbon, and nitrogen atoms as possible in their composition.

In the selection of a fuel binder, prime attention is allotted to their technological properties in the liquid state and their physico-mechanical properties in the solidified state.

The fuel binder employed in propellants was butadiene and polyisobutylene rubbers, polyurethanes, polysulfides (thiocols), bitumens, and certain other polymers.

Butadiene and polyisobutylene rubbers $\left(\begin{matrix}-C=CH_2\\ |\\ CH_3\end{matrix}\right)_n$ are obtained artificially and contain carbon and hydrogen atoms. Unsolidified rubbers are very viscous, sticky liquids. The density of rubbers somewhat greater than unity. They can take a large quantity of oxidizer and bind well with it. It is possible to prepare a mixture of one part rubber and ten parts oxidizer without any particular difficulties.

Polyisobutylenes retain their elasticity to a temperature of -70°C. They are stable to the action of water, oxygen, and ozone, and burn well. They are very stable to aging. They mix well with bitumens (rubberized bitumens).

Polyisobutylenes can be molded at a temperature of 180-200°C. They are treated with fillers at lower temperatures. The heat of combustion of rubbers in oxygen is 10,000-11,000 kcal/kg.

The main deficiency of polyisobutylenes is their "cold fluidity," i.e., the ability to change shape ("flow" at room temperature even under the action of gravity).

Polysulfide rubbers (thiocols) $[-(CH_2)_m - S - S -)]_n$ are obtained artificially and, in addition to carbon and hydrogen, contain up to 40% sulfur.

Unsolidified thiocol is a viscous, sticky liquid with a sharp unpleasant odor. The density of thiocol is greater than unity. In solidified form, it takes on a rubber-like state. At a temperature above 80°C, thiocol decomposes gradually; upon cooling below 15°C, the polymer becomes brittle.

Vulcanized (solidified) thiocol is very stable to oxidation, the action of light, atmospheric oxygen, ozone, and also aging.

Thiocol can take a large quantity of mineral filler and does not lose its vulcanizing ability.

Thiocol is vulcanized with the liberation of water, for the binding of which special additives are introduced into thiocol. To increase the strength of vulcanized thiocol, strengthening additives are introduced into it. The heat of combustion of thiocol in oxygen is almost twice as less than that of polyisobutylenes and is equal to 5500-6000 kcal/kg.

Thiocols are widely applied in industry for the manufacture of various vessels and wire insulation. A variety of thiocol is fuel binder C-12.

Fuel binder C-12 is a high-molecular compound similar to thiocol but with a

larger content of carbon and hydrogen and a smaller quantity of sulfur. As compared to ordinary thiocol, C-12 makes it possible to obtain a propellant with a larger value of specific thrust.

Polyurethanes $\left(-\overset{H}{\overset{|}{N}}-\overset{O}{\overset{\|}{C}}-O-\right)_n$ are obtained artificially. They are a class of polymers whose properties can vary within wide limits depending on the selection of the appropriate parent substances. Their density somewhat higher than unity. Their heat of combustion in oxygen is 6500-7000 kcal/kg.

Liquid polyurethanes are employed for manufacturing propellants. They are monomers which solidify after mixing with an oxidizer.

Liquid polyurethanes are very viscous, sticky liquids which take to mineral oxidizers very well. In the solidified state, they are durable materials that can melt at temperatures of 150-200°C. Their elastic properties of polyurethane are retained even at negative temperatures. They are stable to the action of oxygen.

Low-molecular polyurethanes are used for the manufacture of films and fibers. Higher-molecular polyurethanes are used for the manufacture of various instrument components by pressure die casting. Polyurethanes are widely employed for the manufacture of foam plastics, thermal insulation, and building materials.

Polyurethanes are very widely used as fuel binders in hydrid solid propellants.

Bitumens are the final products of petroleum and coal processing. They are a complex mixture of saturated and unsaturated hydrocarbons and carbon and their elemental composition is similar to that of kerosene. The density of bitumens is somewhat great than unity and the heat of combustion in oxygen is the same as for kerosene, i.e., 10,000-11,000 kcal/kg.

Bitumens, just as many other polymers, are thermoplastic and are easily softened at a temperature of 50-70°C; in the softened state, they are easily mixed with oxidizers and can take them up to 90% by weight; at low temperatures, they are brittle vitreous materials; they are chemically stable to the action oxygen, air, and sea water; they are very inexpensive and are widely employed in building technology. In the presence of a good oxidizer (with a large reserve of free oxygen) bitumen can provide a propellant with a very large reserve of energy.

A serious deficiency of bitumens as binders is their low mechanical strength at low (brittleness) and high (fluidity) temperatures; upon mixing with rubbers

(rubberized bitumens) their mechanical properties can be improved.

The process of manufacturing grains from hybrid propellants depends on the nature and properties of the fuel binders and can be set up according to two plans (Fig. 4):

a) for thermoplastic (Fig. 4a) fuel binder (bitumen type);

b) for polymerized and solidified (Fig. 4b) monomers (polyurethane and other rubbers).

Prepared oxidizers (they are pulverized to specified dimensions) and fuel binds are mixed in special mixers 1 that have Z-shaped mixing rods.

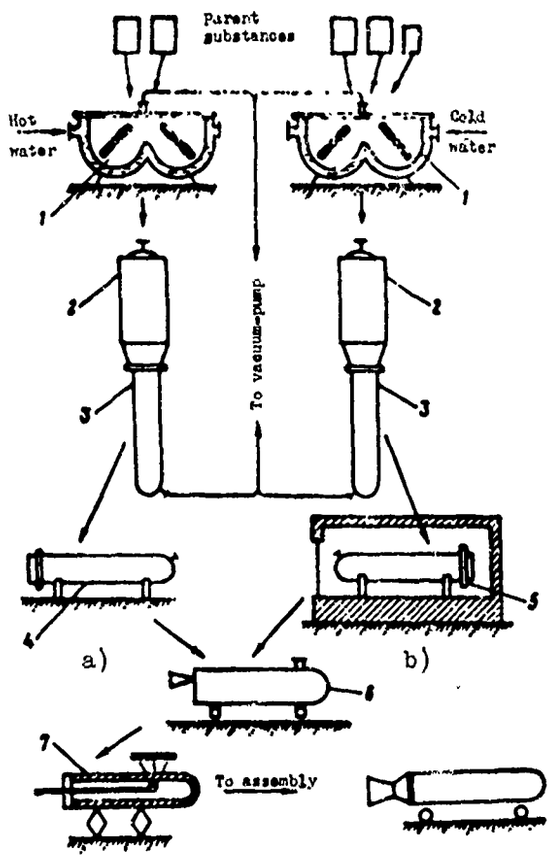



Fig. 4. Fundamental diagram of the production of hybrid propellants: 1 – mixers with Z-shaped mixing rods; 2 – container for transporting propellant mass; 3 – engine chamber; 4 – cooling of engine with molding rods; 5 – propellant solidification directly in engine with heating; 6 – machining; 7 – quality control.

On the diagram in Fig. 4a mixing occurs with the mixer preheated, and in Fig. 4b, cold water can be fed to the mixer to delay the process of polymerization.

After mixing the fuel binder and oxidizer, the propellant mass is transferred to a container 2, from which under air pressure, by means of pumps or under slight pressure of presses, it is poured into molds or directly into the engine 3. If it is transferred directly to the engine, its internal walls are first lined with special putty to which the propellant durably adheres. A central molding rod is inserted into both the mold and the engine to format the internal burning surface of the grain.

On the diagram in Fig. 4a, the grain is solidified by cooling 4, and in Fig. 4b, by heating 5 to a temperature of 60-80°C for 20-70 hours. During that time, the liquid monomer is polymerized into a solid polymer.

The final operations consist in facing 6, trimming the excess propellant mass,

and quality control 7 of grain uniformity with aid of flaw detectors.

Air bubbles are removed from the propellant by creating a vacuum in the mixers and engine chambers during loading.

The operations of mixing and loading are dangerous in the sense of fire and explosion. They are controlled from behind thick partitions and at a distance.

The production of hybrid propellants is considerably simpler than that of nitrocellulose ones and this is one of their advantages.

## § 5. Types of Propellant Charges

Solid rocket propellants in rocket engines are used in the form of charges, i.e., products of a specific geometric shape. Charges can be made from identical elements or one similar in shape, i.e., grains, and are also made in the shape of individual articles of complex configuration.

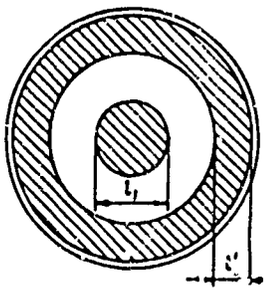



Fig. 5. Thickness of burning sections of a telescopic charge: $l_1$ – thickness of burning section (web) of central cylinder; $l_1'$ – thickness of burning section (web) of external cylinder.

Propellant charges can be freely inserted into the engine chamber or attached to the chamber.

The basic parameters of any charge are the thickness of the burning section (web) and the size of the initial and final burning areas.

The thickness of the burning web depends on the configuration of the charge and is determined by the direction of burning, which occurs in parallel layers in propellants. It determines the time of constant engine performance.

Figure 5 shows the thicknesses of burning sections for a so-called telescopic charge which consists of a tubular grain, inside which a cylindrical rod is inserted.

In the telescopic charge the central cylinder (grain) burns over the entire surface, while the external one burns only over the internal surface.

In a correctly designed charge $2l_1' = l_1$; this ensures simultaneous combustion of the entire charge.

Depending upon what part of the initial surface of the charge starts to burn upon ignition, propellant charges of fuels are subdivided into two types:

a) with unrestricted burning (distributed burning);

b) with a restricted burning surface (restricted burning).

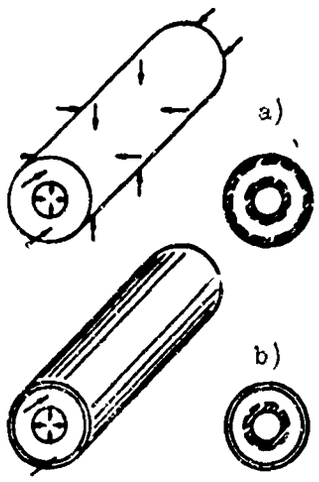



Fig. 6. Burning of a propellant charge: a) burning over the entire surface (distributed burning); b) burning only around the internal perforation and from the end (restricted burning).

Figure 6 shows the burning of a propellant charge in the form of an exposed cylindrical grain (Fig. 6a) which burns from all surfaces, and the same charge, but with a closed external surface (coated also external surface) which burns only around the channel perforation and from the ends (Fig. 6b).

Depending upon how the burning surface changes during engine operation, we distinguish one following charges:

a) with a constant burning surface;

b) with an increasing burning surface (<u>progressiv burning</u>);

c) with a decreasing burning surface (<u>regressive burning</u>);

d) with burning surface according to a specified program.

A change of the burning surface shows up in a change of engine pressure and thrust. A constant burning surface will also correspond to constant engine thrust, while a decreasing burning surface will correspond to decreasing thrust, and conversely. Figure 7 shows cross sections of different charges, and the graphs illustrate the change in engine thrust during the time of charge burning which corresponds to them.

The most popular shapes of charges made from nitrocellulose propellants are charges of type a, a', f, and g. Shapes b, e, and g are characteristic for hybrid propellants. These charge shapes ensure constancy of the burning surface.

The charge with the star perforation is convenient because the engine wall during propellant burning is protected from the influence of hot gases. The deficiencies of this type of charge shape include the propellant particles that remain after combustion of the main portion of the charge which, while burning at low pressures in the chamber, lead to a lowering of specific thrust.

The appearance of designs for powerful and superpowerful solid-propellant engines that are capable of developing a thrust up to thousands of tons and contains charges weighing up to hundreds of tons place a number of complicated problems before the propellant specialists. The fact is that the manufacture of a

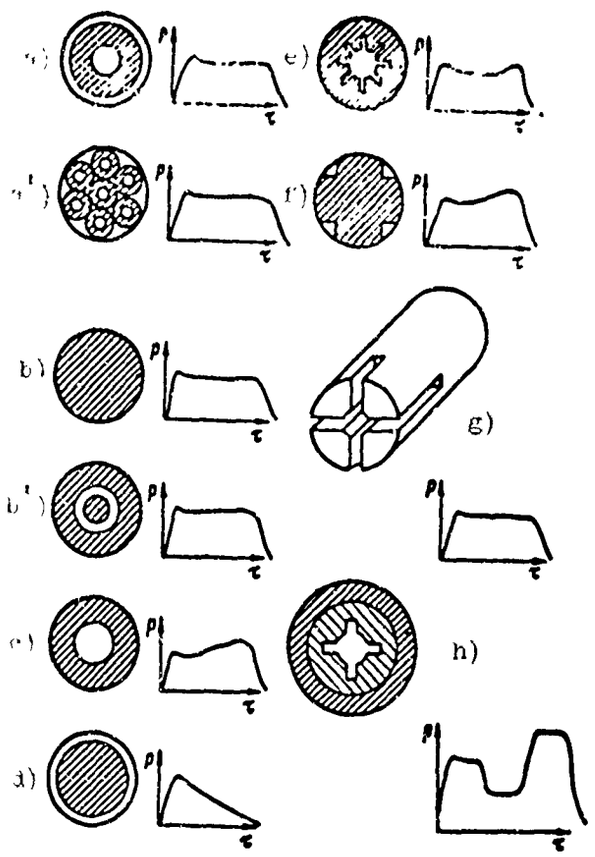



Fig. 7. Types of charges and character of change of engine thrust P in time: a and a') unrestricted burning with constant surface; b) end burning; b') telescopic charge; c) burning with increasing surface; d) burning with decreasing surface; e) internal star-surface burning; f) external cruciform-surface burning; g) slotted-groove charge; h) charge with internal shaped surface and two propellants which differing in burning rate: slow-burning internal and fast-burning external.

large-size charge, its transportation and utilization, involve large difficulties.

In the United States there have appeared projects for the manufacture of charges directly at the launch site by means of loading the raw propellant mass into the engine followed by its solidification. It has also been proposed to make the charge in separate sections and assemble it at the launch site.

It has been suggested that large engines be assembled from separate finished sections, as shown in Fig. 8.

The designations of propellants and charges, and also their names, have not yet been firmly established; therefore, it is possible to encounter the most diverse designations.

If propellants are designated by the letter H (for domestic propellants) and the letters D and E (for U.S. propellants), they indicate a nitrocellulose nitroglycerine propellant.

Next to the first letter there can also be other letters and numbers which designate the nature of the additional or special substances introduced into the basic composition of [illegible] propellant. Numbers and additional letters that follow the designation of the [illegible]ture of the propellant may signify the variety of the given propellant.

In the United States, propellants for boosters are designated by the following symbols according to the [illegible]ure and physical state:

A — bitumen + [illegible]ate;

B — [illegible] or granular powder of the ballistite type;

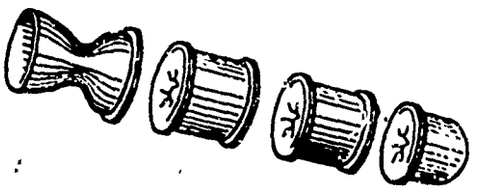


Fig. 8. Design of a large SPRE consisting of various sections.

C – solid hybrid propellant on a picrate or nitrate base;

D – nitrocellulose propellant obtained by pressure;

E – nitrocellulose propellant obtained by extrusion (pressing from a device similar to a meat-grinder);

K – cast solid propellant on a perchlorate base which is different from the bituminous type;

N – nitrates or nitro compounds that differ from cellulose nitrates and nitroglycerin;

P – plastic composition that can be shaped easily by the application of small loads;

S – solid, difficult to shape, propellant.

The general designation of a booster denotes the propellants only by letters. For instance, JATO 15KS-1000 designates:

JATO – the name of the booster;

15 – its operating time in seconds;

1000 – thrust in pounds (453 kg);

KS – solid perchlorate propellant obtained by casting.

With respect to the nature of the oxidizer, propellants in the United States are designated in the following manner:

SPP – potassium perchlorate propellant;

SPN(AN) – ammonium nitrate propellant;

AP – ammonium perchlorate propellant.

Finished charges of solid propellant, as a rule, satisfy the majority of requirements which are presented to them.

At the same time, the nature of all solid propellants to a certain extent make them unstable systems and comparatively sensitive to a change of external conditions.

Reliable and unfailing [SPRE] (РДТТ) operation is possible only under the condition of the careful adherence to the rules of maintenance and storage of charges. The rules for the storage and handling of charges are set up on the basis of the operational properties of the propellants.

## CHAPTER III

## OPERATIONAL PROPERTIES OF PROPELLANTS

The operational properties of propellants are determined by their chemical, physical, and mechanical properties.

Solid propellants are not used immediately for launching rockets, and are frequently stored for a long time in warehouses and in troop areas.

During storage, propellants are subject to cooling (in the winter) as well as heating (especially in hot areas and in enclosed places); in addition, they can heat up intensely during the day and cool off at night, be subject to the action of moisture, high temperature, and sunlight. All this affects the physical and chemical properties of the propellants and can alter them to some extent.

It is necessary also to know how to handle propellants during engine assembly and disassembly, overloads, and transporation, i.e., in the process of their utilization.

### § 6. Physical Properties

Appearance. The appearance of a solid propellant charge resembles a dense article of chiefly dark colors.

The color of tom . a solid propellant is determined by the nature of its parent substances and additives.

Type H nitrocellulose propellants usually have a dark-brown color and their appearance is similar to a corniculate substance. If carbon black is added to this type of propellant, it takes on a black color.

The color of hy . lid propellants depends on the fuel binder: bituminous — black; polyurethane — black-gray.

In distinction from nitrocellulose propellants, for instance, polyurethane and thiocol hybrid propellants are similar to strong, vulcanized rubber, but are less elastic and more brittle.

It should be borne in mind that it is difficult to evaluate solid pr on the basis of appearance alone. However, external inspection of charges is necessary since it permits the detection of possible rejects and surface defects of the charge.

The density of propellants is a critical characteristic and always is checked during propellant production.

Low propellant density indicates that there are pores and gaps in the propellant, which are impermissible for high-quality propellant charges. Low density, also affects the burning rate of the propellant: with the decrease of density, it increases, and conversely.

The density of solid propellants is determined by the density of their components and the production method. It has following value for high-quality propellants:

| | |
|---|---|
| For regular nitrocellulose propellants without additives . | 1.58-1.6 g/cm$^3$ |
| For nitrocellulose propellants with mineral-oxidizer and metal additives . . . . . | 1.6-1.7 g/cm$^3$ |
| For hybrid propellants based on various oxidizers, including propellants which contain aluminum . . . . . | 1.7-1.9 g/cm$^3$ |

The density of hybrid propellants is somewhat more than that of nitrocellulose ones, which is one of their advantages, since the greater the density the higher the effectiveness of the propellants.

The thermo-physical characteristics of propellants, i.e., the coefficients of linear $\alpha$ and volume $\beta$ thermal expansion – give an idea of what changes in length and volume of the propellant charge can occur when its temperature is changed.

The conditions of attaching charges to engines, the size of the clearances, and the requirements for the strength characteristics of charges that are attached to the engine chamber depend on the change of the geometric dimensions of the charges with the change of temperature.

In the temperature range from -40 to +40°C, the thermo-physical characteristics of propellants have the following values:

– for nitrocellulose propellants, $\alpha = (1.2\text{-}2.0)\cdot 10^{-4}$ and $\beta = 0.3\cdot 10^{-3}$ 1/°K;

— for hybrid propellants, $\alpha = (0.5\text{-}1.5)\cdot 10^{-4}$ and $\beta = (0.3\text{-}0.4)\cdot 10^{-3}$ $1/^{\circ}K$.

The values of $\alpha$ and $\beta$ are close for various propellants, but they are 7-10 times greater than those of steel. The difference in the values of $\alpha$ and $\beta$ for propellants and for steel complicates the conditions of attaching a propellant charge directly to the steel wall of an engine chamber.

The thermo-physical characteristics also include the specific heat $c_p$, the heat-conductivity factor $\lambda$, and thermal diffusivity a.

These quantities characterize the ability of propellants to perceive heat under the influence of temperature ($c_p$) and conduct (diffuse) it throughout the thickness of the propellant ($\lambda$ and a). They are used in theoretical calculations of thermal stresses of charges that are attach to engine chambers and burning rates of propellants in engines. The numerical values of the thermo-physical characteristics are given in Table 5.

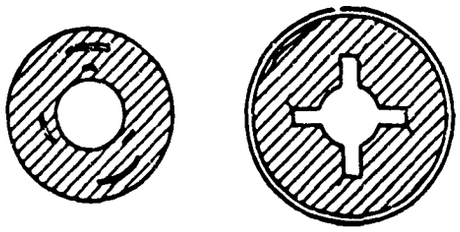
Table 5. Mechanical and Thermo-Physical Properties of Solid Rocket Propellants and Steel

| Characteristic | Designation | Dimension | Nitrocellulose propellants | Hybrid propellants | Steel |
|---|---|---|---|---|---|
| Tensile strength | $\sigma_p$ | $kg/mm^2$ | 1 | 0.09 | 48-60 |
| Coefficient of linear thermal expansion | $\alpha$ | $\frac{1}{deg}$ | $(1.2\text{-}2.0)\ 10^{-4}$ | $(0.5\text{-}1.5)\ 10^{-4}$ | |
| Specific heat | $c_p$ | $\frac{kcal}{kg\cdot deg}$ | 0.35 | 0.30 | 0.11 |
| Heat-conducitivity | $\lambda$ | $\frac{kcal}{cm\cdot sec\cdot deg}$ | $(0.50\text{-}0.53)\ 10^{-6}$ | $(0.7\text{-}0.75)\ 10^{-6}$ | $1.1\cdot 10^{-4}$ |
| Thermal diffusivity | $\alpha$ | $\frac{cm^3}{sec}$ | $0.215\cdot 10^{-4}$ | $0.30\cdot 10^{-4}$ | $0.31\cdot 10^{-2}$ |
| Specific gravity | $\gamma$ | $\frac{g}{cm^3}$ | 1.58-1.7 | 1.7-1.9 | 7.8 |

A change in the physical properties of propellants during storage occurs under the influence of a change in external temperature, moisture, and time.

The ability of propellants to resist to changes of physical properties in time is called physical stability.

When there are considerable changes in temperature, physical instability of solid rocket propellants can be noted as a disturbance in continuity of the charges and the appearance of cracks (Fig. 9). This form of physical instability to a large degree is characteristic for large, thick-web charges and charges that are attached



a) b)

Fig. 9. Cracks in propellant charges. a) longitudinal cracks; b) crack in the most stressed places and breaking away from the wall of a charge attached to a chamber.

to the engine chamber. In the last case the appearance of cracks is caused by the appearance of temperature stresses due to the various coefficients of linear expansion of the propellant and the material of the wall.

Charges in which cracks are formed or discontinuities appear are unconditionally unsuitable for use and must be replaced. The formation of cracks can be established by a special flaw detector.

Another form of physical instability of solid propellants is the tendency of individual component parts of the propellant to be separated on the surface of the charges and to volatilize.

Volatilization of propellant components strongly increases at high temperatures. Nitroglycerin from nitrocellulose propellants is very strongly volatilized. Thus, at 50°C after 24 hours of storage, about 0.1% nitroglycerin is volatilized from the propellant, and up to 1.5% after 300 hours.

Volatilization of the component parts of a solid propellant is an extremely undesirable phenomenon since the propellant composition then changes, the continuity of the charges can be disturbed, and the energy characteristics can be lowered.

Hybrid propellants do not have volatile components and therefore they are not dangerous at temperatures up to 100°C.

Physical instability of hybrid propellants can appear in the form of continuing polymerization of monomers, and then aging of polymers in the process of storage.

Polymer aging appears as a disturbance in the continuity, strength, and the structure of the charge.

The influence of moisture is related to the hygroscopicity of propellants, i.e., to property of absorbing and retaining a certain quantity of moisture.

The hygroscopicity of nitrocellulose propellants is relatively low. Certain hybrid propellants are more hygroscopic. Intense moistening of hybrid propellants is impermissible since it can lead to the partial dissolution of the oxidizer and thereby change the composition of the propellant.

Charges are protected from the influence of moisture by placing them in a

watertight seal and by hermetically sealing the engines. The airtightness of the seal and engines should not be disturbed; but if it is disturbed, it is necessary to correct the damage.

Physical stability, volatility of components, and hygroscopicity of propellants are evaluated according to the results of tests conducted on them in laboratories and on the basis of the results of long-term storage.

Cracks in charges are determined visually or with special instruments. The volatility of components is estimated by the decrease in weight of a propellant sample while it is at a high temperature (50, 75, and 95°C). Hygroscopicity is determined according to the increase in weight of a propellant sample while it is in an atmosphere with high humidity, and sometimes simultaneously at a high temperature.

The tests are accelerated by creating more rigid conditions than those in which the propellants will be stored in warehouses and troop areas.

## § 7. Chemical Properties

The chemical properties of propellants imply their interaction with the material of the engine walls, toxic properties (toxicity), and the ability of propellants to retain the invariability of their chemical composition in the process of prolonged storage.

The ability of propellants to keep their chemical composition constant in the process of prolonged storage is called their chemical stability. Chemical stability, as a rule, determines their service life.

As for their agressiveness towards structural materials and their toxic influence on the human organism, solid propellants are practically safe. When stored under normal conditions, they do not give off aggressive substances and do not interact with the materials of the engine wall.

Nitrocellulose propellants, due to the volatility of nitroglycerin, can cause brief, not very severe, headaches, which occur when handling propellants constantly. This influence of nitroglycerin on the human organism is not dangerous.

Chemical stability of propellants is related to those slow spontaneous processes of decomposition which occur inside the propellant and are very expressed for nitrocellulose propellants.

Cellulose nitrates and nitroglycerin, as unstable chemical compounds in the process of storage and under the influence of high temperatures and a small

quantity of moisture, are able to disintegrate comparatively slowly with the detachment of the $ONO_2$ group. In turn, the $ONO_2$ group, which is an active oxidizer, enters chemical reactions with the nitrocellulose radicals with the liberation of water, low nitrogen oxides, and other intermediate products.

The nitrogen acids and oxides that are formed are able to accelerate the process and thereby cause self-accelerated decomposition of the propellants. Not only are reaction products released during decomposition, but also heat. If decomposition is not retarded, the propellant can self-ignite.

The process of chemical decomposition of propellants is retarded by chemical stabilizers. Upon entering chemical compounds with nitrogen oxides, they restrict the process of decomposition and do not let it develop by its own acceleration. In this case, naturally, the chemical stabilizer is expended; therefore, one of methods of evaluating chemical stability is to determine the remaining amount of the stabilizer.

Decomposition of nitrocellulose propellants in the presence of a chemical stabilizer occurs so slowly that the serviceability of the propellants is retained for 15-20 years.

Chemical stability of nitrocellulose propellants is checked regularly in special chemical laboratories.

Inasmuch as the process of propellant decomposition under normal conditions occurs very slowly, control samples of propellants are tested at high temperatures for a long period of time. Stability is checked, for instance, by the reddening of blue litmus paper (it turns red due to the influence of acids on it).

Chemical stability is estimated according to the total number of test hours in ten days under the condition that every day the samples are heat for no longer than seven hours. Each propellant has its own norms of stability hours.

As a rule, the more nitroglycerin in a nitrocellulose propellant, the greater the reserve of energy in it, and the lower its chemical stability. This is an essential deficiency of propellants with a large content of nitroglycerin and it limits their use and manufacture.

The chemical stability of hybrid propellants is different.

Polymer compounds of hybrid propellants can interact with atmospheric oxygen and be destroyed (age). The various intermediate reaction products can react simultaneously with the oxidizer and thereby lower the chemical stability of the

propellant. The chemical stability of hybrid propellants has not yet been studied sufficiently.

Despite the fact that solid rocket propellants are chemically unstable systems, under normal conditions of storage they are not destroyed for a long time and do not cause difficulties in utilization.

## § 8. Mechanical Properties

Solid propellant charges are subjected to the influence of various kinds of overloads during the operation and launching of rockets. These overloads can be from several units to hundreds of terrestrial accelerations and cause stresses the propellents, which they are not always able to sustain.

Overloads during rocket launching appear due to the fact that the engine thrust is greater than the rocket's weight. Under the action of thrust, a rocket obtains an acceleration a that is many times greater than the acceleration of terrestrial gravity g and directed in an opposite direction. As a result, the rocket on the whole and the instruments and propellant on board become "heavier," depending on how much greater the rocket's acceleration is than acceleration due to terrestrial gravity g. The relationship a/g also will be an overload.

During the transportation of assembled rockets and containers with finished engines, the overloads can reach 10 units.

For charges that are attached to the engine chamber, there are additional thermal stresses which are caused by the difference in values of the temperature expansion coefficients of the propellant and the material of the engine chamber.

One of the conditions of high reliability of the action of [SPRE] (РДТТ) is the solid propellant charge keeping its given shape and continuity, and the absence of breakdowns during the time of its complete combustion in the engine. Disturbance of the geometric shape of a charge can lead to the fact that the bypass sections for the combustion products will overlap (Fig. 10). A consequence of this, as a rule, is unstable engine operation, which frequently causes its destruction.

Destruction of a charge of solid propellant in the beginning and at the end of burning also leads to a disturbance in normal engine operation and even can cause it to malfunction.

In turbojet missiles, whose speed in flight reaches 20,000 rpm, solid propellant charges can be destroyed under the action of centrifugal forces at the time when the larger part of the thickness of the burning web is burning.

Fig. 10. Distrubance of geometric shape of charge during overloads.

In order to eliminate abnormal engine operation due to the indicated causes, solid propellants must possess sufficiently high mechanical properties.

The mechanical properties of solid rocket propellants are estimated by a number of characteristics. The most important ones are: tensile strength, compressive strength, impact (dynamic) strength, and the increase in length of a propellant sample as a result of extension.

Compressive and tensile strength are determined for static (nonchanging) loads and are designated by $\sigma_b$ and $\sigma_p$, respectively. The strength of solid propellants is 20-100 times less than that of ordinary steel and durable aluminum alloys.

If, for instance, $\sigma_p$ = 48-60 kg/mm$^2$ for ordinary steel and aluminum alloys (duralumin), $\sigma_p \approx 1$ kg/mm$^2$ for nitrocellulose propellants, and $\sigma_p$ = 0.09 kg/mm$^2$ for polybutadiene hybrid propellants.

Impact (dynamic) strength (e.g., flexural strength) is estimated by the amount of work that occurs per square centimeter of the destroyed section. It is called impact toughness $a_k$. For the best propellants, this magnitude is no more than 15-20 kg-cm/cm$^2$.

Unit elongation characterizes the ability of propellants to be deformed by the beginning of destruction. Solid propellants possess two to five times greater unit elongation than metals. Most propellants have an elongation to 40% and, for instance, to 60% for a polybutadiene propellants.

The mechanical properties of propellants depend on the temperature and rate of application of the load. This is explained by the fact that the structural base of propellants is composed of polymers. Most polymer materials change their mechanical properties when the temperature changes.

With a decrease of temperature to -50°C, brittleness increases ($a_k$ decreases) four or five times, and elongation decreases to 20% for nitrocellulose propellants. At the same time, compressive and tensile strength increase four or five times.

Nitrocellulose, bituminous, and other thermoplastic propellants are softened at high temperatures and can, in general, lose any strength.

For nitrocellulose propellants with an increase of temperature, a lowering of $\sigma_b$ and $\sigma_p$ by four or five times, an increase of unit elongation to 50%, and

a two-fold increase of impact toughness are characteristic.

The decrease in the various propellant characteristics with the change of temperature makes it necessary to limit the positive and negative temperatures at which charges can be normally used. For instance, the upper temperature of storage for fuel M-8 is +50°C, +65°C for ALT-161, and +65°C for AP.

## § 9. Sensitivity of Propellants to Various Forms of Initial Impulse

Solid rocket propellants are explosives that are capable of chemical transformation either in the form of burning or in the form of an explosion. Under combat conditions, propellant burning is accomplished.

Under normal conditions of storage and utilization of propellants, the process of burning cannot start by itself since it requires an external initial impulse. During the production, storage, and utilization of propellants, the external initial impulse. During the production, storage, and utilization of propellants, the external initial impulse can be expressed in the form of a shock, friction, or the influence of heat.

Independently of the form of the initial impulse, its magnitude always can be equal to the minimum energy which is necessary in order to cause intense transformation of the propellant into combustion products. The magnitude of this energy, expressed in various units, also will determine the sensitivity of propellants to various forms of initial impulse.

The sensitivity of propellants to an external initial impulse determines the degree of their safety during production and utilization, and the reliability of their use in engine. The sensitivity of propellants to shocks usually is estimated by the frequency of explosions (in percents) under specific test conditions. For instance, a 10 kg weight is dropped onto a propellant mass from a height of 25 cm.

Impact sensitivity depends on many factors: character, composition, and others. For nitrocellulose propellants, it increases with the increase of the nitroglycerin content, the presence of solid impurities, and at high and low temperatures. The impact sensitivity of certain solid propellants is a few times greater than that of an [illegible]tive such as trotyl (tolite). High-energy propellants are especially sensitive to impact. The handling of propellant charges and assembled engines should be orderly, they should not be dropped, and sharp impacts should be avoided.

Propellants also are sensitive to friction. Strong friction can be occur during assembly and disassembly of charges in an engine during the application of large forces. Propellants ignite and burn without explosion due to friction.

Of the destructive factors of an atomic explosion, the shock wave and the flash are dangerous to solid propellant charges; they are capable of igniting open propellant charges at comparatively long distances from the epicenter of the explosion.

The sensitivity of propellants to a thermal impulse is estiamted by the temperature of self-ignition. The temperature of self-ignition of propellants depends on the nature of the propellant, the rate of heating, and the time of holding the propellant at a given temperature. When the rate of heating is 30°C per minute, the temperature of self-ignition for nitrocellulose propellants is equal to 200-230°C, and about 300-340°C for hybrid propellants. Under ordinary conditions of propellant utilization, such high temperatures do not occur. However, a temperature close to 200°C can appear during long-term flights of rocket-type flight vehicles. In this case, propellants that are utilized either in the form of primary charges or in auxiliary devices can be heated to high temperatures. Propellants with high thermal resistance are employed in such vehicles.

Solid rocket propellants, with regard to their physical and chemical properties, are comparatively stable to the vaious external influence by the chamical energy sources of rocket motion. Their handling is comparatively simple and does not require any special measures or particular conditions. However, only their proper utilization and timely quality control can ensure their reliable and effective use in engines.

## CHAPTER IV

## BURNING OF SOLID ROCKET PROPELLANTS

### § 10. Ignition of Propellants

The chemical energy which a rocket propellant possesses is converted into thermal energy when it burns. The perfection of the transformation of chemical energy into the thermal energy of the combustion products depends on the organization of the burning.

Burning of solid propellants begins with their ignition by a special igniter (Fig. 11). The role of the igniter consists in heating the surface layers of the propellant to a temperature at which there begins an intense chemical transformation of the propellant, and in simultaneously creating the pressure that is necessary for normal burning of the charge. Igniters frequently employ black powder or a metal-oxidizer mixture (e.g., aluminum or magnesium and potassium perchlorate). The solid metal oxides that are formed as a result of burning promote the best propellant ignition. The igniter usually is placed in the bottom portion of the engine and is actuated by an electric squib.

In end-burning engines, the igniter is mounted at the nozzle.

The first black powder was a mechanical mixture of finely pulverized potassium nitrate $KNO_3$, carbon, and sulfur, and was used in this form for fireworks, igniting compositions, and primitive rockets. Then they learned how to pack it, granulate it, and make articles from it, including the rocket charges which were still employed in the Second World War.

Contemporary black powder consists of 75% potassium nitrate, which serves as the oxidizer, 15% charcoal, and 10% sulfur. The last two components are fuels, while the sulfur is also a binder which ensures the necessary density and strength

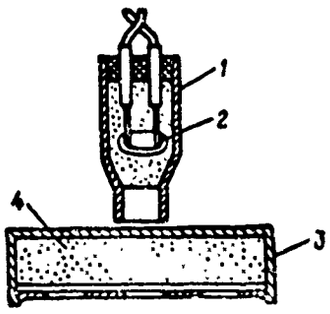



Fig. 11. Igniter: 1 — electric squib; 2 — incandescence bridge with inflammable composition; 3 — aluminum or plastic igniter case; 4 — black powder.

of the black powder.

Black powder is manufactured either in the form of grains of various dimensions (ordinary granular), the form of small articles shaped like pri[illegible] or several channels and cubes (geometric); it is dark-gray and its specific gravity is equal to 1.50-1.65 g/cm$^3$.

Black powder is very sensitive to the flame and spark which appears upon impact with metallic objects and therefore requires especially orderly handling.

Granular black powder does not [illegible] uniformly; it burns at a very high speed at high pressures. Black powder that is pressed to a specific gravity of 1.8 g/cm$^3$, even at large pressures, burns uniformly in parallel layers.

Up to 47% solid and 53% gaseous products are released when black powder burns. 585 kcal of heat, 280 liter of gases, and 680 g of solids are released (per kg of powder). Its burning temperature is on the order of 2000°C.

Due to the formation of a large quantity of heated solid particles, black powder has a good igniting ability and ensures reliable actuation of the main charges of rockets and cannon-typed artillery.

The weight of black powder for an igniter is selected experimentally in order to ensure reliable ignition of the entire surface of the charge, but not to cause its destruction.

The response time of the entire igniter is very short measured in hundredths of a second. In order to obtain a faster growth of pressure, the nozzle is closed by plug (cover) which is ejected or destroyed upon reaching a specified pressure.

The ignition of a charge occurs in the following way. Current is fed from the ground power source to the bridge of the electric squib. The inflammable composition inflames and lights the black powder of the electric squib. The combustion products that are formed pierce the cover of the igniter and ingite the black powder which is located there. The hot gases and solid particles of the burned-out igniter ignite the main charge of solid propellant.

The solid propellant charge starts to burn along the surface in parallel layers, releasing a large quantity of gases which, in passing through the nozzle, also create engine thrust. In distinction from ordinary industrial furnaces, the burning

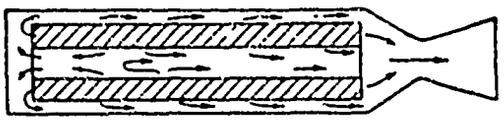


Fig. 12. Motion of gas flows during burning of a charge in an engine.

of a solid propellant in an engine chamber occurs under very tense conditions.

A charge of solid propellant that is burning in an engine chamber is surrounded on all sides by gases which are compressed to a high pressure and heated to 2500-3000°C. The formed gases move along the charge at high speeds (100-200 m/sec) to the nozzle (Fig. 12), frequently forming counter flows. These gas flows render a strong influence on propellant burning, which leads to abnormal phenomena in some instances.

The process of propellant burning in an engine is estimated according to the change of pressure during the time of charge burning. To do this, when the charges and engines are being adjusted and tested, an electric pressure pickup is placed in the combustion chamber and its readings are recorded on moving photographic paper or film in the form of a pressure-time curve.

The normal form of this curve is shown in Fig. 13. The section 0-a on the curve reflects the response time of the igniter; section a-b indicates the burning time of the main charge, and section b-c characterizes the escape time of the combustion products of burning after burnout of the charge.

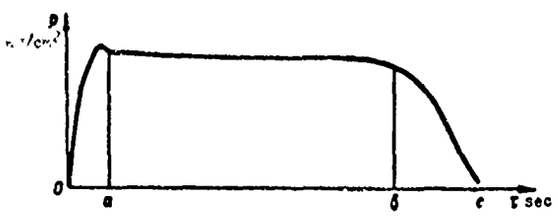



Fig. 13. Change of pressure in engine during propellant burning.

Propellant burning is a very complicated physical and chemical process of the rapid transformation of a solid, dense substance into gases.

The rational use of propellants and control of the process which occurs in the engine requires a knowledge of the essence of the burning process.

## § 11. The Burning Mechanism

The burning mechanism of nitrocellulose propellants has been studied most fully and in most detail.

During burning, the solid propellant is converted into gaseous combustion products due to the reactions of thermal disintegration and subsequent chemical reactions.

The heat released as a result of burning, in turn, influences the still unburned propellant and thereby automatically supports the reaction of thermal

disintegration and then the chemical reactions. The burning of solid propellants occurs both in solid phase (on the surface) and in gas phase (in the volume).

The burning temperature always increases, beginning with the initial propellant temperature $T_0$ to the highest possible temperature under the given conditions of burning $T_{max}$.

As a result of experimental observations of the burning process, it was possible to establish that the whole process of burning is multistage and fully consecutive. In accordance with this, the entire burning region is conveniently separated into a series of zones (Fig. 14).

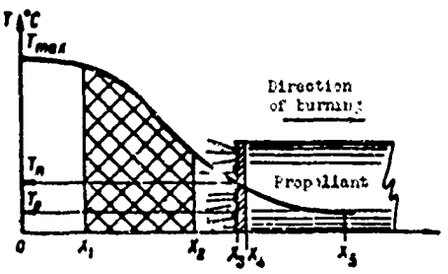



Fig. 14. Diagram of burning zones for nitrocellulose propellants.

The burning zones which conditionally divided into sections, are characterized by the following processes.

Zone $x_5$-$x_4$ is the heating zone. Sometimes it is called the zone under the burning surface. In this zone the propellant does not yet burn, but only is heated from the initial temperature $T_0$ to the temperature of the beginning of the intense chemical reactions which occurr on the burning surface.

The width of this zone (the heating depth) depends on the temperature of the surface, density, heat capacity, and thermal conduction of the propellant, and also on the burning rate. The greater the thermal condition of the propellant and the surface temperature, the greater the depth of heating, and the greater the burning rate of the propellant the smaller the depth of heating. The value of this zone in the burning mechanism is essential since propellant burning under unfavorable conditions will depend on how much heat was stored in the heating zone.

Zone $x_4$-$x_3$ is the zone of thermal disintegration of cellulose nitrates and nitroglycerin and intense chemical surface reactions. Due to heat withdrawal from the flame zone, the propellant surface melts, and the cellulose nitrates start to thermally disintegrate approximately at a temperature of 190-200°C into nitrogen oxides and intermediate substances.

Nitroglycerin decomposes analogously.

The process of decomposition of cellulose nitrates and nitroglycerin occurs with the liberation of heat, which can lead to partial thermal disintegration of the other organic substances contained in the propellant.

The free nitrogen oxides that have been released partially enter chemical reactions with the intermediate products of thermal disintegration. More heat is then released, and the surface temperature rises to 300-350°C.

The external appearance of the burning surface resembles a fast-changing, foaming with gas bubbles, partially melted and luminescent region of propellant burning.

The value of this zone in the overall burning process is very great since the sensitivity of the burning rate of propellants to the change of pressure and initial temperature depends on the specific gravity of the chemical reactions of this zone in the whole burning process and the quantity of heat that is liberated. The more intensely the reactions occur in this zone, the less sensitive the propellant is to a change of pressure and initial temperature, and its advantages are even greater.

Zone $x_3$-$x_2$, the mixed or "boiling" zone, is directly adjacent to the burning surface, and externally resembles paths of flying incandescent solid particles mixed with gas flows. In this zone there occur intense chemical reactions between gaseous nitrogen oxide and the solid intermediate products of the disintegration of cellulose nitrates and other parent substances, heat is also liberated, and temperature increases.

Zone $x_2$-$x_1$, the dark or induction zone, does not glow at low pressures (15-20 kg/cm$^2$) in an atmosphere of inert gas and is similar to the lower nonluminous section of a candle flame.

In this zone there occurs accumulation of the active intermediate combustion products (NO, CO, $H_2$, and others) which then energetically react and form final products. The presence of the dark zone is explained by the fact that the reactions of nitrogen oxide NO with the intermediate products are comparatively slow and require a definite time, i.e., induction period.

The induction period is reduced with the increase of pressure and initial propellant temperature, and conversely.

At certain pressures these reactions, in general, cannot appear, and then in the reaction products there will be many nitrogen oxides NO. The value of this zone in the overall burning process consists in the fact that its width and composition of combustion products determine the fullness (completeness) or incompleteness of propellant burning at a given pressure.

If the external conditions are favorable, the intense chemical reactions of the induction zone lead to final combustion products and the formation of a flame zone $x_1$-0.

The composition of the final reaction products is established in accord with the laws of chemical thermodynamics and with the final burning temperature $T_{max}$ and pressure.

It should be borne in mind that the zonal consideration of the burning process has a somewhat conditional character since in the actual process the zones are not always clearly discernible, and the chemical reactions in them can occur in series as well as in parallel. The detailed mechanism of the burning of solid propellants at present is also an object of study.

The burning mechanism of hybrid propellants has been studied in less detail than the burning mechanism of nitrocellulose propellants. In principle, it could be represented by the same diagram as that for nitrocellulose propellants.

However, the burning mechanism of hybrid propellants has a number of peculiarities that are determined by the composition and nature of the substances in them.

The burning of hybrid propellants, just as nitrocellulose ones, begins in the solid phase with the thermal disintegration of oxidizers and fuel binders. The burning process is completed in gas phases due to the intense chemical reactions between the gaseous products of thermal disintegration of the components.

In distinction from nitrocellulose propellants, higher temperatures of the burning surface (to 500-600°C) and maximum burning temperatures closer to the burning surface are most characteristics for the burning of hybrid propellants.

The process of burning solid rocket propellants is very sensitive to external influences: e.g., pressure and initial propellant temperature.

With the increase of pressure and temperature, zones $x_1$-$x_3$ are sharply reduced, and the flame zone approaches right to the burning surface. The heat supply to the burning surface increases, the burning rate increases, and the heating zone is narrowed.

When pressure and temperature is lowered, conversely, the zones are expanded, and at a certain critical pressure the flame zone disappears and the burning becomes smoldering; the temperature in the zones does not rise above the temperature of the dark zone. In the combustion products these appear many nitrogen oxides,

energy is not completely released and, as they say, there occurs incomplete burning.

In order to avoid these unfavorable conditions, burning catalysts are employed that accelerate the chemical reactions in the solid and gas phases, which promote more complete burning and in the final result improve the propellant characteristics.

## § 12. Propellant Burning Rate

A quantitative appraisal of the process of propellant burning is made by using either the rate of movement of the burning front or the mass of propellant burning per unit time from a unit of the surface.

In first case the burning rate is said to be linear and is expressed in mm/sec or cm/sec; in the second case it is called the mass burning rate and expressed in $g/cm^2$ sec. In practice, the linear burning rate is used more frequently.

The burning rate is a very important operating characteristic of a propellant since it is used to estimate the quantity of gases which are formed during propellant burning per unit time from the surface of a charge. It is one of the basic parameters when designing propellant charges.

The burning rate of a propellant depends on the pressure in the engine, the initial temperature of the propellant, its density, energy characteristics, the nature of the component parts of the propellant, the size of the oxidizer particles (in hybrid propellants) and the burning catalysts.

For practical purposes, it is always necessary to first of all know the relationship of the burning rate to pressure.

The relationship of the burning rate of solid propellants to pressure is determined experimentally and expressed by formulas which have been called the laws of the burning rate. The laws of the burning rate for many propellants have the form

$$u = a + bp^{\nu},$$

where u is the burning rate in mm/sec or cm/sec; p is the pressure at which the propellant burns in $kg/cm^2$; a, b, and $\nu$ as experimental coefficients that characterize the nature of the propellant, the presence of catalysts, the dimensions of the oxidizer particles, and other properties of the propellant.

The law of the burning rate is found experimentally for each propellant in the desired pressure range.

According to the law of the burning rate, it is possible to calculate burning

rate for any pressure.

Table 6 gives the values of burning rates and the laws of burning rates for typical propellants, and they are depicted graphically in Fig. 15.

Table 6. Burning Rate of Solid Rocket Propellants

| Pressure range | Law of burning rate | Burning rate in mm/sec for p in kg/cm² | | |
|---|---|---|---|---|
| | | 30 | 50 | 100 |
| Nitrocellulose propellants, type H, T-6 and HM-2 | | | | |
| 30-100 | $u = 0.7\ p^{0.6}$ | 4 | 6.4 | 9 |
| 100-200 | $u = 4.0 + 0.05\ p$ | | | |
| Nitrocellulose propellants, type M-8 and T-5 | | | | |
| 30-120 | $u = 0.885\ p^{0.69}$ | 12.0 | 14.0 | 21.2 |
| Hybrid propellants with $NH_4ClO_4$ type AP | | | | |
| 14-120 | $u = 2.2\ p^{0.4}$ | 9.6 | 10.5 | 12.0 |
| Hybrid propellants with $KClO_4$ type ALT-161 | | | | |
| 70-140 | $u = 1.24\ p^{0.7}$ | 16.4 | 19.1 | 31 |
| Hybrid propellants with $NH_4NO_3$ type AN | | | | |
| | $u = 0.4\ p^{0.5}$ | 0.6 | 1.0 | 3.0 |

When evaluating propellants with respect to burning rate, not only is the value of the burning rate at the given pressure taken into account, but also its dependence on the change of pressure. In many cases the propellant will be better suited for use in an engine, the less sensitive the burning rate is to the change of pressure, i.e., the smaller the coefficients $\nu$ and b.

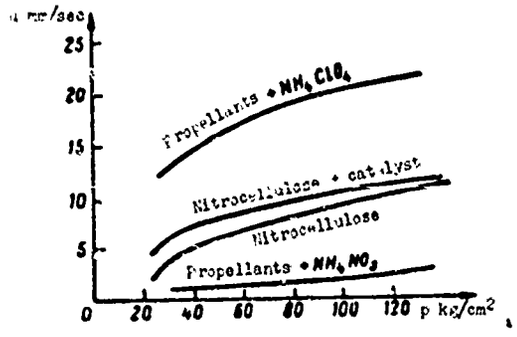



Fig. 15. Dependence of burning rate on pressure for various propellants.

## § 13. Temperature Coefficient of Burning Rate

Besides the absolute value of the burning rate, another no less important characteristic of solid propellants is the dependence of their burning rates on the initial temperature of the charge. This dependence is expressed by the temperature coefficient (gradient) of the burning rate $\Delta u/\Delta t$, which may be calculated by the formula

$$\frac{\Delta u}{\Delta t} = \frac{u_{t_1} - u_{t_2}}{t_1 - t_2},$$

where $\Delta u$ is the burning rate increment, which depends upon the temperature increment; $\Delta t$ is the temperature increment; $u_{t_1}$ is the burning rate at temperature $t_1$; $u_{t_2}$ is the burning rate at temperature $t_2$.

This is shown graphically in Fig. 16.

The temperature gradient of the burning rate shows how the burning rate changes when the temperature change by 1°C.

The burning rate of certain propellants with a change of temperature, e.g., from -40 to +40°C, can increase from one and a half to two times.

The strength of the walls of a rocket engine and the flow area of a nozzle usually are calculated for a specific pressure and quantity of formed gases. The latter depends on the burning rate.

If the engine is calculated for minimum pressure during propellant burning at low temperatures, an increase in temperature results in an increase of the burning rate, an increase in pressure, and the engine can be destroyed.

Conversely, if the engine is calculated for maximum pressure, the gas entry will be small and pressure will drop at low temperatures due to the small burning rate. Thrust then decreases and the engine's service life increases.

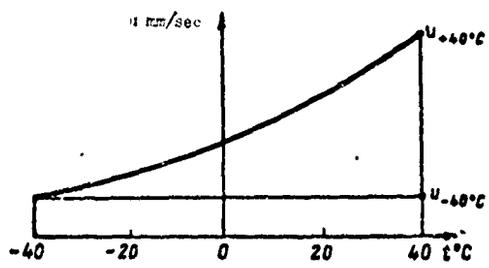



Fig. 16. Dependence of burning rate on initial temperature of charge.

As an example, Table 7 shows the change in thrust and operating time depending upon temperature for the booster JATO 15 KS-1000. This engine is calculated for a thrust of 450 kg and a temperature interval of use from -54 to +60°C.

As can be seen, all engine parameters change sharply during temperature variations.

In order to exclude abnormal engine operation, propellants are selected with a small temperature dependence of the burning rate and the temperature interval of its use is assigned.

Table 7. Change in Engine Performance of JATO 15 KS-1000 Depending Upon Initial Temperature

| [illegible] | Ignition delay, sec | Thrust, kg | Service life, sec |
|---|---|---|---|
| -54 | 0.21 | 370 | 18 |
| +15 | 0.11 | 480 | 14 |
| +60 | 0.09 | 600 | 11.5 |

Table 8. Temperature Gradients of Burning Rate and Temperature Intervals of Propellant Use

| Propellant | Temperature gradient of burning rate, mm/sec deg | Temperature interval of use, °C |
|---|---|---|
| Ordinary nitrocellulose . . . . . | 0.015-0.020 | -15 - |
| Nitrocellulose with high-energy characteristics, type M-8 . . . . . | 0.039-0.040 | -30 - +60 |
| Hybrid, type ALT-161 . . . . . | 0.057-0.060 | -55 - +75 |
| Hybrid, ammonium perchlorate base, type AP . . . . . | 0.03-0.02 | -55 - +75 |

The temperature gradients of the burning rate and temperature intervals of use for typical solid rocket propellants are shown in Table 8.

In cases when it is not possible to select the necessary propellant with respect to $\Delta u/\Delta t$, the flow areas of the nozzles are adjusted or the engines are specially heated. In the first case, at low temperatures, the size of the critical area of the nozzle is partially overlapped or several nozzles are completely closed off if the engine has more than one nozzle. In the second case, as was done for the American rocket "Honest John," and electric blanket is placed on the rocket and the charge temperature is sustained at the necessary level in the winter.

## § 14. Erosional Burning and Critical Pressure of Complete Burning

The above-considered dependences for the burning rate of solid rocket propellants are not always observed under the conditions of an actual rocket engine.

Experimental data, in particular, show that with the increase of the velocity of the gas flow parallel to the burning surface of the charge, the burning rate increases to values which exceed its normal magnitude as obtained from the law of the burning rate.

This phenomenon is called erosional burning.

There are opinions that there is a limiting velocity of gas flow (threshold velocity) below which the speed of flowing gases does not affect the burning rate.

Calculation of erosional burning is especially necessary in engines with high internal flow velocities.

Erosional burning also can be caused by the collision of counter flows and jet streams. In turn, it can be the cause of unstable, resonance burning.

Solid propellants also have a limiting critical pressure, below which the burning is incomplete. In incomplete burning, engine thrust drops sharply, and the

combustion products contain many intermediate products that have not been completely burned.

Propellants have pressure limits, below which it is impossible to use the propellants.

These limits (approximate) are shown in Table 9 for various propellants.

From the data given in Table 9, it follows that:

— the higher the energy characteristics of nitrocellulose propellants, the lower the critical pressure of complete burning;

— the critical pressure of complete burning of hybrid propellants is lower than the actual pressures at which SPRE operate.

Table 9. Limits of Critical Pressure for Various Propellants

| Propellant | Lower limit of critical pressure, $kg/cm^2$ |
|---|---|
| Ordinary nitrocellulose, type H . . . . . | 40 |
| Nitrocellulose with high-energy characteristics, type M-8. . . . . | 15 |
| Hybrid, type ALT-161 . . . . . | 50 |
| Hybrid, ammonium perchlorate base . . . . . | 14 |
| Hybrid, ammonium nitrate base . . . . . | 7 |

The limit of complete burning of nitrocellulose propellants is lowered by introducing burning catalysts into their composition. The most effective catalysts lower the critical pressure of complete burning from one and a half to two times.

## § 15. Abnormal Burning

Abnormal propellant burning in an engine appears as an irregular change of pressure in the engine chamber (Fig. 17). Despite the fact that the phenomenon of abnormal propellant burning in an engine was known long ago, there is still no exhausting explanation of the causes which bring about such burning.

It is assumed that the various cases of abnormal burning usually have two of the most characteristic forms: unstable and incomplete burning.

Unstable burning (Fig. 17a) is characterized by a sudden growth of pressure in rocket engines or by a sharp increase of the burning surface (internal defects or partial destruction of the charge), or due to the appearing resonance of high-frequency sound vibrations of gases in the engine (resonance burning).

Resonance burning is related to the presence of a critical point in the

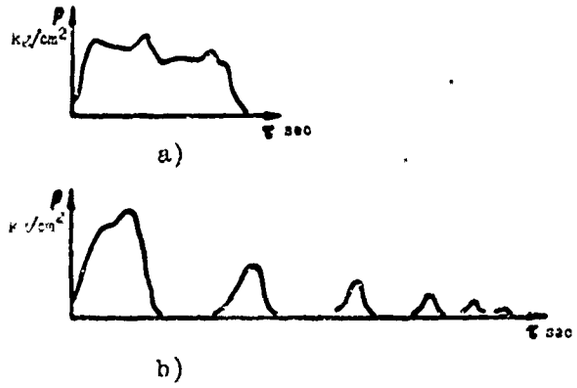



Fig. 17. Abnormal burning: a) unstable; b) incomplete.

burning zone which has a zero gas velocity. The burning of a charge in this point is accompanied by the separation of gas flows in the [illegible] of the nozzle and in the opposite direction.

Incomplete burning (Fig. 17b) appears usually as a sharp drop of pressure in the engine and is accompanied by pauses, "gasps," and "sputtering."

This character of burning is explained by the following:

Propellant burning at low pressures is slow and takes place at some distance from the burning surface. If burning ceases due to a drop in pressure or because the gas flow along the charge surface is so great that it carries incompletely burned products from the nozzle, the flame temperature drops sharply and the quantity of gaseous products decreases. This leads to a lowering of pressure in the chamber, a drop in surface temperature, and the cessation of burning.

The following cycle begins due to the fact that the exothermic reactions in the heated layer of propellant do not stop and the propellant, which obtains additional heat from the engine walls, again ignites and increases the pressure in the engine. However, the heated layer burns quickly and does not ensure normal pressure, as a result of which the pressure again drops and the cycles can be repeated several times.

Burning catalysts promote acceleration of the chemical reactions in the propellant burning zones and thereby ensure complete propellant burning at lower pressures and initial charge temperatures.

The stability of propellant burning is increased by changing not only their properties, but also the geometric shapes of the charges, and also by closing off part of the charge's surface with a nonburning material, i.e., an inhibitor.

The charge is then placed in the engine in such a way that it is always possible for the gases formed during burning to pass through the nozzle without any obstructions.

Consequently, a solid-propellant engine, with the exception of the end-burning type, always has a free area inside, which also means a free volume which

is not filled with propellant.

Thus, for a typical SPRE, the following distribution of volume between its aggregates is characteristic:

| | |
|---|---|
| Propellant . . . . . | 75.7% |
| Insulation of chamber wall . . . . . | 1.3% |
| Front and rear bottoms . . . . . | 0.2% |
| Diaphragms . . . . . | 0.6% |
| Igniter . . . . . | 0.4% |
| Free volume for passage of gases . . | 21.8% |

The size of the free volume in an engine determines the charging and consequently, the relative propellant weight in the engine.

In turn, the charging density is equal to

$$c = \frac{F_T}{F_K},$$

where $F_T$ is the cross-sectional area of the end of the charge; $F_K$ is the cross-sectional area of the combustion chamber.

## § 16. Energy Characteristics of Solid Rocket Propellants

Up till now we have been considering the various properties of finished propellants. When describing the properties of the separate components, we took into account the possibility of manufacturing the propellants and their physical, chemical, and mechanical properties.

However, the most important for solid propellants, just as for any propellants, are their energy characteristics, i.e., their calorific value and specific impulse (specific thrust).

The calorific value of a propellant is determined by the quantity of heat which is released during combustion of 1 kg of substance in oxygen or air under the condition that all combustion products are reduced to standard conditions (to a temperature of 25°C and a pressure of 760 mm Hg).

The calorific value, or caloricity, of rocket propellants, which is a measure of their potential chemical energy, does not yet completely characterize rocket propellants as sources of energy of rocket motion. The fact is that during the discharge of propellant combustion products from the nozzle of a jet engine, they are not cooled to the [illegible] temperature at which the calorific value is determined. Usually the temperature of the gases at the nozzle outlet is greater than 1000°C; therefore, the calorific value of propellants in a jet engine is used not completely.

The incompleteness of the use of the calorific value of propellants in an engine is estimated by efficiency [KPD]$\eta$ (КПД )$\eta$, which is always less than unity.

The calorific value of propellants is an important and necessary characteristic of the energy capabilities of propellants: the greater it is, the better the propellant as a source of energy. But this, it seems, is not enough to evaluate the propellant completely. It is also necessary to consider the properties of the combustion, products.

The quantity which considers both the energy source and the properties of the working substance is specific thrust.

Specific thrust is the engine thrust referred to a unit of the weight rate of propellant flow, i.e., to the amount of it which passes from the nozzle in the form of combustion products per second.

If the combustion products of the propellant in the nozzle of a jet engine are expanded to external pressure, the specific thrust can be determined by the formula

$$P_{уд} = \sqrt{\frac{2k}{g(k-1)} RT\left[1-\left(\frac{p_a}{p_0}\right)^{\frac{k-1}{k}}\right]} \quad \frac{\text{kg thrust}}{\text{kg propellant/sec}},$$

where R is the specific gas constant in kgm/kg deg; T is the propellant burning temperature in $^{o}$K; $p_0$ is the pressure in the combustion chamber in kg/cm$^2$; $p_a$ is the pressure at the nozzle cutoff in kg/cm$^2$; g is acceleration due to gravity in m/sec$^2$; k is the adiabatic exponent.

The specific thrust of solid propellants is frequently called the specific impulse, or the unit impulse of thrust – $I_1$.

The product of the value of the unit impulse multiplied by the weight of all the propellant in the engines gives the value of the total impulse of the engines

$$I = I_1\omega = P\tau,$$

where $P$ is engine thrust in kg; $\tau$ is the service life of the engine (propellant burning time) in sec; $\omega$ is the propellant weight in kg.

Specific thrust (unit impulse) may be calculated if the calorific value of the propellant $H_u$ and its engine utilization factor $\eta$ are known:

$$P_{уд} = I_1 = 9{,}34\sqrt{H_u\eta}.$$

However, it is not always possible on practice to directly determine its calorific value and utilization factor since they depend on the pressure and

temperature of propellant burning in the engine chamber and the combustion products at the nozzle cutoff.

In other words, they are variable quantities and depend on the specific conditions of propellant burning; therefore, specific thrust (unit impulse) is the most common energy characteristic of rocket propellants. Thus, if the calorific value of rocket propellants characterizes them as sources of chemical energy, the specific thrust (unit impulse) makes it possible to evaluate propellants as source of energy of rocket motion when they are used in specific engines.

In the formula for specific thrust, the pressure in the engine $p_0$ and the pressure at the nozzle cutoff $p_a$ can be specified beforehand by the nozzle design and are in no way connected with the propellant. The relationship $p_0/p_a$ is called the expansion ratio.

If we assume that pressure $p_0$ and the expansion ratio in the engine will remain constant, the specific thrust will depend only on the composition of the propellant, its calorific value, and the properties of the combustion products, i.e., on T and k.

It should be recalled that propellants can be compared among themselves with respect to the magnitude of specific thrust (unit impulse) only in if the expansion ratio is the same. The greater the expansion ratio, the greater the specific thrust (Fig. 18). The greater the specific thrust at a constant expansion ratio, the better the rocket propellant as a source of energy of rocket motion.

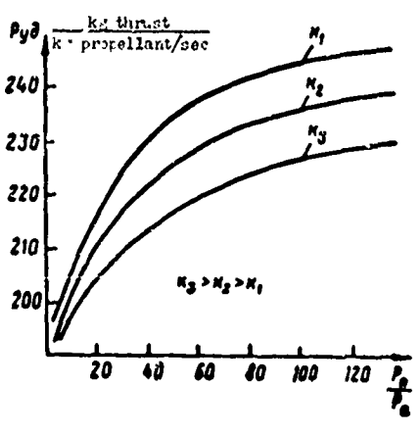



Fig. 18. Dependence of specific thrust on expansion ratio for design conditions of discharge of combustion products.

The relationship between the oxidizer and fuel elements in a propellant, independently of what their combinations are is determined by the excess oxidant ratio $\alpha$.

For propellants that contain oxygen, hydrogen, carbon, and nitrogen atoms, the excess oxidant ratio is defined as the ratio of the number of oxygen atoms in the propellants to the number necessary for the combustion of hydrogen to water and carbon to carbon dioxide.

When there is exactly the amount of oxygen in the propellant necessary for complete combustion of the substances remaining in it, the mixture is

said to be stoichiometric and $\alpha = 1$. But inasmuch as there are heavier gases in the combustion products (steam and carbon dioxide), it is unprofitable to increase $\alpha$.

With the increase of temperature, the gases that are formed begin to dissociate, and break up into simpler ones; therefore, the components of solid propellants are selected in such relationships so that the excess oxidant ratio is not very large, but corresponds the maximum value of specific thrust.

An important condition that limits the value of $\alpha$ also are the technological capabilities of manufacturing the propellants and their physical-mechanical properties. For instance, nitrocellulose propellants which are prepared with the relationship of the entering substances corresponding to the optimum value of $\alpha$ are not suitable for use with regard to their physical-mechanical properties. Many hybrid propellants which are optimum with respect to their energy characteristics cannot be prepared technologically. In virtue of these reasons, solid propellants as a rule have $\alpha = 0.58$-$0.70$ for nitrocellulose propellants and $\alpha = 0.70$-$0.85$ and up to 0.90 for hybrid propellants.

Table 10. Energy Characteristics of Solid Rocket Propellants

| Characteristic | Dimension | Propellants | | | | | |
|---|---|---|---|---|---|---|---|
| | | Nitrocellulose | | Hybrid | | | |
| | | H, HM-2, T-6 | M-8, M-13, JPN | AN | ALT-161 | AP | Polyurethane without aluminum |
| Burning temperature at pressure 40-70 kg/cm$^2$ | $^\circ$K | 2200-2300 | 3100-3200 | 1755 | 2000 | 2800 | 2800-3000 |
| Specific thrust (unit impulse) at $\frac{p_0}{p_a} = 40$ | $\frac{\text{kg thrust}}{\text{kg propellant/sec}}$ | 208-210 | 225-230 | 182 | 175 | 232 | 233-236 |
| $\frac{p_0}{p_a} = 100$ (theoretical value) | The same | 220-224 | 240-246 | 200 | 190 | 249 | 250-253 |
| Calorific value | kcal/kg | 850-880 | 1170-1200 | — | — | — | — |

Table 10 gives the energy characteristics and thermodynamic properties of certain propellants.

It follows from the data in Table 10 that the specific thrust of solid rocket propellants varies in wide limits, but is not very great in absolute value. In order to be convinced of this, it is sufficient to compare the energy characteristics of liquid and solid propellants (Table 11).

Table 11. Energy Characteristics of Liquid and Solid Propellants

| Propellant | Specific gravity, $g/cm^3$ | Burning temperature, $^oK$ | Specific thrust at $p_0/p_a = 50/1$, kg thrust / kg propellant/sec |
|---|---|---|---|
| Liquid propellants | | | |
| Kerosene + 98% $HNO_3$ . . . . . | 1.36 | 3000 | 235 |
| Kerosene + nitrogen tetroxide ($N_2O_4$). . | 1.38 | 3200 | 245 |
| Kerosene + liquid oxygen . . . . . | 1.00 | 3650 | 280 |
| 93.5% ethyl alcohol + liquid oxygen . . | 0.99 | 3350 | 260 |
| Dimethylhydrazine $(CH_3)_2N_2H_2$ + liquid oxygen. . . . . | 1.02 | 3400 | 290 |
| Liquid hydrogen + liquid fluorine . . . | 0.75 | 4980 | 350 |
| Applied solid rocket propellants. . . . | 1.6-1.7 | 2600-3000 | 220-240 |
| Prospective solid rocket propellants. . | 1.7-1.8 | 3200-3500 | 2 5-250 |

One of the simplest ways of increasing the energy capabilities of hybrid propellants is to use metals in their composition in the form of powders (e.g., aluminum or magnesium). This method makes it possible to increase specific thrust in some cases by 10-15 units. Table 12 gives the comparative energy characteristics of various hybrid propellants with various metals.

It follows from the given data that the most effective additive is aluminum in a quantity of no more than 15-20%.

In addition to raising the energy characteristics of propellants, metals also increase their density (they are supposed to reduce the specific gravity to approximately 2 $g/cm^3$). However, the manufacture of such propellants requires powders with a particle diameter of less than 10 microns (from 1 to 0.1).

This improves the combustion of metals, but the production of such powders and their preservation in an unoxidized state is a difficult task.

An essential deficiency of such propellants is the fact that during their burning very high temperatures are developed and a large quantity of solid products are released.

Another way of increasing the energy characteristics of hybrid propellants is to find new oxidizers with a large reserve of free oxygen and fuel binders in which the carbon atoms would be replaced by atoms of metals (Al, Mg, B). At present, such methods are only being investigated abroad.

The following conclusions can be made from the data given in Tables 10, 11, and 12.

Table 12. Energy Characteristics of Propellants Containing Metals

| Characteristic \ Propellant | 75% — $NH_4ClO_4$<br>25% — polyester | 80% — $NH_4ClO_4$<br>20% — polyester | 67.5% — $NH_4ClO_4$<br>22.5% — polyester<br>10% — aluminum | 63.75% — $NH_4ClO_4$<br>21.25% — polyester<br>15% — aluminum | 72% — $NH_4ClO_4$<br>18% — polyester<br>10% — aluminum | 68% — $NH_4ClO_4$<br>17% — polyester<br>15% — aluminum | 67.5% — $NH_4ClO_4$<br>22.5% — polyester<br>10% — magnesium | 71.25% — $NH_4ClO_4$<br>23.75% — polyester<br>5% — boron |
|---|---|---|---|---|---|---|---|---|
| Burning temperature in °K | 2420 | 2790 | 3002 | 3221 | 3290 | 3519 | 2915 | 2481 |
| Content of solids in % | — | — | 18.9 | 37.85 | 18.85 | 27.9 | 16.6 | 0 |
| Specific thrust at $p_0/p_a$ = 70/1 in $\frac{\text{kg thrust}}{\text{kg propellant/sec}}$ | 224 | 236 | 248.3 | 253 | 252.6 | 254 | 243.4 | 241 |

With regard to effectiveness and engine design features, liquid propellants still surpass solid propellants. Contemporary liquid-propellant rockets have a very improved design, the weight of which, as compared to total gross, weight, is insignificant. The weight of the liquid propellant placed in a rocket, with respect to the weight of the entire rocket is a [LPRE] (ЖРД), reaches 80% and more. The relative propellant weight in contemporary solid-propellant rockets and solid-propellant engines amounts to a total of 30-60%.

The larger specific thrust and better design characteristics of LPRE provide the liquid propellant with a greater effectiveness as compared to solid propellants.

The application of light and durable materials for the manufacture of solid-propellant engines will make it possible to considerably improve their design characteristics, which will also increase the effectiveness of the solid propellants.

There are projects for rockets and engines (e.g., those designed in the United States by Rocketdyne) which will make it possible to have a relative propellant weight up to 90-93%. However, this is still only a project and the only data available are taken from advertisements.

Nonetheless, solid propellants and solid-propellant rockets are more convenient for operation. Solid-propellants rockets always are ready for launching and possess greater reliability as compared to liquid-propellant rockets. Moreover, they are less expensive.

The ground equipment for liquid-propellant rockets is very complicated and expensive. For instance, from the total cost of an "Atlas" rocket complex the rocket itself comprises only 25%; the remaining cost is taken up by the propellant,

the monitoring and observing equipment, the wages of the maintenance personnel, and expenditures for the construction of the launch site.

The replacement of liquid-propellant rockets by rockets with SPRE will save the armed forces from using the complicated and bulky equipment which is necessary when liquid rocket propellants are employed.

In addition, liquid propellants are poisonous substances which require special precautionary measures during handling.

A large advantage of solid-propellant rockets over liquid rockets also is their high operational reliability during launching.

According to American data, the reliability of liquid-propellant rockets does not exceed 80-98%, whereas solid-propellant rocket engines ensure a reliability of 99.96-99.99%.

The convenience in handling, safety and simplicity of storage, and high chemical and physical stability of solid propellants make it possible to employ them in rockets of the most diverse assignment and almost under any conditions. However, they do not compare very well with liquid rocket propellants with respect to energy characteristics.

Research on new materials for the manufacture of engines and the creation of more modern charge designs and new chemicals for the manufacture of solid propellants will make it possible to create more improved, reliable, and inexpensive rockets which will be nearly as effective as liquid-propellant rockets and will utilized extensively for the solution of the most deverse problems.