

FOREIGN TECHNOLOGY DIVISION



DISCUSSION OF ROCKET PROPELLANTS
(SELECTED PARTS)

by

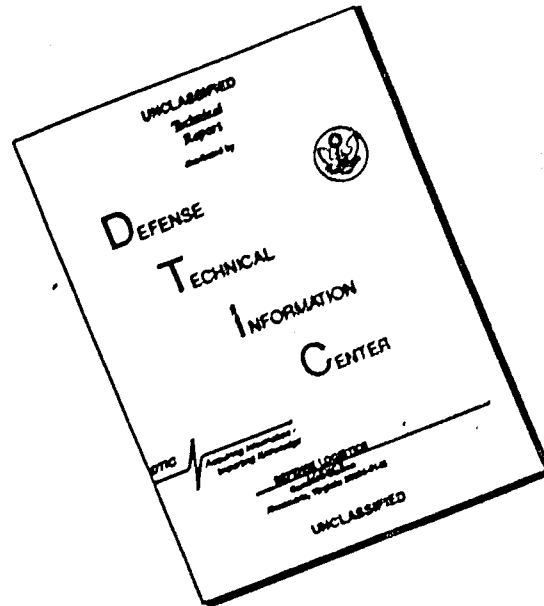
D. D. Kulinich



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EDITED TRANSLATION

DISCUSSION OF ROCKET PROPELLANTS
(SELECTED PARTS)

By: D. D. Kulinich

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CHAPTER II

FLYING FUEL STATIONS

What Does the Designer Require?

Even Tsiolkovskiy mentioned that old familiar fuels could not be used for rocket engines. Therefore, scientists of all nations, as soon as work began on rocket engines, started to look for substances which could give more heat, more energy during combustion. These problems had previously concerned scientists, but they had been only interested in fuel, which they called propellant; they had virtually ignored oxidizers, except when they had to design blowers for forcing air into fire boxes of steam boilers and compressors for feeding the same air into the cylinders of engines or for determining the air supply necessary to operate the motor of a torpedo. For reaction engines, regardless of the medium, the oxidizer is as important as the fuel.

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The chemical reactions of many compounds were theoretically studied and many practical tests were made. Frequently, these tests were hazardous; sometimes they ended with the death of the researchers. And all this was done to achieve a propellant for a rocket, 1 kg of which would give a great quantity of heat - kilocalories*, or, as they say, great heating capacity, and Soviet scientists have made great advances.

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*Let us remember that a kilocalorie is a unit of heat equal to the heat necessary for heating 1 l of water 1°Celcius.

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Our achievements in rocket building and in mastering space would have been impossible without propellants with very high heating capacity.

As mentioned earlier, the heating capacity of the propellant is determined during the combustion of 1 kg of the entire propellant - fuel and oxidizer together. If, however, the oxidizer is not taken into account, and the heat released during combustion is related to only 1 kg of fuel during its combustion in oxygen or air, then this heat is called the heat of combustion. This last quantity is conveniently used to compare fuels when the oxidizer has not yet been selected, or to compare fuels of all engines (air-breathing jets, hydroreaction engines) and nonreaction engines, regardless of the medium. Naturally the heating capacity of propellants is considerably less than the corresponding heat of combustion since the fuel in 1 kilogram of propellant is only a certain part of the propellant.

What else do the scientists and designers require of rocket propellant?

The heating capacity is only one property of the propellant - the ability to obtain a certain quantity of heat in order to convert it into work. For nonreactive thermal machines, a substance can always be found which, by taking heat from combustion products and being heated itself, will produce work. For such a substance we can use, for example, water, mercury, low-melting metals. The substance directly performing work in thermal machinery - pushing cylinder pistons, turning the working wheels of turbines - is called the working medium.

In rocket engines with chemical propellant there is no such auxiliary substance. Here the combustion products of the chemical propellant are also the working medium. Therefore, it is very important to select a propellant so that in its combustion, the heat is as fully as possible converted into work.

We know that the reactive force of a quantity of substance will be greater the faster it is thrown back. The speed will be greater, the greater the volume of combustible gases formed from the propellant.

This means, the greater the gas-forming ability of the propellant, the better it will be.

Even Tsiolkovskiy calculated that each kilogram of propellant should have the very smallest volume, i.e., with equal heating capacity, the best propellant will be the heaviest propellant. In this case, the volume of the fuel tanks will be less, their weight (without the propellant) will be less, and the rocket itself will be less cumbersome.

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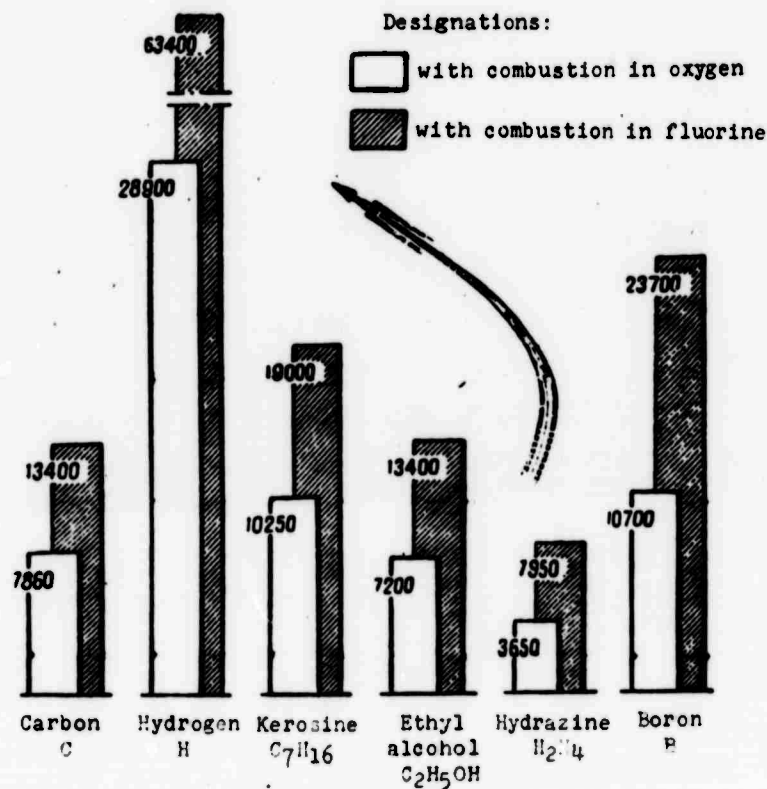


Fig. 11. Heat of combustion (in kcal) of certain fuels. It is also shown, conditionally, for those cases when the atmosphere in which the fuel burns consists of neither oxygen nor air, but of fluorine.

For heat of combustion	Per kilogram of fuel
Worst propellant	hydrazine
Best propellant	hydrogen

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Having the same reactive force as before, a rocket would achieve greater climbing range. Since the trend is toward as heavy a propellant as possible, gaseous fuel is not required in rocket engines. Gas is hundreds of times lighter than liquids and solids. However, it is presently assumed that the great weight of a unit volume of propellant is significant for rockets designed for comparatively short ranges; for long-range rockets, however, heating capacity is more important. This is apparent in the example of American projects on space rockets, on which engines are installed which operate on comparatively light fuels (liquid hydrogen) but have high heating capacity during combustion with various oxidizers.

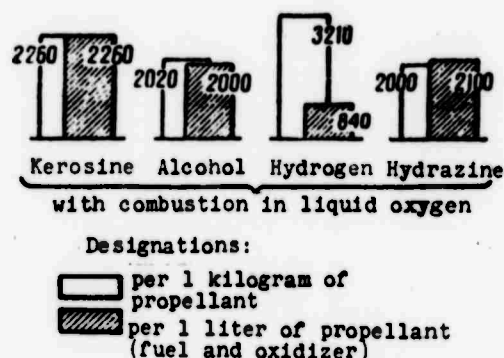


Fig. 12. Comparison of heating capacity (in kcal) calculated per kilogram and per liter of propellant (with a ratio - stoichiometric - of fuel and oxidizer at which they burn without residue).

For heating capacity	Per kilogram of prop.	Per liter of prop.
Worst prop.	hydrazine	hydrogen
Best prop.	hydrogen	kerosine

The requirements for the propellant - to have high heating capacity and great gas formation - can be combined into one requirement - to have high specific thrust (specific reactive force). Specific thrust means the thrust which can be obtained during combustion in a reactive engine of 1 kg of propellant in 1 s. For the characteristic of solid

propellants, we use a quantity called specific impulse. Specific impulse is numerically equal to specific thrust, but it is understood somewhat differently: it defines the burning time of one kilogram of propellant during which one kilogram of thrust is imparted to the rocket.

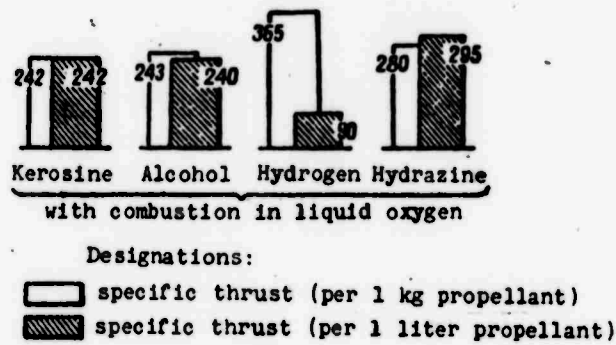


Fig. 13. Comparison of specific thrust (in kg per kilogram and per liter of propellant in a second).

For specific thrust	Per kilogram of propellant	Per liter of propellant
Worst propellant	kerosine	hydrogen
Best propellant	hydrogen	hydrazine

However, neither specific thrust nor specific impulse, per kilogram of propellant, accounts for the requirement for the propellant to be the heaviest, since 1 kg of propellant, depending upon its type, can occupy a smaller or larger amount of space. Specific thrust or specific impulse, obtained with the combustion of not one kilogram of propellant, but one liter (one cubic decimeter) of it,* combines all three requirements for a propellant. This characteristic of the

*Sometimes this quantity is called specific thrust density (specific impulse density).

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propellant includes the ability of the propellant to give more or less heat and its ability to form more gases, and indicates a heavy or light propellant.

The best propellant with respect to heating capacity, gas formation, and density, is difficult to use in a rocket if it is dangerous to handle. There are substances which when burned have good heating capacity, but are very toxic, explode, spontaneously ignite, or evaporate very rapidly. This means we must select a propellant which is convenient to handle and easy to store.

However, the desire for a propellant with the greatest heating capacity forces designers to use toxic and dangerous propellants, while creating safe conditions for their storage and use. For example, it is proposed to use a propellant whose combustion products are toxic for the upper stages of rockets which fly in space, while the engines for the lower stages of the rockets will operate on liquid hydrogen and liquid oxygen, which when burned, while combining, give off only water vapor. Other propellants, which explode at ordinary temperatures, are safe at very low temperatures, when inhibitors are used, or during storage under a layer of inert gas, for example, argon.

When a chemical engineer selects a propellant with good heating capacity and prescribes the conditions for its use and storage, he must also keep in mind whether industry can produce it cheaply enough. How much, for example, does a kilogram of kerosine cost? Copecks! Certain fuels - boranes, fuels with beryllium additives, and others, according to American data - cost hundreds of dollars (rubels) per kilogram! Some rocket propellants cost even more. If we consider that sometimes, in one rocket the quantity of propellant is measured in tons, tens of tons, and in the distant future, by hundreds and thousands of tons, then it becomes clear that cost plays no small role in the choice of propellant. Maybe the expense could be ignored with one rocket, but with the mass building of rockets, it must be taken into consideration.

Rocket designers frequently encounter contradictory requirements. In order to get the greatest range, the propellant should burn rapidly;

however, for the best control, the propellant should burn as long as possible. This means that the designer must find some solution which satisfies both requirements, for example, give the rocket a special supplementary control motor with completely different propellant than in the main rocket engines. Control motors are particularly necessary for space vehicles designed for flights lasting several days, weeks, and even months, wherein various maneuvers are performed: maintaining prescribed trajectories, transitions to other orbits, rendezvous, landings on various celestial bodies, takeoffs from them, etc.

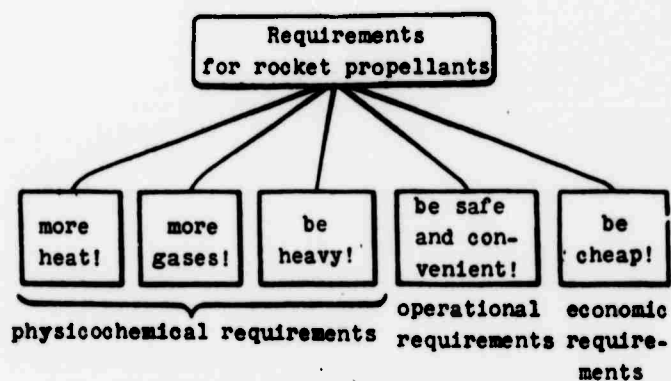


Fig. 14. Requirements for rocket propellants.

In this section we have discussed only the general requirements for ordinary chemical propellants; however, even greater difficulties arise when using "unusual" or, as they say, "exotic" chemical propellants and, in addition to chemical, other propellants of the near future.



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CHAPTER III

STRUGGLE FOR POWER

This fight between man and nature!..
This front.
Hand-to-hand combat between Light and Darkness.

Pavel Antokol'skiy

The House on Sadovo-Spasskaya

Few of the passersby, going about their daily affairs, paid any attention to one of the houses near the Lermontovskaya subway in Moscow. A house like thousands of other "profitable" houses of prerevolutionary design, with communal quarters for migrants in the years of the housing crisis. Now the house lives an ordinary peaceful life.

But old-timers, who have not moved to new quarters, remember that in the beginning of the thirties the house sometimes shook from the shocks of explosions, flames came from windows of one of the basements, the yard was darkened with smoke. People leaned out their windows and cursed the disturbers of the peace, some threatening to go to the Moscow Soviet and complain.

In spite of all this, the young people in the basement worked, the oldest of them hardly past thirty. A space in the basement, several tens of meters in area, held their design office, mechanic's shop, and laboratory, which were similar to the alchemists' establishments of the Middle Ages. Only, instead of medieval scientists in cloaks and

starry caps, young women in cotton kerchiefs, in the style of the times, the wives of the young men, ground various mixtures in mortars or mixed them in retorts.

This was officially called the GIRD - the reactive motion research group - and unofficially, in jest, a group of engineers working for nothing.



Fig. 15. Here began the assault on space.

Since then, in many countries of the world, multistoried, sparkling glass scientific research institutes have risen, launch sites have been equipped, and rocket factories built. It is difficult to estimate how many hundreds of thousands of people work in jobs related to rocket production. But this young group in Moscow, without any hope of reward, in an unsuitable location, and risking their lives, created one of the first rockets operating on liquid propellant. The chief designer of this rocket, launched near Moscow in August 1933, was Mikhail Klavdiyevich Tikhonravov.

The struggle for better rockets and propellants, which began then, continues now and will proceed in the future. The further man goes into space, the more necessary better fuel and more advanced rockets will be.

Nature sometimes does not give up its secrets easily, but we can rest assured that man will win this battle.

Soviet scientists and engineers, fighting for each additional calorie in rocket propellants, for better designs of rocket propellant systems, and for a deeper knowledge of the combustion process, go forth as scouts to find the secrets of the universe.

Rockets Drink the Blood of Earth

What, then, can burn as fuel in the reaction engine of a rocket?

First, petroleum products can be used. Theoretically, almost any known petroleum products can be burned in liquid-propellant reactive engines: gasoline, kerosine, diesel oil, and even crude oil. Their heat of combustion is almost the same - approximately 10,000 kcal per kilogram of fuel or 8000 kcal per liter of fuel with combustion in air or oxygen. Their heating capacity per kilogram of propellant, i.e., taking into account the weight of the oxidizer, is considerably less. For example, if the oxidizer in a rocket is liquid oxygen and the fuel is kerosine, a kilogram of the propellant kerosine + liquid oxygen gives approximately 2300 kcal. All similar propellants (petroleum product + liquid oxygen) give approximately the same figure.

However, although heating capacity is the same, other physical properties of petroleum products vary considerably. Gasoline is very fluid, while mazut at low temperatures is thick; gasoline presents a fire and explosion hazard, mazut considerably less, etc. Best of all the petroleum products as a fuel for turbojet engines (in aircraft, winged missiles) and a number of liquid-propellant rocket engines (in ballistic rockets) is kerosine.

Kerosine is not as dangerous to handle as gasoline, not as thick as mazut, does not contain harmful impurities which could corrode tanks, but gives almost the same quantity of heat as the best aviation gasolines. However, if we consider that kerosine is heavier than gasoline and this, as we know, is very important, particularly for engines which are not

dependent upon the medium, then it becomes clear why kerosine, of all the petroleum products, is used most frequently in such engines and has almost entirely replaced other types of fuel in aviation turbojet engines.

But what about gasoline? Gasoline performs the secondary role in rocket propellants. It is used, first, when it is necessary to ignite the propellant since gasoline ignites easily even at temperatures below minus 35° at atmospheric pressure.

In order to compare various fuels with respect to flash point, it is necessary to understand how liquid propellant is ignited. The fact of the matter is there is always vapor over the surface of liquid fuel. At low temperatures there is not much, while with an increase in temperature there is more and more vapor. When the fuel vapor reaches a certain temperature, it is sufficient to introduce a match, a glowing hot piece of metal, or an electric spark through the vapor for it to ignite.

The temperature at which the vapor ignites is called the flash point.

But remove the fire and the flame goes out. In order that fuel continue to release sufficient gases for the liquid to continue burning, surface temperature of the fuel must be higher than flash point. The lowest temperature at which the fuel will burn even after ignition is called the ignition temperature.

If the flash point for gasoline is minus 35° and for various types of kerosine is from 15 to 57°, ignition temperature for gasoline is only 1° higher than flash point, while ignition temperature for kerosine is several degrees higher than its flash point.

Self-ignition temperature is different yet, i.e., that temperature at which liquid is ignited spontaneously. This temperature is considerably higher than either flash point or ignition temperature and is approximately the same for kerosines and gasolines, 250-300°.

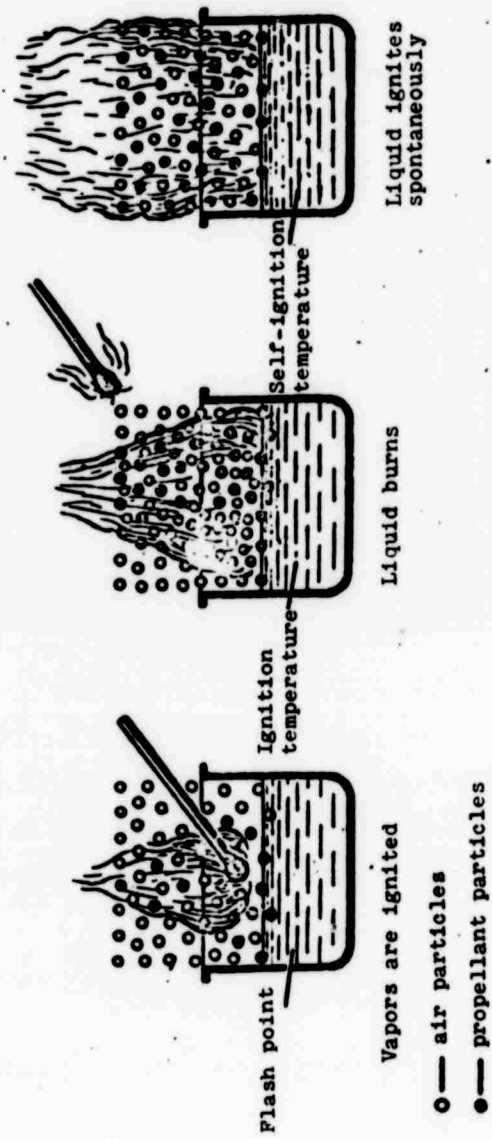


Fig. 16. Flash point, ignition temperature, and self-ignition temperature.

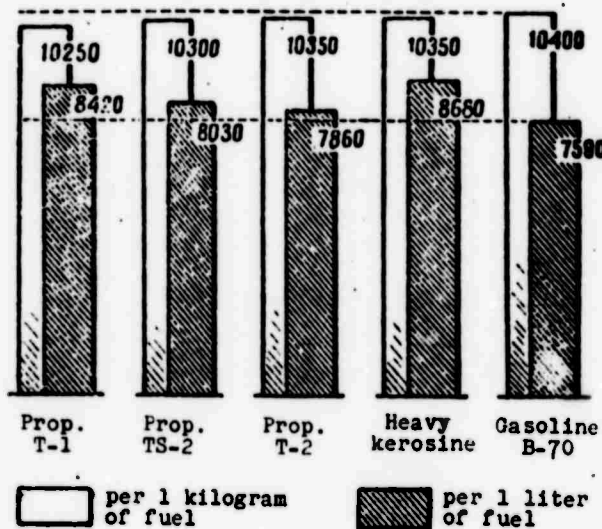


Fig. 17. Comparison of heat of combustion (in kcal) for reactive propellants - petroleum products - per kilogram and per liter of fuel.

For heat of combustion	Per kilogram of fuel	Per liter of fuel
Worst propellant	T-1	gasoline B-70
Best propellant	gasoline B-70	heavy kerosine

In the Soviet Union specifications for five types of fuels (petroleum products) for aircraft jet engines have been published. These fuels are T-1, TS-1, T-2, T-4, and T-5.

From the chemical point of view, all petroleum products, including kerosine, are complex blends of various hydrocarbons. Hydrocarbons are chemical compounds made up of carbon C and hydrogen H only. Both these elements burn completely in oxidizers.

Undesirable foreign matter can be found in kerosine - compounds containing sulfur, water, and mechanic impurities - but attempts are made to get rid of them since they can, for example, clog up the injector, thus keeping the propellant from the combustion chamber.

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Sulfur, released from compounds, can corrode the walls of the fuel tanks; water, freezing at low temperatures, can plug the lines and the injector and affect combustion. According to engineering standards, sulfur is limited to 0.25%, ash content to 0.005%, while water is not permitted at all. This is why any components of a propellant going into storage must be accompanied by documents concerning its composition and other properties, and inspectors must check this information against the standards and verify the data in laboratories both upon receipt and upon storage.

The disadvantage of all petroleum products is the fact that their composition, as a rule, is not uniform. Kerosine obtained from petroleum in one place differs from kerosine obtained from petroleum elsewhere. Moreover, the composition of hydrocarbons in petroleum, and thus in its products, can vary even when it comes from the same source and is taken at the same time. Therefore, in order to obtain fuels similar to petroleum products, but with a specific composition, with a higher heat of combustion, and without impurities, sometimes blends similar to kerosines or gasolines are artificially made for rocket engines, from various hydrocarbons obtained chemically. Such fuels are called synthetic. Their cost is high since the selected pure hydrocarbons in the blends are sometimes produced from petroleum or natural gases by the use of complicated engineering processes. But, in this case, the chemist can select hydrocarbons with a high heat of combustion for the blend and obtain a more effective fuel than kerosine or gasoline produced directly from petroleum.

Alcohols - Serious Liquids

Substances which consist of carbon, hydrogen, and oxygen can be used as rocket fuels. Alcohols belong to this group of substances and this includes the widely used ethyl alcohol. The chemical formula for ethyl alcohol is C_2H_5OH . Ethyl alcohol was used in the first designs of liquid-propellant rocket engines. As is seen from the formula, its composition includes bound oxygen as do all alcohols. Therefore, the heat of combustion for alcohols is lower than for petroleum products; thus alcohols began to be replaced by more effective fuels.

Ethyl alcohol was not used pure, but combined with water (up to 25% water in the alcohol). The more water in the alcohol the less heat released during combustion. But diluting the alcohol with water increases the heat capacity of the mixture and the mixture will remove more heat when the combustion chamber is cooling - the combustion chamber will operate in better temperature conditions. This was of great value when the first liquid-propellant rocket engines were being produced and the heat resistance of the materials was still not too good, i.e., the materials which were subjected to high temperatures during operation.

In addition, pure ethyl alcohol (100%) is very expensive since it cannot be produced by ordinary distilling methods. The engines of the first rockets (for example, the FVU-2 "Redstone") burned tons of 75% ethyl alcohol in a matter of minutes.

Methyl, or wood, alcohol was also used as a fuel for rocket engines. This gives less heat during combustion than ethyl alcohol, but cools the walls of the chamber better and is considerably cheaper.

The disadvantage of methyl alcohol is the fact that it is very toxic. Such poisoning can easily lead to complete loss of vision, and in serious cases to death. This is why it is forbidden to use an alcohol of unknown composition for any purpose, anywhere, anytime, or under any circumstances. When working with alcohol, breathing its vapors must be carefully avoided.

Although ethyl and methyl alcohols have outlived their usefulness as fuels for rocket engines, they can be used in various fuel mixtures or for various auxiliary engines. In addition, other alcohols can be used, which have a better heat of combustion and other advantages of more use to rocket engines.

Thus, we have established the first two groups of fuels - the group of hydrocarbons and the group of alcohols.

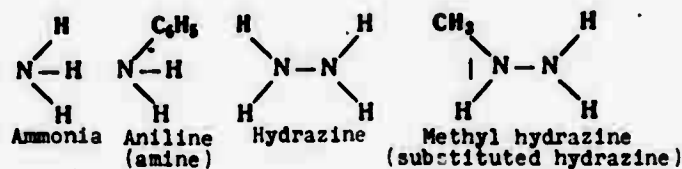
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Liquid Matches

A third group includes amines and substituted hydrazines. The first are products of the well-known ammonia gas NH_3 , in which one or several atoms of hydrogen are replaced by hydrocarbon radicals; the second has a similar replacement of hydrogen atoms for a specific hydrazine liquid N_2H_4 . In chemistry, a radical is a group of atoms which, without any change, goes from one compound to another. Outside of natural compounds, there are also radicals in ordinary conditions, which either cannot exist at all or exist for insignificant periods of time - fractions of seconds. For example, there also hydrocarbon radicals such as CH , CH_3 , and more complex C_6H_5 , as well as others similar. The origin of amines and substituted hydrazines is apparent from a comparison of the structural formulas of ammonia and amine, hydrazine and substituted hydrazine:



As follows from the formulas, there is no oxygen in the composition of amines and substituted hydrazines; however, there is nitrogen. Thus, they consist of carbon, hydrogen, and nitrogen. These substances include aniline $\text{C}_6\text{H}_5\text{NH}_2$, xylidine $\text{C}_6\text{H}_3(\text{CH}_3)_2\text{NH}_2$, methyl hydrazine CH_3NHNH_2 , dimethyl hydrazine $(\text{CH}_3)_2\text{NNH}_2$, etc.

For these compounds, it is characteristic that they will ignite from without without any heat source, when coming in contact with certain oxidizers, for example, nitric acid. This makes it possible to use them for rocket engines. Such a fuel as xylidine, for example, has only to be fed through the injector into a combustion chamber where nitric acid is simultaneously being sprayed for a flame to occur; the rocket engine starts and a stable source of flame is created. Then, in place of the xylidine and nitric acid, other components of rocket propellant, which are not self-igniting, can be used, for example, alcohol plus liquid oxygen, and the engine will continue to operate.

We could, of course, continue to use the self-igniting propellants, but such propellants are not easy to find with good qualities and they are dangerously inflammable as well as expensive. In addition, nitrogen, which does not burn, is in the composition of each of the fuels in this group. It is easy to understand that the heat of combustion for substances in this group will be less than, for example, for the group of hydrocarbons. However, nitrogen does have the advantage of increasing the volume of the fuel gases and this has a positive effect on specific thrust.

Nevertheless, at the present time, fuels in this group are not only components of priming propellants, but also are used in engines on a number of rockets ("Titan," etc.) as components of basic, operational*, propellants since their disadvantages, such as dangerous inflammability and high cost, are being successfully surmounted in the course of the development of chemical sciences and rocketry. Dimethyl hydrazine, a fuel in this group, has had considerable use.

Below minus 57°, dimethyl hydrazine is a liquid. It is self-igniting with nitric acid and liquid oxygen and is mixed with alcohols and petroleum products. This enables us, for example, to add it to other propellants to improve burning stability. It is dangerously inflammable and toxic; therefore, when working with it, safety measures are taken and protective clothing is worn.

Propellant Hybrid

The fourth group of fuels consists of substances which include oxygen in addition to carbon, hydrogen, and nitrogen. These substances are called nitrocompounds. The fact that they include oxygen, separated by nitrogen atoms from hydrogen and carbon, makes these substances dangerously explosive. This group, which includes nitromethanes in

*Unlike priming propellants, operational propellants are those propellants on which rocket engines operate in the basic phase of the active trajectory. Active phase of trajectory means that phase in which the engines operate; rocket trajectory phases where engines do not operate are called passive; in these phases rockets move from forces of inertia or gravity or both.

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liquid state, nitromethane CH_3NO_2 , nitroethane $\text{C}_2\text{H}_5\text{NO}_2$, trinitromethane $\text{CH}(\text{NO}_2)_3$, and tetranitromethane $\text{C}(\text{NO}_2)_4$, is being carefully studied by scientists in a number of countries. Actually, these substances can be either fuels (composed of carbon and hydrogen) or oxidizers (having oxygen); they can even be single-component propellants, i.e., both fuel and oxidizer at the same time. They can be used independently or as additives to certain rocket propellants. They are usually stored at very low temperatures in order to prevent their explosion.

This fourth group of substances includes organic compounds. These compounds are called organic because living organisms (animal and vegetable) consist of such compounds. Hundreds of thousands of organic compounds are known. They are frequently complex in composition and structure, but many of them have already been produced artificially. All organic substances must contain carbon.

Career of the Lightest Element

The fifth group, inorganic, includes nonmetals and their compounds. Of the nonmetallic fuels, liquid hydrogen has the highest heating capacity. It is very light and, therefore, was assumed to be unsuitable for rocket use. However, at the present time, plans have been made to use liquid hydrogen for the first-stage engines in virtually all the American space rockets under construction or in the planning stage. It is particularly suitable if burned in fluorine instead of liquid oxygen. However, the combustion products of such a propellant are very toxic and can contaminate the atmosphere; therefore, it is proposed to burn liquid hydrogen in oxygen in engines of the first stages of rockets operating in the atmosphere, and to burn it in fluorine in engines of the subsequent stages operating in space. Hydrogen is stored at a temperature below minus 252° in special double-walled vessels - Dewar flasks which have the air evacuated from the space between the walls, and no air is left, not even a molecule, which can carry the thermal energy from the ambient medium to the liquid hydrogen. There are also other designs for Dewar flasks.

This same group includes substances containing nitrogen and hydrogen, such as ammonia NH_3 and hydrazine N_2H_4 . These propellants give sufficient specific thrust at a low combustion temperature. A very important property of hydrazine is the fact that it can self-ignite with certain oxidizers.

Ammonia derivatives (amines) and hydrazine derivatives (substituted hydrazines) are organic compounds, but they were discussed in our examination of the third group.

A Propellant Ignited with Water

Nonmetallic liquid fuels include boranes - boron and hydrogen compounds. Pentaborane B_5H_9 is in liquid state at ordinary temperatures and pressures. Other boranes with a high boron content, for example, decaborane, are solid under these conditions. Boranes attract rocket engine designers because of their high heat of combustion and great density, considerably greater than that of hydrocarbons. Reports have been published that boranes can be used in hydroreaction engines and also as components for rocket propellants and additives to various other fuels to increase the heating capacity of propellants and their density. Certain of the boron compounds can ignite spontaneously upon contact with water, which makes them suitable for use in reaction engines operating in water, for example, in torpedo engines.

Metals - Energy Sources

The sixth group of fuels include metallic fuels. Attention abroad has been given to beryllium, aluminum, lithium, magnesium, and other metals. Beryllium has a very high heat of combustion, but is very expensive and its combustion products are extremely toxic. Therefore, foreign scientists have proposed that beryllium and its compounds be used for rocket stages operating in space. Ordinarily, metals are added to liquid fuels in the form of powders suspended in these liquids (suspensions). This increases density and heating capacity of rocket propellants. The first to introduce the idea of using metals as fuels for rocket engines were the talented scientists K. E. Tsiolkovskiy, F. A. Tsander, Yu. V. Kondratyuk, and G. E. Langemak in the twenties.

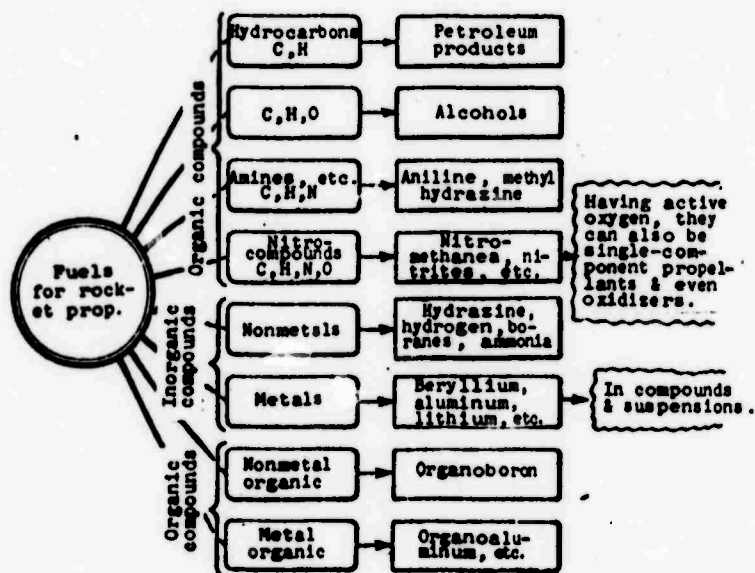


Fig. 18. Fuels for liquid chemical rocket propellants.

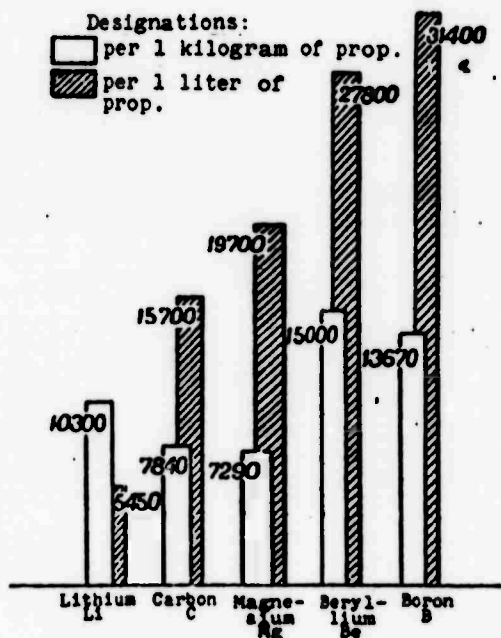


Fig. 19. Heat of combustion for certain metals and solids (in kcal).

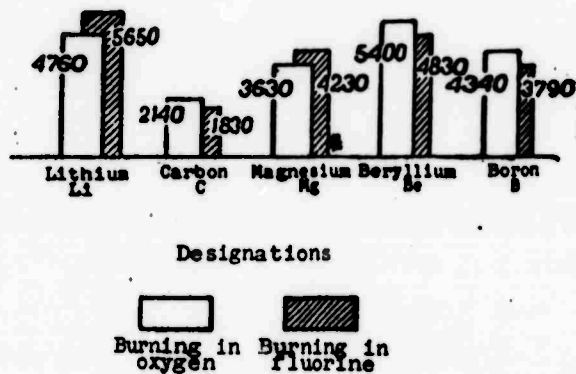


Fig. 20. Heating capacity of certain metals and solids (in kcal).

Two More Groups of Fuels

Nonmetallic and metallic substances replacing some component part of an organic fuel can create a new substance. Organic substances which have nonmetals or metals usually not found in organic compounds are called nonmetalorganic or metalorganic compounds. Thus, these two

compounds should be considered the seventh and eighth groups of fuels.

The nonmetalorganic fuels (seventh group) include, for example, the organoboron compounds - methylborane B_2CH_3 , ethyldiborane $B_2C_2H_5$, trimethylborane $B(CH_3)_3$, etc.

The group of metalorganic fuels (eighth group) includes compounds such as trimethylaluminum $Al(CH_3)_3$.

The heat of combustion for substances of the last two groups is almost the same as the heat of combustion for hydrocarbon fuels, but they are being carefully studied by scientists since it is assumed that these fuels create stable burning in those cases when hydrocarbon fuels are extinguished, for example, at the high speeds of ramjet engines. At the present time, they are used more rarely than the other fuels.

Limited Selection

However, as we know, it is not enough to have a rocket fuel; we must also have an oxidizer. Although we have the choice of many fuels, oxidizers for liquid-propellant rocket engines can still be counted on the fingers of our hands. In addition to liquid oxygen, we can only add those substances containing it - nitric acid, nitric oxides, hydrogen peroxide - as well as fluorine with its compounds and chlorine compounds. Ozone is also quite suitable as an oxidizer for rocket propellants.

"Pure" Oxidizers

Ozone is also oxygen, but each of its molecules has three oxygen atoms instead of two. Air is one-fifth oxygen, with only an insignificant amount of ozone.

The advantage of ozone over oxygen lies in the fact that liquid ozone is heavier than liquid oxygen. A liter of liquid oxygen is 1.13 kg, while a liter of ozone is 1.46 kg, which is an advantage for rocket use. Moreover, expended on the formation of ozone from oxygen

is heat, which is released during the combustion of fuels in ozone, in addition to the heat of combustion of the substances in oxygen. Liquid oxygen boils at a temperature of minus 183°, and ozone at minus 111°. Liquid oxygen is bright blue, ozone dark blue. Ozone has a particularly pungent odor, which can be present after thunderstorms when the amount of ozone in the air is greater than usual. The ability to convert oxygen into ozone with an electrical discharge was used by scientists to create ozone artificially. Oxygen is passed between two tubes which are under very high voltage (10,000-30,000 V). Under the effect of a silent electrical discharge, the oxygen passing through this space is converted to ozone. Ozone can be obtained by heating oxygen to very high temperatures and then rapidly cooling the ozone together with the oxygen. The disadvantage of ozone is the explosive danger. If the smallest impurity gets into the ozone, while decomposing into oxygen and releasing heat, it explodes. Therefore, in most cases, oxygen, not ozone, is used for rocket engines. However, it has been proposed that ozone can be added to liquid oxygen to increase the heat of combustion for rocket propellants, and that its storage at low temperatures is not so dangerous.

Many methods to obtain oxygen exist, but the most widely used method is to obtain it from air by deep cooling to a temperature at which air converts to liquid. Then from liquid air at minus 190° nitrogen is evaporated, and only liquid oxygen, whose boiling point is somewhat higher, remains. Oxygen can be obtained not only from air but also from solids. When man lands on other celestial bodies - the Moon, Mars, etc. - he will first seek ore containing oxygen, for example, permanganates - manganese compounds with oxygen, which decompose when heated and release oxygen. Oxygen is not only an oxidizer for rocket engines, which can be used for the return trip to Earth, but part of the "propellant" needed by living organisms - for the breathing of man and animals and for the vital activity of plants. An entire industry can arise on these planets for the extraction of oxygen and the creation of conditions under which man can live and work.

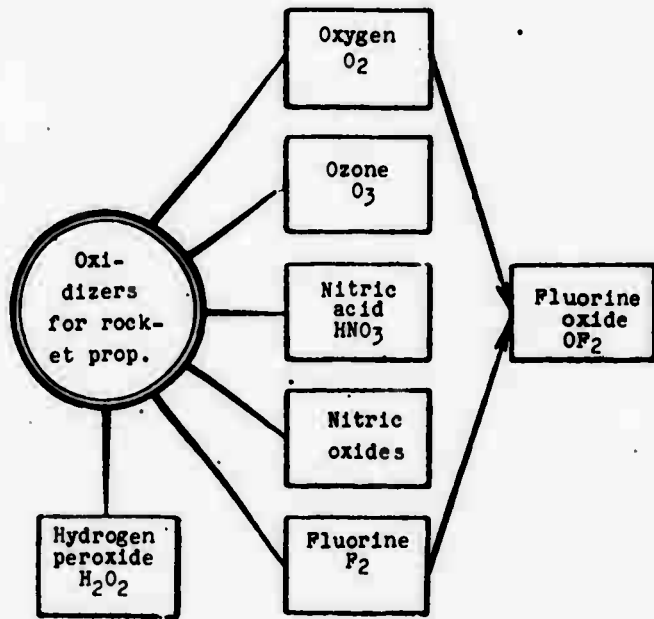


Fig. 21. Oxidizers for liquid chemical rocket propellants.

As for an oxidizer like fluorine, its disadvantage is its extreme toxicity. At temperatures below minus 188° it is in liquid state. Liquid fluorine is one and one-half times heavier than water; it is heavier than liquid oxygen and even than ozone. Its oxidizing ability is considerably greater than all other oxidizers. The heat of combustion of any fuel in fluorine is considerably higher than in oxygen. This is why the Americans plan to use it as an oxidizer for upper-stage engines on space rockets, paired with some such effective fuel as liquid hydrogen or fuels based on boron and beryllium.

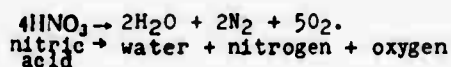
Chlorine, on the other hand, when substances burn in it, releases comparatively little heat. However, chlorine can be used as a component part of complex fuels and oxidizers. In this case, the oxidizing ability of chlorine is also taken into account.

In addition to "pure" oxygen, ozone, fluorine, and chlorine, various combinations of them with each other or with other substances can be used as oxidizers. For example, fluorine oxide OF_2 is a chemical compound of two oxidizers: oxygen and fluorine. Propellants based on it are characterized by high heating capacity and high density.

Of the compounds of "impure" oxidizers with other substances, we shall examine nitric acid and hydrogen peroxide, which are widely used in rocketry.

Nitric Acid - an Oxidizer

In its own composition, nitric acid HNO_3 has active oxygen, i.e., oxygen which can be used for oxidizing fuel. Actually,

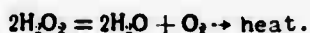


Nitric acid has great density (1.5). If we add nitrogen tetroxide to nitric acid, the mixture obtained is called red fuming nitric acid. The percent of oxygen in the mixture rises. It is interesting that a liter of the mixture will weigh more than a liter of each component separately. Nitric acid is good for reaction engines since upon coming into contact with many organic fuels, combustion begins without any ignition. This good quality for rocket engine operation is dangerous when handling nitric acid since it can inflame, if a number of substances get in it, or explode during storage. Nitric acid has a strong effect on ordinary metals, corroding them; therefore, the vessels used to store it are made from specially alloyed (improved composition) metals or pure aluminum. In addition, for this purpose, it is diluted with sulfuric acid.

As stated above, a mixture of nitric acid with nitrogen tetroxide is a stronger oxidizer than nitric acid alone. Nitrogen tetroxide is also more effective than nitric acid as an oxidizer, but it is difficult to use nitrogen tetroxide without mixing it since, at atmospheric pressure, it goes into liquid state at temperatures from only 11 to 21°. Nitrogen pentoxide is an even stronger oxidizer, but it decomposes rapidly during storage. Other nitric oxides - trioxide and oxide - are less effective than nitrogen tetroxide, and nitrous oxide is inferior to nitric acid in its oxidizing properties.

Rocket Propellant in One Tank

Hydrogen peroxide H_2O_2 is one of the most interesting substances used in rocket engines. It can be used as a propellant, giving off heat with decomposition, or only as the oxidizer. There is an excess of oxygen in its composition. The excess oxygen is active and can be used for combustion



Hydrogen peroxide in any amount can be mixed with water. Therefore, we designate the solutions as weak (approximately 3% hydrogen peroxide), strong (30-40%), and low-water (above 60%). In medicine, for cleaning wounds, weak solutions of hydrogen peroxide are ordinarily used; in cosmetics (bleaching hair) stronger solutions, called Perhydrol, are used. Rocket engines need only the low-water solutions of hydrogen peroxide (containing more than 80% hydrogen peroxide). A 100-percent solution of hydrogen peroxide would be much better for rocket engines, but it is extremely expensive, hazardous, and freezes at comparatively high temperatures; therefore, 85 to 87-percent solutions are used. Up until recently, it was assumed that hydrogen peroxide was inferior to other oxidizers for rocket propellants, that it had already played out its role in rocketry, and generally could be used only as an auxiliary propellant for operating the fuel pumps of rocket engines. However, at the present moment, in connection with the use of highly effective fuels for space rockets, interest abroad is again appearing in the use of hydrogen peroxide as an oxidizer which offers good gas formation and has a good cooling capacity.

It is necessary to store hydrogen peroxide in a completely clean vessel since it only takes an insignificant amount of certain substances in low-water peroxide for it to begin to decompose with the release of heat, which can lead to fire and explosion.

When hydrogen peroxide is used in engines as a propellant, catalysts are used for sustaining the decomposition reaction. In storage, on the other hand, in order to make hydrogen peroxide stable so that

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it will not ignite, stabilizers are used. For example, it is sufficient to add 23 thousandths of a gram of phosphoric acid to a liter of hydrogen peroxide to make it stable. If, however, the hydrogen peroxide continues to decompose, more phosphoric acid should be added. With fires, it is necessary to dilute hydrogen peroxide with water to a 67-percent solution and lower until it becomes safe. Hydrogen peroxide is stored in special aluminum tanks (more than 99% pure aluminum) since copper, lead, and many other impurities cause it to slowly decompose (they are catalysts). When hydrogen peroxide touches the skin, it can burn.

In the example of hydrogen peroxide, it is apparent that it is not necessary that fuel and oxidizer be in separate tanks on a rocket. Hydrogen peroxide can be in both. Such an indivisible reactive propellant is called unitary, and if it consists of one substance, such as hydrogen peroxide, it is called single-component.

In addition to hydrogen peroxide and other substances, in the obtaining of which heat was expended and, this means, in the decomposition of which heat must be released, we can also find other unitary propellants. This second group of unitary propellants includes safe mixtures of fuel and oxidizer. Thus, we can turn nitric acid into a unitary propellant, consisting of a mixture of fuel and oxidizer, if we dissolve in it 60% dichloroethane $C_2H_4Cl_2$. This unitary propellant will consist of 40% nitric acid (oxidizer) and 60% dichloroethane (fuel). It is interesting to note that the oxidizer - nitric acid - has a fuel substance in its composition (hydrogen), and the fuel - dichloroethane - has an oxidizer (chlorine Cl_2). To avoid error in determining the designation of the component (fuel or oxidizer), we have chosen to call the component by whichever substance is greater - fuel or oxidizer. We cannot call a propellant of nitric acid and dichloroethane single-component, but it is unitary since it does not require separate storage and delivery. Frequently, no distinction is made between unitary and single-component propellants, and any propellant which can be placed on a rocket in one tank is considered single-component.

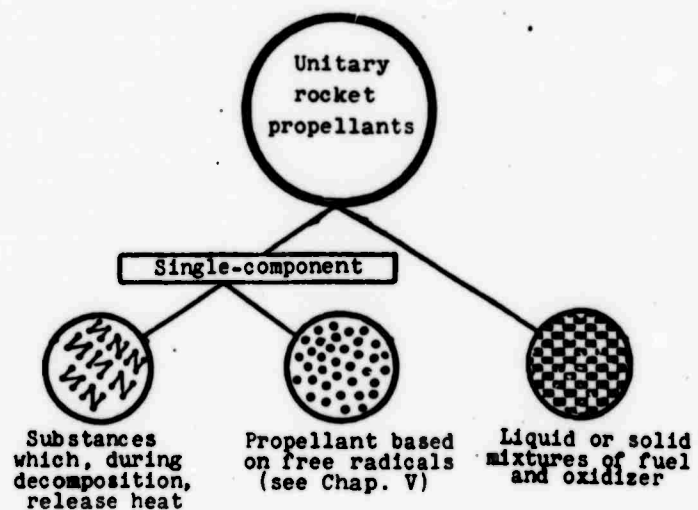


Fig. 22. Unitary or single-component propellants.

Another substance which can be single-component propellant is nitromethane CH_3NO_2 .

A third single-component propellant is tetranitromethane $\text{C}(\text{NO}_2)_4$. It is usually mixed with alcohols; such blends are better called unitary propellants.

There are also substances which can be single-component propellants or the base of unitary propellants, such as ethylene oxide $\text{C}_2\text{H}_4\text{O}$ and ammonia ozonate NH_4O_3 .

Later, in Chapter V, we shall become acquainted with a large group of very effective single-component propellants, the so-called propellants based on free radicals, which include elemental (not to be confused with atomic) propellants.

Unitary propellants are good because there is no need for separate fuel and oxidizer tanks, separate pumps, etc. All equipment for propellant delivery is considerably simplified with unitary propellants, and therefore weighs less. However, all unitary propellants present the danger of explosion, as if matches and gunpowder were kept in the same box. Scientists are presently studying conditions under which these fuels can become safe.

How to Feed Propellant to a Combustion Chamber

When selecting a fuel and oxidizer for a rocket engine, it is necessary to consider how this propellant will be fed to the combustion chamber. The pressure in it is higher than in the ambient medium by a factor of several tens.

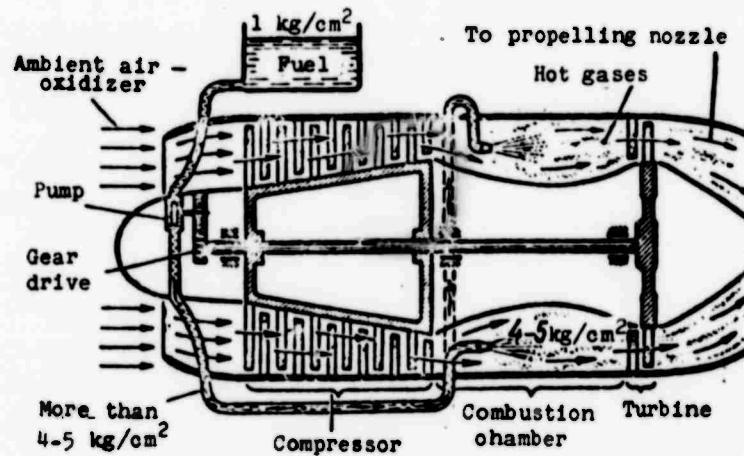


Fig. 23. Propellant feed to combustion chamber of turbojet engine.

Propellant-feed systems are set up to feed propellant to the combustion chamber. They consist of fuel lines, valves, devices for creating pressure higher than that in the combustion chamber, and injectors from which the propellant is sprayed into the combustion chamber.

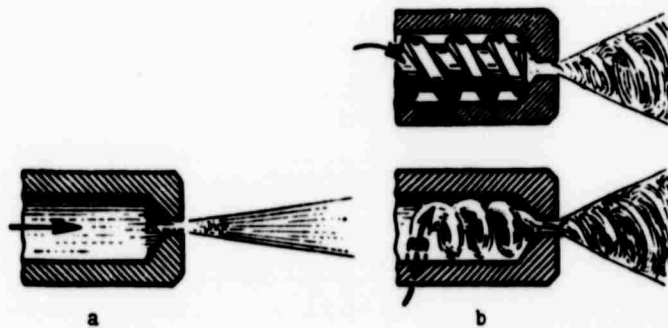


Fig. 24. Reaction engine injectors: a - spray, b - swirl.

If a turbojet engine is installed on a winged missile, then it is sufficient to install the fuel pump on the compressor shaft which the turbine turns, and the turbine will turn the pump along with the compressor. The fuel pump will be under great pressure to drive the fuel toward the injectors into the combustion chamber. The higher the pressure under which it is sprayed into the combustion chamber, the finer the drops it will break up into. Thus, the quantity of propellant fed in in one second is the consumption per second; under high pressure it breaks down into a large number of droplets. The total surface of the fine droplets (at high pressure) is greater than the total surface of large droplets (at low pressure), which means that more oxidizer can come in contact with fuel and the fuel will burn more rapidly, without residue.

In order that the fuel atomize better into fine droplets and mix better with the oxidizer, the flow of the fuel is made to swirl at the outlet. Such injectors are called swirl injectors. Injectors from which the fuel does not swirl are called spray injectors. The advantage of spray injectors is their simplicity.

Swirl injectors are usually used in air-breathing jet engines since the consumption per second in these engines is low and there are few injectors (less than ten per engine). In liquid-propellant rocket engines, where hundreds of kilograms of propellant per second sometimes burn in combustion chambers, spray injectors are also used.

In air-breathing jet engines, the fuel pump, working through the drive from the shaft of the turbocompressor unit, feeds only the fuel into the combustion chamber since the air for oxidation enters the combustion chamber either from the compressor (turbojet engine) or by the force of the incident (velocity) flow of air (ramjet engine, etc.). In hydroreaction engines, where seawater is the oxidizer, sometimes a pump is installed to pump the water, in those cases when the dynamic head of the water is insufficient to surmount the pressure in the combustion chamber.

Ramjet and hydoreaction engines have no moving parts and, therefore, their fuel pumps must have an outside energy source. This can be batteries to provide the current for the pump's electric motor or steam gas to move the turbine of the fuel pump. For ramjet engines, windmills, which are turned by the incident air pressure, can be used as the drive for the pump.

Hydrogen peroxide is most frequently used to get steam gas when using a steam-gas turbine for turning the pump. Decomposing into water and oxygen, with the aid of catalysts, it releases so much heat that the products of decomposition are heated above 500-700°. In the form of a mixture of water vapor and oxygen, the decomposition products are directed to the blades of the auxiliary turbine, on whose shaft is the rotor of the fuel pump, which feeds the propellant to the combustion chamber.

The fuel-feed systems in liquid-propellant rocket engines are equipped with such pumps operating on steam gas. However, for liquid-propellant rocket engines, it is usually necessary to feed both fuel and oxidizer into the combustion chamber; therefore, two pumps must be installed - one for the oxidizer and one for the fuel (with two-component propellant). It is possible to have just one turbine in this case, but it must turn both pumps.

Steam gas can also be obtained by compressing in a steam-gas generator the main components of the propellant used in the rocket engine or of secondary propellants, specially chosen for this purpose.

In addition, in order to turn the turbine of the propellant pumps, we can remove hot gases directly from the combustion chamber of the rocket engine and, thus, the necessity for a steam-gas generator is eliminated. The thought may occur to the reader that this resembles a closed circle. Actually, in order to remove hot gases from the combustion chamber, it is necessary that propellant fed by pumps at high pressure burn there, and in order for the pumps to operate, the burning gases are necessary. So what is done in the beginning, when there are no gases yet in the combustion chamber and, therefore, no energy source for turning the pumps' turbine?

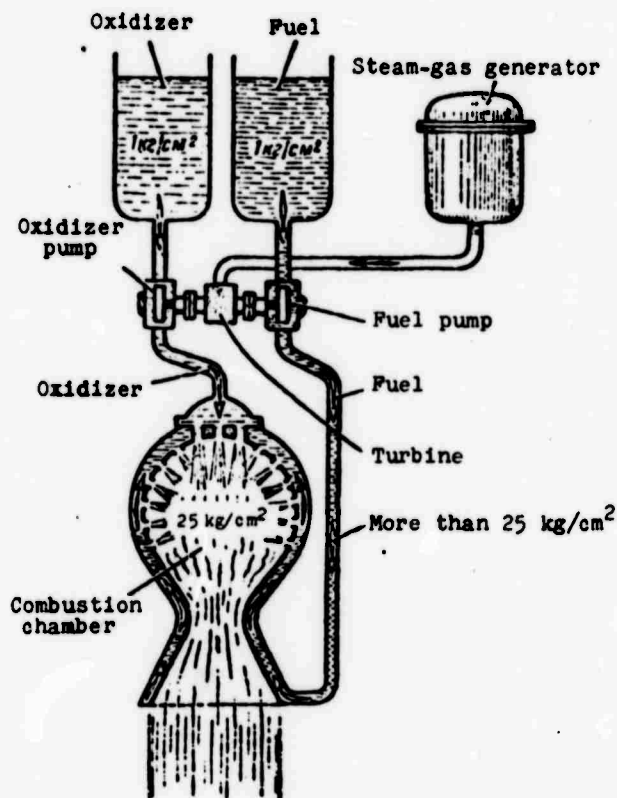


Fig. 25. Pump feed of propellant in liquid-propellant rocket engine.

In this case the turbine is turned first by gases from the combustion of a small powder charge in a special device (starter) or supplied to the rocket by compressed air. As soon as the turbine begins to turn, the propellant begins to enter the combustion chamber and burn; hot gases can be set in motion to turn the turbine, and the initial device becomes unnecessary.

A propellant system with which the propellant is fed to the combustion chamber by pumps is called a pump system.

Instead of delivering the propellant to the combustion chamber by pumps, we can force the propellant from the tanks by gases under higher pressure than exists in the combustion chamber. Such a system is called a pressurized fuel system.

How do we create pressure in the fuel tanks of a rocket higher than that which exists in the combustion chamber?

This can be done with pressure accumulators.

First, pressure can be created in fuel tanks by a small auxiliary combustion chamber, operating on the same components as the main engine. This is the liquid fuel pressure accumulator. Second, such an auxiliary combustion chamber can use powder. Then the pressure accumulator is called a powder fuel pressure accumulator. Third, a high-pressure air cylinder can be installed on the rocket beforehand, and the propellant can be forced from the tanks to the combustion chamber by this air. This is the air pressure accumulator.

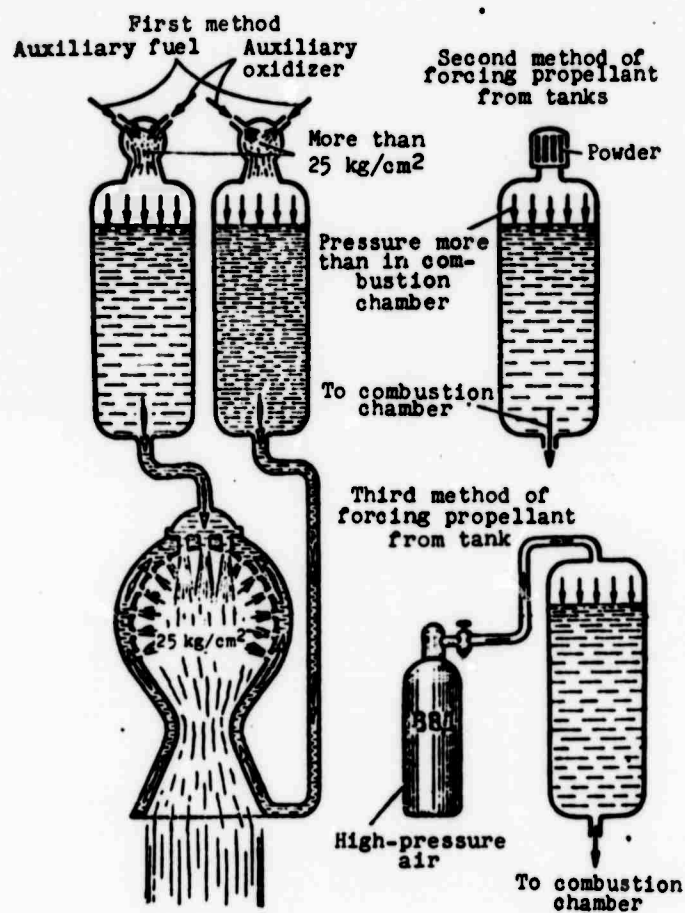


Fig. 26. Pressurized system for fuel delivery in a liquid-propellant rocket engine.

The pressurized delivery system is simpler than the pump system; however, the walls of the tanks under pressurized delivery must be considerably thicker and the tanks themselves are heavy. They must maintain pressure at several tens of kilograms per square centimeter (instead of the approximately 1 kg with pump delivery). Such tanks are called charged.

However, it is not enough to feed the propellant to the combustion chamber; it is necessary to ignite at the beginning since high temperature has not yet been created in the combustion chamber.

In air-breathing jet engines, an electric spark is used for igniting the propellant. The spark comes from spark plugs similar to those in automobile engines.

In liquid-propellant rocket engines, as was already mentioned, ignition is most frequently produced with self-igniting ignition propellants. More rarely propellant grains are located in the combustion chamber and, before delivery of the main propellant, ignite from a spark or an electric heating element (similar to an electric stove).

Songs Are Not Heard on Deck

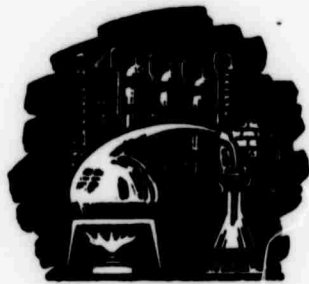
Since the advent of thermal machinery, the work of the people who control the burning - the stokers - has been considered the hardest of all jobs. The stoker not only controlled burning, but also replaced the fuel-supply system with his own muscles. Particularly exhausting was the work of a stoker onboard ship because of the limited space and location of the boiler room, and even more exhausting than the tiring work with steam boilers on shore. Even young men in the best of health frequently could not endure this work in the unbearable heat, in an atmosphere of poisonous fumes. Not so long ago, in our country there was a song "The Wide Sea" about the tragic work of a stoker. In spite of the infernal stress, a stoker in a four-hour shift on a boiler could feed only two tons of coal. In large rocket engines, tons of propellant are burned in seconds, and the fuel is fed and burning controlled without the aid of man, except in those cases when the engine is shut off by radio from Earth or a cosmonaut switches on auxiliary rocket motors to perform maneuvers.

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The ignition propellant is fed, its supply is shut off, the main propellant is switched on, valves are opened and closed, pumps are turned, and burning is discontinued - all the complex equipment of the propellant system on a rocket performs according to a program set up earlier on the ground, and automatic control systems do it.

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However, even on long space flights, automatic systems will aid man. This must be because at the tremendous speeds involved, a cosmonaut cannot always perform a maneuver fast enough. Automation makes his work easier and leaves him time to study the secrets of space.



CHAPTER IV

A GENIE FROM A BOTTLE

Oh, Sire, you say you are all-powerful.
But can you get back into the bottle?

From the Arabian Nights

Carriage of History

A small cardboard rocket, which flew two thousand years ago in China, was started with black powder. Although the Chinese rocket was very small as compared with contemporary military and research rockets, it moved according to the same laws as these multi-ton rockets which send satellites into space and reach other planets, rockets which can strike targets at a distance of thousands of kilometers and bring down supersonic aircraft. And yet for almost two thousand years the development of rocketry has progressed slowly, like a carriage along an impassable road. One of the reasons for this was the fact that, until Tsiolkovskiy's works were published, black powder was considered the only suitable propellant for rockets.

Black powder, the first rocket propellant, includes fuel and oxidizer; it consists of potassium nitrate KNO_3 , charcoal C, and sulfur S. The oxygen of the nitrate is the oxidizer, and the coal and sulfur the fuel. Sulfur is a poor fuel, but is necessary because, while burning first, the carbon is heated up, thus creating the conditions necessary for combining it with the oxygen of the nitrate. In order

to obtain a colored flame, if the rocket is used for fireworks or signaling, different additives are mixed in the powder.

Macaroni Horns

Black powder is a poor rocket propellant. It releases only 600-700 kcal of heat per kilogram. To a considerable extent, this explains why rockets were not developed for a long time. Only after discovering the possibility of using colloidal propellants in rockets did rockets again achieve wide use for military purposes (from rocket devices such as the "katyusch"). The study of liquid propellants, giving off more than 2000 kcal per kilogram, led to the designing of long-range rockets.

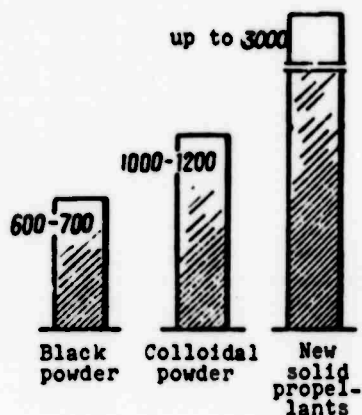


Fig. 27. Comparison of heating capacity (in kcal) of solid propellants (absolute, per kilogram of propellant, since fuel and oxidizer are together).

In quality, colloidal powders are not much better than black powder, although they have greater heating capacity (970-1200 kcal per kilogram of propellant). When used for artillery, colloidal powder is usually made in the form of long tubes, like a horn, similar in form to yellowish brown macaroni.

They are colloidal because colloids are obtained when thickening the jelly-like solutions. The colloids consist of two substances: a liquid solvent and very finely broken up floating particles.

The solvent is nitroglycerin or nitrodiglycol, and the floating particles are nitrocellulose. After thickening, the powder is almost a plastic. In addition to nitrocellulose and the solvent, there are plasticizers (vaseline or oil wax) for flexibility, as well as stabilizers for chemical stability and catalysts for combustion.

Nitrocellulose is made from wood or cotton and the cellulose obtained from them is treated with nitric acid. Nitrocellulose, or cellulose nitrate, is the basic energy source in colloidal propellant; it comprises up to 60%. It is impossible to obtain a 100-percent charge from it since it is porous and burns unstably, with explosions. The solvents - nitroglycerin and nitrodiglycol - are liquid explosives and make up as much as 40% of the propellant. Both nitrocellulose and the solvents are organic matter, consisting of carbon, nitrogen, and oxygen. In the ordinary state, the carbon atoms in colloidal powder are separated from the oxygen atoms by the nitrogen atoms. When the colloidal powder is heated, this wall of nitrogen is disturbed and the carbon atoms combine directly with the oxygen atoms. A thermal reaction occurs; the solid powder is transformed into burning gases.

Plasticizers make up 10% of the propellant, stabilizers and catalysts several percent. Nitrocellulose for the powder has a 13-percent nitrogen content. Such nitrocellulose is called pyroxylin.

Colloidal powders were introduced into rocketry from the artillery, where they were the charges for the artillery shells. They were only "adapted" to the role of rocket propellant, as much as their properties made it possible. However, the possibilities of colloidal powders are not great, their characteristics are similar to modern artillery powder. Clearly, we cannot expect much from a rocket engine with such a propellant. However, there is one area where rocket engines with colloidal propellant are almost irreplaceable; this is for rocket use in close combat. Actually, the storage and care of rockets with engines operating on colloidal propellant are similar to the maintenance of artillery shells, and it is simpler to launch them than shoot a shell from a gun. The firing can be carried out with the most primitive directing devices: directing rails, thin-walled tubes, trays, and

even the packing in which the shell is stored. Special machines, tanks, helicopters, and soldiers, can be armed with such rockets. Such a rocket "and one in the field" can perform against tanks, aircraft, or fortified points of an enemy.

Quiet Flame and Raging Whirlwind

Usually rocket powders, as all powders, burn along the surface. The rate of such burning is slow: in air, several millimeters per second, and under pressure, centimeters per second. Only such burning can be used in rocket engines. However, under certain conditions (impact, rapid heating), there can arise a phenomenon under which powder is ignited throughout its entire volume almost at once. Then a large quantity of gases is instantaneously formed - hundreds of times greater in volume than the powder occupied. A jet nozzle cannot pass so much gas and explosion occurs. This phenomenon, when the powder burns with colossal velocity, is called detonation. The combustion rate of the powder - detonation rate - is approximately several thousands of meters per second. This means that a storehouse of military rockets, located several kilometers away, can explode in seconds. Detonation will not occur if the servicing personnel carefully follow regulations on the storage of ammunition and make certain that shocks, shots, or explosions do not occur nearby.

Detonation can also take place during the burning of not only powder but many other solid and liquid propellants.

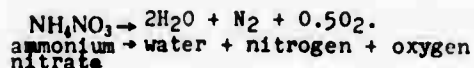
Another disadvantage of powder propellants is the fact that their combustion rate depends upon initial temperature of the powder charge (i.e., storage temperature). At very low temperatures, burning can be generally unstable. The relationship between combustion rate and initial temperature of the powder affects the amount of engine thrust and, thus, the speed and range of the rocket. This is taken into account when launching rockets with powder-propellant rocket engines under various temperature conditions.

Solid propellants, nevertheless, are more convenient when servicing rockets than liquid. For solid propellants, there is no need to fuel up the rocket in special equipment on the ground or on board ship; there is no need either in the device which feeds propellant to the combustion chamber since the propellant is already there. Finally, solid propellants in operation are similar to powders, and the powders are ordinary ammunitions as used in the artillery. This is why, in recent years, rocket builders have been attempting to create a propellant which would be as powerful as good liquid propellants but would be in a solid state similar to powder. These attempts have met with a certain success. At the present time there are a number of rockets - from close-combat rockets to intercontinental and stages of space rockets - which operate on new solid propellants.

Astonishing Mixtures

New solid propellants are mixtures of solid substances - fuel and oxidizer. The fuels in them are various forms of rubber, polyurethane, and bitumen. They are all high-molecular compounds, i.e., their molecules are made up of numerous simpler identical (rubbers and polyurethanes) chains of compounds. Bitumens are the solid products which remain after the processing of petroleum or coal. They consist of mixtures of various hydrocarbons and products of their oxidation and condensation. The molecular chain of rubber also consists of several atoms of hydrocarbon and hydrogen, while chains of polyurethane molecules, in addition, have oxygen and nitrogen in their composition, which, of course, are not combustible. Therefore, the heat of combustion for rubbers and bitumens is higher than the heat of combustion for polyurethanes (with polyurethanes it is 6500-7000 kcal per kilogram) and reaches 10,000-11,000 kcal per kilogram, i.e., almost the same quantity as for kerosines, but kerosines - liquid fuels - are considerably lighter than either bitumens or rubbers. This means, in the latter case, that the new solid fuels have an advantage.

Salts of ammonia, potassium, or lithium, which contain oxygen, serve as oxidizers in mixed propellants. For example, salt of ammonia, the so-called ammonium nitrate NH_4NO_3 , during heating releases oxygen according to the following chemical reaction:



Ammonium nitrate contains 20% oxygen (almost as much as air does), which can be used for oxidizing fuel.

Other solid oxidizers we can name include perchlorates - chlorates - of ammonia NH_4ClO_4 , potassium KClO_4 , and lithium LiClO_4 . All these oxidizers are powders, while the fuels when warming up are a pasty mass. Thus, during the mixing, the fuel wraps around and binds separate crystals of the oxidizer powder; it plays the role of a bond and, therefore, in blended propellants is called fuel-binding. After blending, the propellant is similar to rubber. The combustion chamber is filled with it while it is warm; it thickens upon cooling.

Finally, comparatively small engines are "charged" or fueled up at the plant; however, at present some rocket engines have combustion chambers up to 4 and even 6.6 m in diameter and several tens of meters high, which weigh several hundreds of tons. It is impossible to transport a rocket with such a charge by ordinary means - railroad tow cars. It is suggested to transport the propellant to the launch site in a pasty state and there pack it into the combustion chamber where it will then harden.

However, the creation of large charges of solid propellant is not such a simple matter. When the propellant thickens, it is difficult to obtain a solid monolithic charge. Cracks appear in the propellant and, upon ignition, combustion begins not only along the planned surface, but also along the surfaces of the "unplanned" cracks; the quantity of gas increases so much that the combustion chamber cannot handle the unexpected pressure and explosion occurs.

Scientists are proceeding toward the elimination of these difficulties; methods are being sought to increase the heating capacity of blended propellants. One of these methods is to add to the blended propellant powders of such metals as beryllium, lithium, aluminum, as well as boron and its compounds. It is considered that in this manner

we can achieve the highest heating capacity of propellants, bringing it to the heating capacity of the best liquid propellants and even surpassing that. But here new tasks appear, new difficulties whose solution is a matter for the future.

A Genie is Put in a Bottle

Combustion control for all solid propellants - black powder, colloidal powders, and new blended propellants - is considerably more complicated than for liquids.

Actually, we only have to put automatic valves on a rocket with a liquid-propellant rocket engine, which, at any moment, would shut off the fuel and oxidizer feed to the combustion chamber, and the question of combustion control is solved. The valves start to close - combustion decreases; they close completely - combustion ceases. But how can we do this if solid propellant is burned?

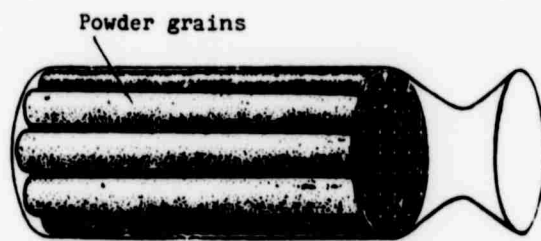


Fig. 28. All solid propellant is in the combustion chamber.

All solid propellant is in the combustion chamber; it does not pass through any valve. If combustion begins, it would seem to be impossible to stop.

There is an Eastern tale about a small boy who found a jug beside the sea, pulled out the plug, and out slipped a giant - evil spirit - a genie. The giant wanted to kill the boy. The small boy managed slyly to get the genie to return to his bottle.

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When working with solid propellant, it is necessary to display greater inventiveness than the quick-thinking little boy from the fairy tale.

We start the rocket, i.e., ignite the propellant in the combustion chamber, a jet of gas is forced from the nozzle of the engine. The rocket lifts upward. But the force which acts on the rocket depends on the quantity of propellant burning in each fraction of a second in the rocket. We know, however, that solid propellants begin to burn from the surface. This means that it is necessary to place the propellant in the combustion chamber in such a manner that as time passes, a certain volume of the propellant layer will burn fully. If the thrust must increase, the propellant must burn more rapidly; if thrust must decrease, the propellant must burn more slowly. Usually, an attempt is made to burn the propellant uniformly.

Uniform combustion can, for example, be obtained if a charge, shaped like a tube, is placed in the combustion chamber. The ends of the tube must be covered with a special noncombustible composition (called armor-plate). Then with burning for a certain period of time, the internal burning surface will always increase, while the external will decrease during this same time, and the quantity of propellant which burns out during this period will be approximately the same.

A solid charge, exposed for burning only at one end, and also charges of more complex form (star-shaped and cruciform channels) burn uniformly.

If the burning surface increases during each interval of time, combustion will not be uniform but progressive; if, however, the burning surface decreases, burning will be regressive. A solid grain, armor-plated on the ends, gives regressive (retarded) combustion, while a grain, which is armor-plated outside and only burns inside, gives progressive.

However, the previous control of thrust is not such a complex problem; it is solved, as we have seen, by the careful selection of

the shape of the charge. The second problem is considerably more difficult to solve: how to stop combustion in the combustion chamber on a flying rocket. Even on the ground, in ordinary conditions, powder is very difficult to extinguish. In a rocket, however, it is necessary to stop burning in fractions of a second. If the rocket engine cutoff is delayed a second, the rocket will fly several kilometers beyond its target. If combustion stops too early, the rocket will not reach its target.

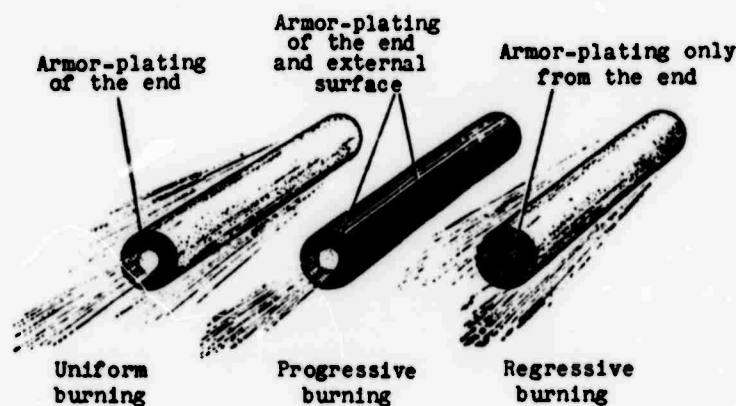


Fig. 29. How powder grains can burn.

In certain rocket engines, combustion does not stop when necessary, but with the aid of deflectors installed on the nozzle, the stream of gases is reversed so that the rocket is not thrust forward, but slowed down instead. Such a device for a solid-propellant rocket engine is complicated, and, as usual, the engine can be started only once until full fuel depletion. Sometimes, instead of deflectors for slowing the rocket, additional nozzles are installed, whose gas streams are directed against the direction in which the rocket is moving, but this also is no complete solution to the problem of simple and reliable control of engine operation.

The most widespread method of stopping the combustion of solid propellant is the rapid reduction of pressure in the combustion chamber. It is known that solid propellants burn stably only at high pressures - above 20-40 kg/cm². In the combustion chamber of a solid-propellant reaction engine, the pressure is considerably higher. If pressure in the combustion chamber is instantly reduced (which can be done by

opening special valves which release gas from the combustion chamber), burning will cease.

Attempts to extinguish the fire in a combustion chamber by shock waves of air have also been made. These waves can be obtained by the electromagnetic acceleration of gas. Such waves can "blow out" the fire as wind a candle. Controlling them will be simple, and burning will cease almost instantaneously.

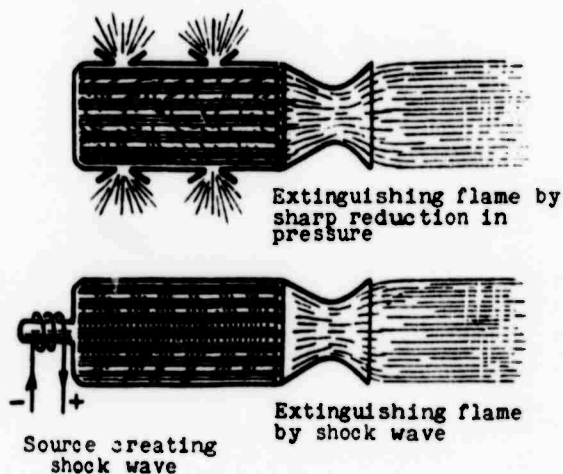


Fig. 30. How to stop the operation of a solid-propellant engine.

Recently rocket engines have been created in which an attempt has been made to combine the advantages of liquid- and solid-propellant engines. Solid fuel, which has a high heat of combustion, and liquid oxidizer, with good oxidizing abilities, are usually used in them. Only the oxidizer is fed into the combustion chamber from the fuel tanks, while the fuel is kept in the chamber itself. It is sufficient to cut off the entrance of oxidizer into the combustion chamber for combustion to cease. If the oxidizer is fed again into the combustion chamber and the propellant ignites, the engine will operate again. We can switch the rocket engine on and off repeatedly until the propellant burns out completely.

Thus the spirit from the bottle is tamed.

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13. ABSTRACT A wide range of fuels and oxidizers are mentioned in this dis- cussion of rocket propellants. Heat combustion is compared for carbon, hydrogen, kerosine, ethyl alcohol, hydrazine, and boron as well as the petroleum products Prop. T-1, Prop. TS-2, Prop. T-2, heavy kerosine, and gasoline B-70. Heating capacity and specific thrust are compared for kerosine, alcohol, hydrogen, and hydrazine with combustion in liquid oxygen. Heat of combus- tion and heating capacity are discussed for Li, C, Mg, Be, and B. Single-component and unitary propellants are defined, pro- pellant feed systems are described, and solid propellants are discussed and compared.		

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