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AIR FORCE SYSTEMS COMMAND

ENGINES OF UNPRECEDENTED SPEEDS

by

K. A. Gil'zin

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ABSTRACT

(U) A popularly written coverage of the historical development of jet and rocket engines, covering their beginnings, design developments and problems, competition with and ultimate supersession of the reciprocating engine in flight applications. Final chapters are divided to discussion of engines of new types. The book concerns the heart of contemporary high-speed aircraft, rockets, and spaceships-different reaction engines. Interestingly, in simple, understandable language, the book covers prospects for development of reaction engines, scientific problems faced by scientists in this area, and the place of engines of different type in the vast family of reaction engines. ( )

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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

* <u>ye</u> initially, after vowels, and after ъ, ь; <u>e</u> 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.

This book concerns the heart of contemporary high-speed aircraft, rockets, and spaceships — different reaction engines.

Interestingly, in simple, understandable language, the book covers prospects for development of reaction engines, scientific problems faced by scientists in this area, and the place of engines of different type in the vast family of reaction engines.

In the last chapters of the book we will discuss the question of reaction engines of new type, to which the future likely belongs.

The book is intended for a broad spectrum of readers.

INTRODUCTION

ABOUT THE CONTENTS

What "unprecedented" speeds are discussed here? After all, now, wherever we look back, we find everywhere "unprecedented" speeds, previously unknown and which seemed unattainable. We constantly see life's tempo accelerated – motor vehicles and aircraft become swifter, ships and conveyer belts become faster, machines turn faster, and technological processes of metallurgical, chemical, and other production are accelerated. Even pedestrians on streets seems to move with greater speed!

This general acceleration of rhythm and speed is not accidental. People are rushing to accomplish in the years of life allotted them, productivity of human labor is increasing with the support of ever more mighty technology and is called upon to satisfy the constantly growing needs of society. The value of the second, the minute, and the hour in any production and in the life of people assumes ever greater importance.

The author's intent was not to discuss the problem of the general struggle for speed being waged by contemporary science and technology. This book is devoted only to those speeds at which those transport machines created by man move. Increase of speed of motion not only is extraordinarily characteristic of our time, but is precisely the reason behind recent remarkable victories of human genius.

We will not concern ourselves with speeds of railroad trains and ships, motor vehicles and motorcycles. Although these speeds are continuously increasing, they are nevertheless considerably less than the maximum speeds already attainable by man. This book is devoted to those speeds at which aircraft and rockets fly — the most high-speed of all means of transport created by man.

But why did we call these speeds "unprecedented"? After all, now every day thousands and thousands of air passengers fly in jet liners at such speeds!

Perhaps the word "unprecedented" must now be applied with caution. That of which not long ago even specialists feared to dream has today become reality. And yet one cannot but call the speed of flight of contemporary aircraft unprecedented if they not only closely approached the speed of sound, but very frequently exceed it considerably? Once man envied the birds — but how far behind have the metallic birds created by man left them! The speeds of contemporary rockets are tremendous. Still more fantastic are the speeds at which new aircraft, as yet existing only on the designer's drawing board, will hurtle!

We all know that these decisive victories in the struggle for speed, gained by man with the help of reaction engines, are the miracle of our time. For many hundreds of years the principle of jet propulsion did not find wide application in transport technology. Only approximately two decades back, at the very end and after the second world war, did the first straight reaction engines appear on aircraft. Now almost all aircraft are jet-propelled.

Acquaintance with reaction engines, at least the most general, can now be considered obligatory for any cultured person.

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CHAPTER I

WHAT IS THE REACTION ENGINE AND WHY IS IT GAINING ONE VICTORY AFTER ANOTHER?

These questions, obviously, are the first to occur to the reader. What actually distinguishes the reaction engine, to whatever type it belongs, from all other engines. Why is the reaction engine the record holder in the struggle for increased speed? Will it not happen that the reaction engine will in the future, in some new stage of the struggle for speed, be forced to yield its place to an engine of another type? Is the reaction engine the permanent, irremovable hegemon in the realm of high speeds?

In order to answer these questions we have to turn to the actual bases of mechanics – to the science of motion. As it is known, the foundation of this science was laid by the works of the great scientists of the past – Galileo and Newton. So-called classical mechanics, created by them, has brilliantly confirmed its irreproachable correctness through an infinite number of examples in the practical activities of man. And only at the very beginning of the present century was it established that with sufficiently high speeds of motion, close to the velocity of light in a vacuum (this speed, equal to 300,000 km/s, is, as considered by contemporary physics, the highest possible in nature), certain laws of classical mechanics cease to be correct. They are replaced in these cases by the laws of relativistic mechanics, comprising the essence of the so-called theory of relativity, developed by Einstein.

In turn, the laws of relativistic mechanics, irreproachably true within the entire possible range of speeds of motion, at speeds that are low compared with that of light, for practical purposes reduce to the laws of ordinary classical mechanics.

In the last chapter of the book we will also encounter such cases when rocket flight and the operation of the jet engine also have to be calculated by the formulas of the theory of relativity. For this, such as they are called, relativistic rockets must move at very high speeds, close to that of light, or of such magnitude must be the exit velocity of working substance from the jet engine. Such rockets and engines do not yet exist — this is a matter for the more distant future. Therefore here we can use the ordinary relationships of classical mechanics exclusively.

We can perhaps see how the reaction engine operates and what the essence of its fundamental distinctions from all other known engines are by example of the ordinary jet aircraft. As the jet fighter rushed overhead, it seems that the agitated air still shrieks, but the aircraft has already vanished over the horizon. Is it really possible to discern anything on the aircraft in those measured instants when it is visible in the sky?

The transparent air conceals the secrets of processes occurring in it. But if our terrestrial atmosphere were to become suddenly colored, for example, bright red or green, the color being deeper, the denser the air, it would then be possible to observe certain very interesting phenomena accompanying the flight of our jet aircraft.

However, science has found methods for making the invisible visible: in particular, this applies to processes occurring in transparent air and gases. Thus, for example, on special apparatus, called the Wilson cloud chambers, physicists studying nuclear processes and cosmic rays can record the flight of many particles of matter invisible because of their minute dimensions and rapid motion. For this the phenomenon of condensation of vapors of liquid along the route of a flying particle is utilized. Inasmuch

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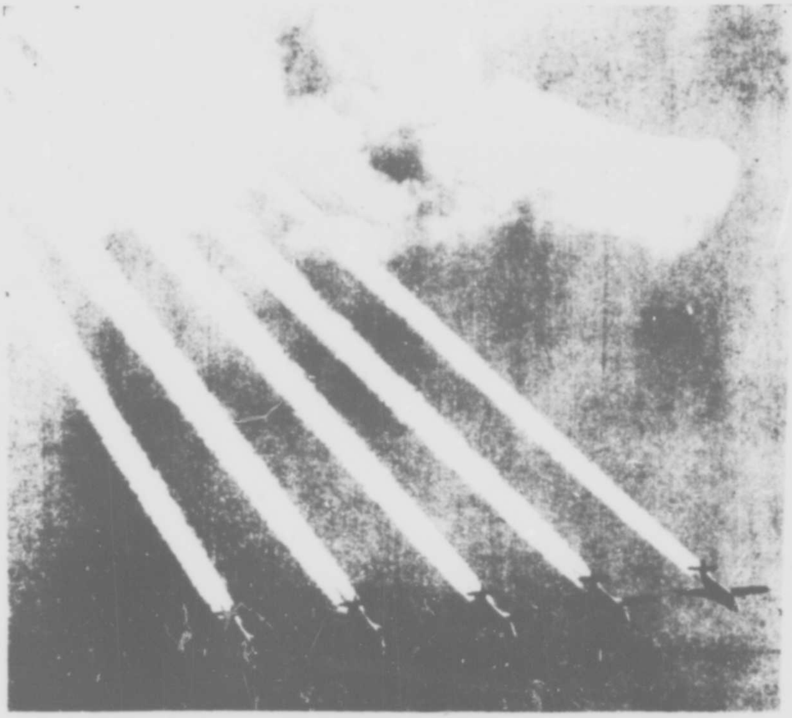

Fig. 1. Flying at high altitude, an aircraft leaves behind at a white contrail.

as drops of the thus forming liquid can be seen, they create distinct paths, so-called tracks of flying particles.[1]

Perhaps it is similarly possible to try to obtain tracks of a flying aircraft. But must we not place it for this purpose in a gigantic Wilson cloud chamber?

Fortunately, there is no need for this, since under certain circumstances the terrestrial atmosphere is transformed into a unique chamber of such type.

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[1] Wilson cloud chamber and bubble chamber, utilized by scientists for the same purpose, sometimes are also called "track instruments."

Probably, everyone has seen how the high-altitude aircraft crosses the sky in a white arc. The aircraft itself is frequently invisible, flying so high, or appears as a scarcely noticeable sparkling dot, as if the tip of a heated pen drafting a white curve in the sky. This curve at times is broken off as unexpectedly as it appears. What causes this "track" of the aircraft in the air?

Usually its origin is the same as in the case of the Wilson cloud chamber. The exhaust gases emanating from an aircraft engine contain a considerable quantity water vapor, formed as a result of combustion of hydrogen contained in the fuel on which the engine operates. During flight in cold air at high altitudes, of the order of 8-12 km, these vapors are condensed. Also condensed are those water vapors which were contained in air before passage of the aircraft – exhaust gases of engine created"condensation centers" necessary for this. It is these drops of water, and sometimes small ice crystals, that form "tracks," or, as they are usually called, contrails. They can help us to examine the principle of operation of the reaction engine.

Actually, as viewed from the earth, the contrail seems stationarily fixed in the sky. Only with time is the thin, clear filament gradually eroded, dissipated, turning into a wide foggy path, and then melting away entirely.

But quite another picture is revealed to the observer if he is, for example, in the gondola of a stratosphere balloon next to the foggy path left in the sky by a flying aircraft. In this case he can readily see that the contrail behaves quite unlike the track of an elementary particle in the Wilson cloud chamber, which is actually a chain of tiny drops of liquid, suspended practically stationarily inside the chamber. The same drops in the contrail appear to rush at high speed (at least, this speed is great immediately behind the aircraft) in a direction opposite that of flight of the aircraft.

What attracts them in this direction? In this swift motion consists the essence of operation of the reaction engine. It is exactly for this reason that behind a flying jet aircraft in air there remains a solid stream of gases, moving rapidly backward (drops of water rush together with the gases – without these drops the stream would be invisible) and propelling the aircraft.

Let us analyze this phenomenon in more detail. Before passage of the aircraft, the atmosphere was stationary, and the observer in his gondola could see no visible shift of air masses. But now the aircraft flies by, and along the entire path of the aircraft in the air there forms a powerful, hot stream of gas in that direction whence the aircraft just came. Of course, such gaseous "Gulf Stream" does not exist eternally. The fast-moving, hot gas very quickly is mixed with nearby air masses, transmitting its thermal and kinetic energy to them. A little time passes and the gas stream vanishes entirely, dissolving in the atmosphere. But immediately behind the flying aircraft it nevertheless exists. Whence does it appear? The cause of it all is the jet engine of the aircraft. It forces the previously stationary air to shift at high speed. More exactly, this no longer is air, but gases, the products of combustion of fuel in the engine (ratio of fuel to air is not more than 1-1.5%; therefore it is possible without great error to consider gases, as before, air, as is usually done).

When any mass of substance m starts to move with speed V, we say that it takes on "momentum" mV. One of the most fundamental laws of nature is the law of conservation of momentum, as is the law of conservation of energy. Consequently, if air (or gas) takes on some momentum mV in one direction, specifically opposite that of motion of an aircraft, the same momentum must appear in the opposite direction, so that the algebraic sum of both these quantities equals zero. This means that the total momentum remains constant.

It is easy to guess exactly what "other" momentum is meant in this case. This momentum, of course, is imparted to the flying aircraft. Thus the jet engine of the aircraft, thrusting its exhaust gases back at high speed (remember the rushing drops of water in the contrail), thereby forces the aircraft to fly forward.

We have just become acquainted with basis of any motion — in order to force some mass (aircraft, rocket, motor vehicle, etc.) to move in one direction, it is necessary to impart motion in the opposite direction to another mass. Here both shown masses must, directly exerting influence on one another, take on strictly defined speeds in accordance with the law of conservation of momentum.

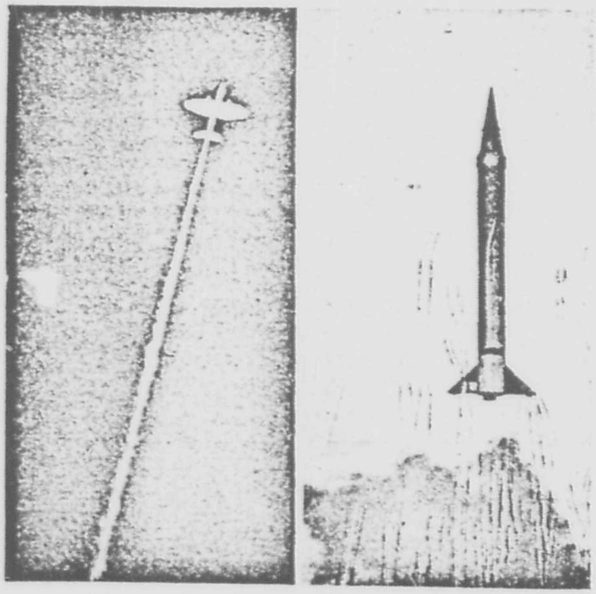
The jet engine itself, directly, thrusts back a mass of gases, which takes on, together with the aircraft, speed in the opposite direction. But far from always is motion created directly by the engine, i.e., the machine "producing" mechanical energy through the expenditure of energy of other forms: thermal, chemical, electrical, etc. It is sufficient to remember the aircraft with internal combustion piston engine. This engine on an aircraft itself throws back nothing directly — does not impart motion to some mass. It only turns the propeller, which throws back the necessary mass of air for flight of the aircraft. Thus, in this case the device for moving the mass, directly providing motion, or the so-called propelling agent, is separate from the engine. The reaction engine, or direct reaction engine, as it sometimes is called, combines the functions of engine proper and propelling agent. Herein lies its fundamental distinction from other engines of transport devices created by man.

But the reader may ask: do we assume that flight of aircraft indeed is accomplished as a result of throwing back a mass of air by propellor or mass of exhaust gases directly by the reaction engine? Let us assume that is so. But what is thrust back when an athlete runs on a track or a machine rushes over the asphalt of a street?

The answer to such question is not so obvious, although, of course, mass is thrust back here also — this requires law of conservation of momentum. That which is thrust back in this case is not air, but the earth. The earth with each impact of the athlete's leg or turn of the wheel of a motor vehicle takes a push in the opposite direction. It is understandable that the earth scarcely senses this push: momentum transmitted to it is not able to impart any noticeable speed to the huge mass of the earth. But this, of course, does not change the essence of the matter. In this case also there is a thrusting back of mass, to which is imparted momentum. Mechanics teaches us that for certain momentum to be imparted to mass a force must act on it for a certain time (according to one of the basic laws of mechanics, momentum is equal to impulse, i.e., the product of its magnitude and duration of the action).

But, after all, force never exists singly, since by its very definition, its very essence, it is the result of the influence of one mass on another, of one body (in general this can be a field of force) on another. When a running man is repulsed from the earth, he acts on it with certain force. With the same, but oppositely directed, force the earth acts on the man. The same applies in the case of the reaction engine. In all such cases, in accordance with one of the basic laws of mechanics (it frequently is called Newton's third law), action is equal to reaction, one force is equal to another. We can consider one force active; then the other will be the reactive force, or simply reaction (from the Latin reagere to react). If the force of action of the man on the earth is active, the retroactive force is reaction, although we are fully justified in considering the reverse, of course.

Thus we have encountered the idea of the aircraft jet engine: motive, or tractive. force is created in it as a result of the thrusting out of a certain mass of gases (which for practical purposes can be considered air). In certain types of reaction engines it can be the products of different chemical reactions taking place in the engine. There also can be created such engines, to be discussed at the end of the book, in which the "repelled mass" consists of quite unusual particles — ions, plasma, and even quanta of electromagnetic energy. We can also distinguish engines in accordance with the origin of force causing repulsion of mass. But one way or another, independently of the arrangement of the engine, the force of reaction of the repelled mass is that tractive force which forces the aircraft, rocket, or spaceship to move with tremendous speed.



GRAPHICS NOT REPRODUCIBLE

Fig. 2. Jet aircraft and rockets fly because their engines "repell mass."

But just why are reaction engines predestined to become engines of unprecedented speeds?

This is for a number of causes. One of them is the fact that the family of reaction engines is especially extensive. There now exist a great number of different types of reaction engines (many of them will be discussed below) and ever newer types are appearing. Each of these engines manifests its best properties under certain operating conditions, in particular, at defined speeds of flight. Thus it is that reaction engines provide a whole spectrum of possible speeds of motion, up to the very greatest. To every speed or, more exactly, to every section of the total speed range, corresponds some best type of reaction engine. However, it is significant that the best properties of reaction engines are manifested at very high speeds of flight.

The second cause is that many reaction engines do not need the air surrounding us for their operation. Owing to this, they are capable of operating in the vacuum of outer space, where only the highest speeds of motion are possible.

When we say that only some reaction engines are able to operate outside the terrestrial atmosphere, we make this reservation because many engines use atmospheric air for combustion of their fuel. It is very important to understand that only this prevents such engine operating outside the atmosphere, and in no way has to do with the method of creation of reactive force. These engines, like all others, without exception, create reactive motive force as a result of discharge of their own exhaust gases – for this they do not need air (as it is needed, for example, by the propeller on aircraft with reciprocating engines).

Another important cause is the fact that reaction engines, thanks to their fundamental simplicity, usually possess remarkable characteristics with respect to specific power (i.e., the power which they develop per unit of their mass). As a rule, in this respect they have no equals among existing engines. It is easy to understand how important this is for achievement of high speeds. With growth of speed the role of each extra gram on an aircraft or rocket becomes ever greater – in order to carry this gram and to accelerate to predetermined speed ever greater and more rapidly increasing power is required.

With the help of reaction engines we have already achieved the first important successes in the struggle for sharp increase of speed – with aircraft the speed of sound has been exceeded, in rocketry and astronautics the boundaries of orbital and escape velocities have been reached. There is no doubt that increase of speed will now take an ever faster pace – such is the indisputable law of development of reaction engineering. Today we have mastered speeds yesterday thought unattainable; ahead of us lie new, still greater speeds. And these new boundaries will be taken with the help of reaction engines, called upon to be the engines of unprecedented speeds.

CHAPTER II

THE REVOLUTION IN AVIATION, OR THE BRILLIANT SUCCESS OF THE TURBOJET ENGINE

The first properly remarkable success of reaction engines is connected with aviation. This in no way means that it was in aviation that such engines were first used. As it is known, the first application of the reaction engines belongs to a time when aviation did not even exist. Many centuries before man rose into the sky the rocket appeared. This happened long before science explained the principle of jet propulsion – in this case, as in a number of others, human practice outstripped theory.

The first rockets were probably used in the ancient East. From there they spread throughout other countries, in particular, to Russia, where they found considerable application.

The first rockets were rather primitive tubes – bamboo, paper, then iron – sometimes filled, in addition to powder, with some other combustible composition. Gases emanating from the rocket, as a result of combustion of the powder, forced it to fly at high speed. They left a trail of fire in the night sky, and upon falling to earth, set fires, so that it is not surprising that they came to be used as combat weapons. But frequently such rockets were also used for amusement – as "fireworks".

In the course of many centuries the application of solid-propellant rockets remained limited. Certainly, they improved somewhat, and with time their role increased and became more significant (so, in particular, it was in Russia as a result of the fruitful work of the military specialists A. D. Zasyadko and K. I. Konstantinov in the 19th Century).

Only in the course of the second world war did rockets for the first time become formidable weapons, used with success by Soviet soldiers. Such weapons were the guards' rocket mortars - the famous "Katyusha" rocket launchers, the salvos of which destroyed the German fascist aggressors. This was the first truly big victory for military jet engineering. It was followed by still more remarkable successes in aviation.

Although rocket artillery appeared during the war years as armament in a number of countries, it did not then become the main direction in development of the "God of war," artillery - ordinary barreled artillery held its positions. Another situation existed in aviation. The first jet aircraft appearing at the war fronts demonstrated so great a qualitative superiority over piston aircraft that immediately after the war decisive transition of military aviation to jet power began.

This swift rearmament of military aviation was so all-embracing that it is possible with good reason to speak of a technical revolution in aviation, connected with the introduction of jet engines on aircraft.

Nor did civil aviation stand aside, although here the advantages of using jet aircraft were not so evident in the beginning. This is normal, since in this case, in contrast to military aviation, not purely technical, but a complex technical and economic characteristics have decisive effect. Furthermore, in civil aviation considerably greater reliability is required of engines. However, in recent years in civil aviation also a decisive breakthrough has been made. Now on passenger airlines numerous jet aircraft are used. Old civil piston aircraft still fly; they number approximately twice the jets and they will fly in the future, but, at the same time, they have not only lost their monopolistic position, but their role has become ever more modest. By the example of our Aeroflot it is clear that the leading position is confidently occupied by jet-powered passenger aircraft. It is well-known that on all of our principal airlines now fly liners – Tu-104, Il-18, Tu-114, An-10 and others. They now transport more than 3/4 of the total number of air passengers in our country.

The singularity of successes gained by the jet engine in aviation and the swiftness of its victories are especially striking because these victories were gained over such strong contenders as the aircraft piston engine. After all, by the time the first jet engines were installed on aircraft, reciprocating engines had behind them fully four decades of intense development. During those years reciprocating engines attained an exceptionally high degree of perfection. Their reliability, low weight, high economy, and tremendous power were unprecedented in all the history of engine building. With the help of reciprocating engines aviation gained a great many victories in the unending struggle for speed, distance, and altitude of flight.

It was precisely when the reciprocating engines were, it would seem, at the zenith of their glory, and long before that, that the first jet aircraft appeared, while science predicted the inevitable demise of these engines in their future skirmish with the jet engine. In a number of scientific investigations it was incontrovertibly proven that aviation could not rely on further fast progress if reciprocating engines were to be used as before. In the first place, it cannot take the "sound barrier," i.e., reach flight speeds exceeding the speed of sound.

At first glance this role of the speed of sound, then the fact that it is so important a boundary for aviation, may seem unexpected. Certainly, we are not speaking in this case about the noise accompanying flight of aircraft. Here the matter is quite different.

Even if an aircraft flew entirely noiselessly, making no sounds, the speed of sound would characterize conditions of its flight in exactly the same way.

If flight speed is considerably less than the speed of sound, we say that flight is subsonic; when it starts to approach to the speed of sound, flight becomes transonic; then sonic, supersonic, and finally hypersonic. Here the character of flight and physical phenomena accompanying it change so sharply that they lead to radical changes in construction of both the aircraft and its engine. And, probably, the most radical changes are in the engine.

But what is the reason for such unusual influence of the speed of sound? Why does this speed so sharply affect conditions of flight?

The essence of the matter consists in that sound constitutes essentially, weak changes of local pressure or, so to speak, weak disturbances, propagated in air. Sound waves constitute moving thickening and rarefaction of air, i.e., regions of raised and lowered pressure. It is these alternating pressure waves, acting on the eardrum, that we perceive as sounds. The amplitudes of these waves, i.e., values of pressure and rarefaction, are very small — sound vibrations constitute weak disturbances. It is necessary to increase somewhat the intensity of sound waves, i.e., the loudness of sound, and in crossing a certain limit we reach a point at which sound starts to cause painful sensations in the ear.

The speed at which sound vibrations spread in air is generally very high: it is equal to approximately one-third kilometer per second.[1] The exact value of this speed depends on air temperature: it is changed as the root mean square of this temperature.

Consequently, in summer the speed of sound is greater than in winter; at the earth's surface it is greater than at altitude, where

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[1] This is determined by the value of average speed of random thermal motion of air molecules.

it is colder.

Were the speed of sound considerably less, this would introduce a number of troubles in our daily life. Thus, for example, sirens on motor vehicles or bells on streetcars could be useless – their sounds would reach pedestrians too late. But the main troubles connected with such low speed of sound would be quite different. Thus, for example if the speed of sound were less than those speeds at which trains and motor vehicles now move, let's say 80-100 km/h (instead of the true value of the order of 1200 km/h), it is doubtful whether contemporary speeds of railroad and automotive transport would be possible. It is most probable that the world would in this case be much "slower": the speed of a motor vehicle or train would not exceed approximately 70-80 km/h, and many record-breaking achievements of sportsmen – motorists and motorcyclists – would not have been realized.

How can all of this be explained? Why does the speed of sound so "retard" motion? These questions can be answered only if we know what physical processes accompany the motion of bodies in air (these processes are studied by the aerodynamics). After all, during motion outside the atmosphere, for example, in the vacuum of cosmic space, such phenomena are absent. However, sound does not propagate there, so that even the concept of the speed of sound is absent.

A body moving in the atmosphere directly ahead of itself somewhat compresses the air acting on it, similarly to a piston. This small (inasmuch as we also consider speed low for now) increase of pressure spreads, naturally, in all directions in the atmosphere, as occurs with any small disturbance, and with sound in particular. The speed of such propagation of pressure wave, as we already know, is the speed of sound. Inasmuch as the speed of the body is less than the speed of sound, the pressure waves induced by the moving body move ever further and further depart from it, gradually weakening and fading out. In this case, as can be seen, pressure waves are connected with the moving body only at the very moment of their conception. Subsequently there is no interaction between them.

When the speed of the body gradually increases, this picture at first does not change qualitatively, only disturbances start to spread more slowly relative to the moving body. But here, finally, the speed of the body has increased so much that, although it still is less than the speed of sound, on separate sections of its surface the speed of air flowing around it becomes equal to the speed of sound, or may even exceed it. This is not surprising, since we know that as air flows around a body its speed on various sections of the surface of the body can considerably exceed the average flow rate (or the speed of the body itself if it moves). As soon as this occurs, the character of the stream flowing around the body undergoes sharp, qualitative changes. In this case the surface of moving body has supersonic speed relative to the air, and therefore local thickenings of air no longer can "depart" the surface and spread in the atmosphere. They move together with the body at speed greater than the speed of sound. Thus is formed a powerful wave of raised pressure, connected with the moving body and rushing through the air together with it. This wave no longer constitutes a weak disturbance similar to a sound wave. In it pressure is increased very strongly, sometimes many times, such growth of pressure being the result of deceleration of flow, i.e., decrease of its speed, and a discontinuity is born in the very thin layer of air. Therefore such a wave, moving together with a body, is called a <u>shock wave</u> (thus emphasizing the sharp, shock character of growth of pressure) or a <u>shock compression</u>.

It is well-known that when the shock occurs, i.e., sharp deceleration of moving mass, a considerable part, and sometimes all, of the kinetic energy of this mass is lost, being turned into heat. Such is the case when one solid strikes another, for example, hammer against anvil, when a stream of liquid strikes a barrier, and in other analogous cases. The same thing happens in a shock wave, or compression shock, accompanying an aircraft moving at supersonic speed. In all cases of shock transition of kinetic energy to heat constitutes a loss of useful energy. After all, even if we were to decide to use the heat generated by the blow for accomplishment of effective work (which in the majority of cases is impossible), we

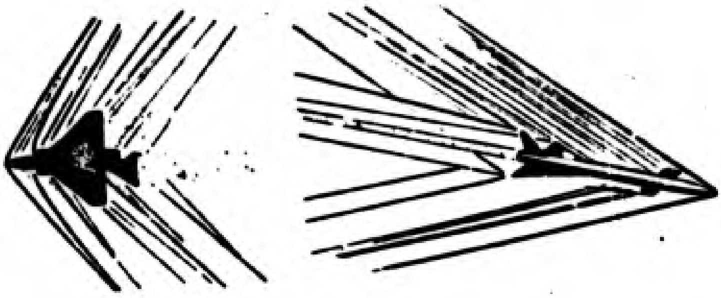

Fig. 3. Such shock wave (it also is called ballistic, or compression shock) accompanies aircraft flying at supersonic speed. Under certain conditions of illumination it can even be be seen and photographed.

could convert, or, so to speak, recover, only a certain part of this heat; that remaining is irretrievably lost. This is stated by the second law of thermodynamics, according to which all heat cannot be converted in some thermal machine to effective work: a certain part of heat is inevitably lost.

This is why the formation of shock waves on the surface of flying aircraft is connected with significant growth of drag, i.e., the force which must be surmounted by the engine in order to maintain stabilized horizontal flight. This additional drag, induced by the appearance of shock waves, or compression shocks, on surface of an aircraft, is therefore frequently called wave drag.

It is easy to understand that with approach of flight speed to the speed of sound an ever greater part of the surface of an aircraft is apparently under conditions of supersonic flight, inasmuch as the speed of air flowing around this part of the surface becomes supersonic. Furthermore, and this is primary, the intensity of shock waves is increased. Naturally, the proportion of wave drag in the total value of the rapidly increasing frontal drag of the aircraft also increases. This occurs up to that moment when flight speed becomes equal to the speed of sound.

We see now why approach of flight speed to the speed of sound demanded of the aircraft propulsion system – reciprocating engine with propeller – rapid and very considerably increase of the motive force or tractive force developed by it. For this an engine must, with low weight, develop ever higher power. The increasing of engine power necessary for achievement of sonic speed turned out to be so great that it exceeded the capabilities of the reciprocating engine. Thus the "sound barrier" stood in the path of development of aviation.

It became clear that successful surmounting of the "sound barrier" would require engines of different principle than the piston type.

The aviation world turned with hope to the jet engine. And, it must be confessed, these hopes were justified brilliantly. Wherein, then, lies the secret of the so remarkable success of these engines?

This secret is connected, first, with the amount of power which engines of given dimensions and weight are able to develop. And on what in turn, depends power?

As it is known, all heat engines (this includes both piston and jet aircraft engines) develop useful power as a result of the fact that fuel is burned in them. Chemical energy of fuel is converted during combustion to thermal energy of the gaseous products of combustion, and this, in turn, into useful mechanical energy. The latter can be either in the form of useful work, accomplished by the revolving shaft of the engine (as in the case of piston and so-called turboprop engines) or in the form of kinetic energy of the jetstream of gases (if a jet engine).

It is absolutely obvious that useful power will, other things being equal, be greater, the more fuel is burned in the engine per unit of time, for example, per second. "Other things being equal" in this case means identical value of efficiency factor, characterizing the degree of perfection of conversion of chemical energy of fuel to useful work. This efficiency depends, in turn, on very many factors: levels of temperatures and pressures in the engine, the ratio by weight of fuel and air in the mixture, and others. It is obvious that in various engines these factors are different in value, but such divergence is not decisive. Therefore it is possible, in first approximation, to estimate the value of useful engine power from the quantity of fuel burned in it.

But what prevents burning fuel in an engine? After all its power will then be greater. Can it be that this is prevented by insufficient strength of its parts, low fuel pump capacity, and similar causes? No, the main reason, of course, is not this.

It turns out that the basic obstacle is connected with air. Solution of the apparent paradox is very simple. We know, of course, that combustion of conventional fuel cannot occur without air. Both these components participate in combustion as equal partners (only in rocket engines are other situations possible, but we are not concerned with them now). Inasmuch as the composition the fuel-air mixture participating in combustion, is determined, as we agreed above, to every kilogram of fuel burning in an engine there must correspond and strictly defined quantity of air necessary for combustion. For the usual hydrocarbon fuels used in aviation this is usually 10-20 kg.

This is why superiority with respect to power belongs to that engine in which there is a greater quantity of air participating in combustion, i.e., passing through the engine per second. Engine with great per-second flow rate of air will generally develop greater power.

Through the aircraft jet engine must pass considerably more air than through the piston engine (sometimes tens of times more).

In order to understand why the situation is such we must compare design features of aviation piston and jet engines. There is no need for detailed study of their construction here; it is sufficient to grasp only the fundamental distinctions.

As it is known, in reciprocating engines the places where all working processes of the engine take place in sequence — suction of air, its compression, mixing with fuel, combustion, working expansion, and exhaust — are the cylinders of the engine. This one thing makes hopeless competition between reciprocating and jet engines. The fact, on the one hand, is that the swept volume of cylinders, filled each time by fresh air, comprises only a small part of the total volume of the engine; on the other hand, even through this small volume does not pass fresh air continuously, but only during the process of suction, constituting a relatively small part of the total working cycle of the engine. Consequently, with respect both to space and to time the process of fresh air feed in the reciprocating engine is very limited.

The situation is quite otherwise in the case of the jet engine. Air flows through it continuously, with very great speed, and this flow passes through almost the whole midsection (i.e., maximum transverse) of the engine. This explains the great distinction in flow rates of air through piston and jet engines.

But if air enters the jet engine over almost its entire cross section, obviously, all further processes of change of state of air comprising the working cycle of the engine and leading to formation of jet thrust, i.e., propulsive force, have to take place beyond the inlet section, somewhere along the axis of the engine. Herein lies one of the most fundamental distinctions between jet and piston engine. In the jet engine working processes occur simultaneously, but in various zones of the engine, as if on a unique conveyer, at the beginning of which enters "raw material" — air, and at the end is issued the end product — jetstream of heated gases. In the piston engine all processes take place in one zone (cylinders), but in various times.

Consequently, in the jet engine working processes take place sequentially in space; in the piston engine they are sequential in time. The character of these processes is basically the same — all of them are necessary for effective conversion of chemical energy of fuel to useful output power.

For example, let us acquaint ourselves with the operation and arrangement of the typical contemporary aircraft jet engine — the turbojet (or TRD). This engine got its name because one of its main parts is the turbine, which we will discuss in greater detail below.

Atmospheric air enters the frontal unit of the engine. If the engine is on a flying aircraft, the sucking of air into the engine is assisted by impact pressure of the incident stream of air. If, however, the aircraft is standing still, the sucking-in of air is accomplished by the engine alone. The front section of the engine, into which atmospheric air passes, is called the air inlet — this is station No. 1 on that "conveyer" of continuous changes in state of air, representing the engine. The air inlet is usually very simple in design, as if a segment of thin-walled tubing of large diameter. But when we speak of an engine intended for great supersonic speeds of flight, the air inlet can be one of the most complex and vital parts of the engine.

From the inlet air goes to the compressor. This is the second important station of the "conveyor" of successive changes in state of air in the engine. At present transition to very high supersonic flight speeds is radically changing matters; but if the air intake is greatly complicated and its role becomes many times more vital, the compressor is simplified and its importance diminished. In essence, these two parts of the engine seemingly change roles. This is discussed in detail in Chapter IV, devoted to supersonic turbojet engines.

The compressor, as its name indicates, serves for compression of air, i.e., decrease of its volume and increases its pressure. Many millions of different compressors throughout the world perform their important duty — compress air and various other gases — in chemical, refrigerating, gas, power, and other branches of industry. Compressors of the most various types, constructions, and dimensions have been created and successfully used. But in turbojet engines compressors of only two types are used, and these two types occupy far from equal positions. Essentially, it is possible to speak of the overwhelming superiority of the so-called axial-flow compressor, which is used in practically all contemporary high-power turbojet engines.

Fig. 4. The turbojet engine constitutes a "conveyer" of continuous changes in state of air flowing through it: a) air intake openings, through which air enters engine (initial station of "conveyer"); b) openings through which jet stream leaves engine (final station of "conveyer").

However, it was not always so. In the beginning, when the first turbojet engines appeared, approximately identical use was made of axial-flow compressors and their competitors, the radial or, as they are more frequently called, centrifugal compressors. The latter were even used somewhat more frequently. And if after several years unconditional victory was gained by the axial-flow compressors, in spite of certain indisputable deficiencies, this is explained, essentially, by one, but then decisive and indisputable advantage. It consists in the fact that for that same frontal area the axial-flow compressor is able to provide greater mass flow rate of air, i.e., it possesses greater productivity. Remember how important this is from the standpoint of augmentation of engine thrust and you will understand why the axial-flow compressor gained decisive victory. A considerable role was played also by the fact that the axial-flow compressor is able to compress air to a higher degree.

The axial-flow compressor was not invented in connection with appearance of the turbojet engine. It was used quite widely in technology long before this. However, the perfection which characterizes compressor at present is connected with its use in aviation, as one of basic elements of the turbojet engine.

In order to understand the operating principles of the axial-flow compressor it is enough to refer to the ordinary table fan. Everyone has probably felt the elastic stream of air that strikes the hand placed in front of such a fan. The rapidly turning blades of the fan gather air and eject it with force, increasing its pressure slightly. It is easy to understand that with the installation of several such fans, one after another, the stream of air would be still more elastic, and compression of air in it would be greater Herein consists the idea of the axial-flow compressor. It constitutes, essentially, several such separate "fans," set one after another. However, these "fans" differ in many ways from the usual table fans. If such a "fan" were set on a table, it would require an electric motor of tremendous power (of hundreds and of thousands of kilowatts) and, accordingly, colossal dimensions; and instead of a light breeze it would create a simoom, sweeping away everything in its path. The point here is not only that dimensions of such a "fan" are much larger (almost a meter in diameter) but that it revolves at considerably higher speed, and its numerous long, thin blades, bent in cross section similarly to the arc of an aircraft wing and somewhat twisted along the radial axis, are a miracle of perfection from the

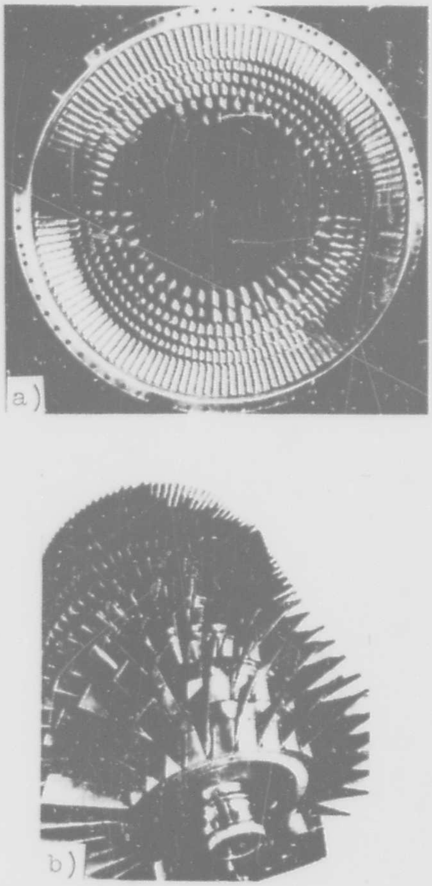

Fig. 5. Axial compressor — one of the most important elements of the contemporary turbojet engine: a) guide-vane assembly; b) rotor.

standpoint of aerodynamics. This ensures high values of efficiency and productivity of compressor.

But distinctions between compressor and several fans placed one after the other do not end here. In order to utilize completely the capabilities of such combination of separate "fans" or, more exactly, compressor rotors, between each two such rotors we place similar, fixed wheels. These rows of stationary blades "prepare" the airstream exiting from the revolving rotor of compressor for compression in the following rotor. If there were no such preparation, the effectiveness of subsequent rotors would be very low.

Each pair – rotor and subsequent row of stator blades, serving to change the direction of flow behind the rotor (they are usually called guide vanes) – is called a compressor stage. In all there can be many such stages in the axial-flow compressor of a turbojet engine – up to 15-17. And although in each separate stage increase of air pressure is relatively small (at best approximately 30%), at the compressor outlet pressure is very high – increased by 10-15 times.

But why is the compressor needed? Why must air entering the turbojet engine first be so strongly compressed?

This question, by the way, pertains, of course, not only to the turbojet engine. After all, for example, and in an aircraft piston engine the fresh air filling a working cylinder (sometimes this is no longer air but a fuel-air mixture which, naturally, does not change things) is first of all subjected to compression. It is true that in such an engine air is compressed not in special compressor but in that same working cylinder, by the piston (and sometimes additionally by a compressor, supercharger, serving for preliminary compression of air entering the cylinder). But this does not change the essence of the matter – one way or another the air is first compressed. But why?

It is necessary to mention that heat engines in which there was no preliminary process of compression existed earlier. However, it was soon found that introduction of the compression process makes an engine much more economic, i.e., strongly reduces the cost of fuel per horsepower developed. The causes of such influence of preliminary compression of air are set by technical thermodynamics – the science studying the working processes of different heat engines. In particular, it has been proven that the more the air is compressed in the compressor of a turbojet engine, the higher the engines economy, i.e., the less the specific fuel consumption per kilogram of jet thrust developed. It is true, as we will see below, the matter changes when flight speed considerably exceeds the speed of sound.

Thus station No. 2 of our "conveyer" is behind. The air is now compressed. What must be done with it now?

The following station, No. 3, is no less important than the preceding to overall operation of the engine. This station is the combustion chamber, in which the air is heated to required operating temperature. The name combustion chamber itself indicates that heating of air is accomplished as a result of the burning of a certain quantity of fuel in it. Therefore station No. 3 constitutes point of connection to the main "conveyer" of another, auxiliary "conveyer," over which moves not air but fuel. In the same way, in a factory, to the main assembly conveyer for motor vehicles at various points are connected other conveyers, for example, those for assembly and supply of engine or body.

Fuel is injected into the combustion chamber by special injectors, as is done in boiler furnaces or in open-hearth furnaces. Fuel is usually light petroleum fractions – kerosene or gasoline, though somewhat different from those used in reciprocating engines. On aircraft fuel is stored in tanks, whence a pump feeds it to the injectors. Along the way it passes through a fuel-feed control, setting and maintaining proper quantity of fuel for injection into combustion chamber. This regulator constitutes one of the most complex and vital parts of the engine, since fuel flow must be regulated with great accuracy, and it depends on many factors, characterizing rating and operating conditions of engine.

But station No. 3 is the point of connection to "main conveyer" of not only the fuel "conveyer," for in order that combustion takes place the fuel injected into the air must be ignited. For this serves an ignition system, the final stations of this auxiliary "conveyer" – ignition plugs – being inside the combustion chamber. In contrast to the one for fuel this second "conveyer" operates only during starting. After this new batches of fuel sprayed into the combustion chamber are ignited by the torch existing continuously in the chamber.

However, ignition of new batches of fuel by the torch and constant maintenance of the stable torch in the combustion chamber are far from simple. The airstream passes so swiftly through the combustion chamber that compared to it the most frightful and destructive of typhoons seem like light breezes. And into such a howling hurricane the injector sprays fuel, which must be ignited and burned completely. This problem is far more complex than, for example, an attempt to strike a match in strong wind, and even this is, indeed, far from always successful.

To what devices will a smoker not resort in trying to kindle a cigarette in the wind. First he turns his back windward and conceals the trepidating flame of the match under the flap of his overcoat or in his cupped palm, trying to find a quiet place where the wind does not whistle. Similar procedures must frequently be followed by the designer of a combustion chamber. The palm of hand in these cases is replaced by a register – special devices, sometimes of very odd form – so-called screens or stabilizers. They shield, i.e., protect the fire torch in the chamber from the swift airflow. Success of design depends on how successfully are chosen the means of shielding the torch, ensuring its stability (flame stabilization).

Unfortunately, general principles of such stabilization have been studied little as yet, in consequence of which creation of every new chamber involves numerous and labor-consuming experiments, tests, and alterations. Science is helping here also by revealing the secret of combustion in high-speed airflow.

But flame stabilization is only one of the problems which the designers must solve. Of the many other problems there is one which we must not forget to mention, since it is connected with the most important peculiarity of the turbojet engine. We are speaking of the temperature at which gases leave the combustion chamber, heading to the following station of the "conveyer."

At first glance, the question of temperature of gases seems somewhat idle. After all, combustion is for the purpose of increasing

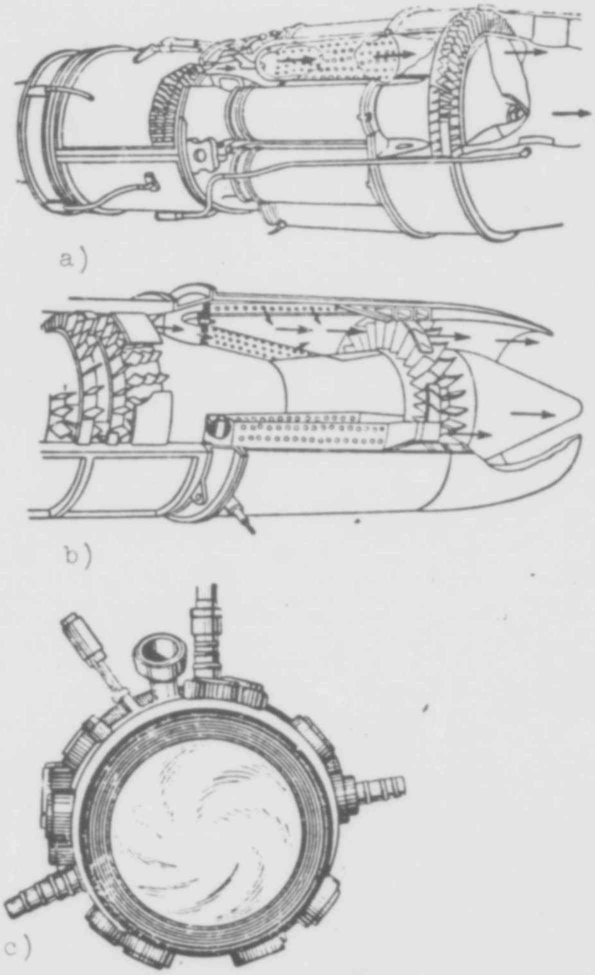

Fig. 6. Combustion chamber of turbojet engine: a) combustion chamber; b) annular chamber, c) in the chamber constantly rages a fire vortex, formed during burning of fuel in swift airflow.

temperature of air flowing through engine, in order to increase its exit velocity or, more exact, that of gases from it, thereby in increasing thrust developed by engine. As thermodynamics teaches us, exit velocity is changed, other things being equal, proportional to the square root of temperature. This means that for a two-fold increase of exit velocity absolute temperature of gases must be increased four times. Since it is desirable that engine thrust be high as possible (remember the quest for speed of flight!), obviously temperature of gases should also be increased as much as possible (we are, of course, not talking here about engine economy, which imposes certain changes, which will be discussed in the following chapter).

During combustion of kerosene or gasoline in air, the temperature of forming gases attains approximately 2000°. We must assume that with just such temperature these gases have to leave the combustion chamber. However, in reality the matter is quite different. Gases at this temperature forming during combustion while still in the combustion chamber are intentionally cooled approximately twice, sometimes still more. The reason for such cooling of gases is connected not with the combustion chamber itself but with the following station of the "conveyer," which will be discussed below.

Meanwhile, the necessity for cooling gives a great deal of trouble to the designer of the combustion chamber. For cooling the gaseous products of combustion it is necessary to dilute them with fresh cold air. Therefore only a certain, smaller part of all air passed by compressor into combustion chamber participates in combustion of fuel. The basic portion bypasses the combustion zone and is mixed beyond this zone with hot gases, cooling them to needed temperature. But this mixing is far from a simple problem. It is necessary to deal here with the most contradictory requirements. Thus, for example, it is quite obvious that mixing of air with gases must be a very rapid process, since otherwise much space is required for its realization, taking from the "conveyer" too large a segment of its overall length — this meaning the engine becomes excessively long. But in spite of its swiftness the process of mixing must not agitate the airflow, disturb its proportions and uniformity. This requirement advances the following station of the "conveyer," where gases proceed from the combustion chamber. For best solution of such contradictory requirements it is again necessary to take the path of numerous experiments, selecting optimum design. Here also science strives to help the designer by establishing general laws of physical phenomena occuring during mixing.

A great many other complex problems must be solved by the designer creating a combustion chamber of a turbojet engine. We will not enumerate them here – space does not permit it. If there now are combustion chambers working effectively and reliably in engines many hundreds of hours in succession, this is the result of the intensive efforts of whole collectives of scientists, designers, and engineers. Certainly, far from all is yet clear. The development of jet aviation poses ever new, pressing problems. Certain of them will be treated in following chapters. One thing is indisputable, however – accumulated knowledge and experience and further persistent investigations will ensure solution of these problems too.

The time has come to move along our "conveyer" to the following station – No. 4. Here the invisible belt of the "conveyer" delivers heated gases from the combustion chamber. What is done with them here?

Obviously, the gases, carrying thermal energy, into which chemical energy of burning fuel was converted, must now give up this energy. Now these gases have to start to work – to accomplish the useful work, for which, after all, the engine was created. Consequently station No. 4 has to be the place where thermal energy is converted to useful mechanical energy.

Remember the functions fulfilled by station No. 2, the compressor? Air was compressed in it, so that mechanical energy expended on rotation of rotors of compressor passed into internal thermal energy of air. If now at station No. 4 the reverse process of transition of thermal energy to mechanical must take place, then, obviously, such process will be accompanied by expansion of air. Such expansion can be carried out in various ways, but it must first of all meet one condition – supply the mechanical energy necessary to drive the compressor.

It is easy to see that for this purpose is best suited a machine similar in design to the compressor, but with diametrically opposite working process – expansion, rather than compression, of air. Such a machine – the axial-flow turbine – constitutes station No. 4 of our "conveyer," which is why the engine itself is called a turbojet. Like the compressor, radial turbines are used here also (in them expanded gas flows from periphery or rim of the rotor to its center, i.e., in the opposite direction as compared to the radial, or centrifugal, compressor). However, they are used only in engines of relatively small dimensions and low power. In the absolute majority engines have axial-flow turbines, single- or multistage. These turbines also consist of rows of stationary blades, called nozzles in this case, and revolving rotors with blades about their periphery. Gases expanded in turbine give up their energy to its rotors, and the turbine revolves, developing tremendous power, measured in tens of thousands of horsepower. Practically all of this power is expended on driving the compressor, for which the turbine is connected with it through the power shaft. The compressor, together with turbine and connecting shaft, is frequently called the engine rotor (essentially, this is its only revolving part).

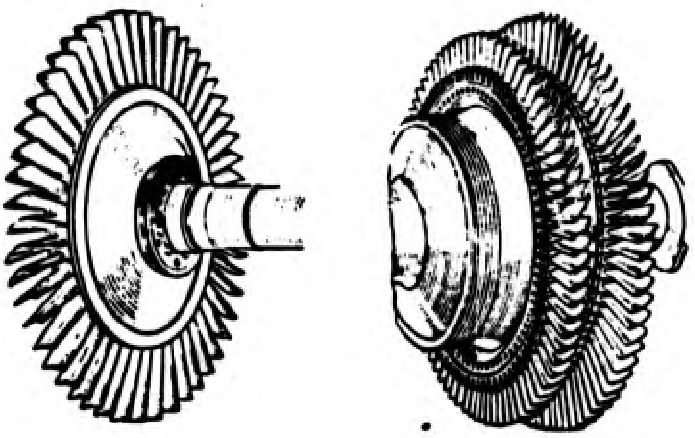

Fig. 7. The rotor of a gas turbine, driving the compressor of the turbojet engine.

Thus we find that the turbine develops power, which is completely expended by the compressor... What is the sense of all this? The engine works, fuel burns, and all power developed by the engine is absorbed by it!

This certainly is not the case, for such engine would be useless. The only conclusion that can be drawn is that station No. 4 is probably not the last in the "conveyer." Obviously, there is one more concluding station – No. 5, and it is its existence that justifies creation of the engine. This is true because it is here that gases give up, for accomplishment of effective work, the reserve of internal thermal energy still remaining in them after expansion in turbine.

The fact that such reserve undoubtedly exists, is demonstrated by the difference in temperatures of air compressed in compressor and of gases expanded in turbine. For compression of cold air less work is required than for compression of hot, and conversely, expansion of hot air is connected with accomplishment of more work than cold. Therefore gases heated in combustion chamber posses greater reserve of energy than does the air ahead of this chamber (i.e., behind the compressor), and are able during expansion of accomplishing a greater amount of work than was expended in the compressor on compression of air. Owing to this, power of turbine can be greater than necessary for driving the compressor, and this excess power can be used, or, so to speak, taken from the shaft of turbine for accomplishment of some useful work. This is precisely the case in the so-called gas turbine engine utilized at electric power stations for generating electrical current, those used on ships to drive propellers, or those on railroad locomotives for transmission of power to drive axles. Such engines are also used in aviation.

But in the case of the turbojet engine (it also, generally speaking, is a gas turbine) the matter is different. Turbine power is almost exactly equal to compressor power. This means the gases do not give the turbine their whole reserve of useful energy – part of it is removed with them. This is seen physically in the fact that pressure of gases behind the turbine is still higher than atmospheric. It is for just this therefore, that they preserve capability of further expansion, with accomplishment of useful work. How and where is this expansion, constituting station No. 5, accomplished?

In order to answer this question it is enough to remember what the assignment of the turbojet engine is. This is to create a jetstream of gases, emanating from the engine at high speed, so that considerable jet thrust is obtained. Consequently station No. 5 is that part of the engine in which formation of such stream occurs. This part is called the jet nozzle.

Acceleration of gases during flow through the jet nozzle is accompanied by their expansion. Work, accomplished by gases during expansion in nozzle is expended directly on their acceleration, i.e., passes into kinetic energy. For such expansion to take place the nozzle must be channel or pipe of gradually decreasing cross section, for example, the frustum of a cone, as is most frequently the case. It is true that at high supersonic speeds of flight the nozzle, like other parts of the engine endures radical changes, which will be discussed later in Chapter IV.

Thus, we have finally reached the very end of the "conveyer." Our description touched on its main stations and we limited ourselves to mentioning only certain auxiliary "conveyers" – different systems of the engine. In reality, of course, the contemporary turbojet engine, besides main parts, includes many various auxiliary systems and units. Without them engine operation would be impossible. The total number of parts in the contemporary turbojet engine sometimes attains almost twenty thousand.

We already know that the result of engine operation is the stream of gases emanating from it, creating jet thrust. The reader may ask the question (the author has heard it more than once): what sections of the "conveyer" directly create thrust? Not in the sense, of course, that they ensure operation of engine (all stations of the "conveyer," all elements of the engine, participate in this) – they simply are interested in knowing what parts of the engine are influenced by those forces from gases, which in the end create jet thrust. After all, tractive force is physically created by forces arising as a result of pressure of gases on internal surfaces of engine parts. The jet stream is like a "mirror image" of these forces – equal to them but oppositely directed, acting from internal surfaces on gases, accelerating them, and forcing them to exit the engine at greater speed. It is for this reason that it is possible to calculate the value of thrust from exit velocity, or more exactly, from momentum of gases emanting from engine.

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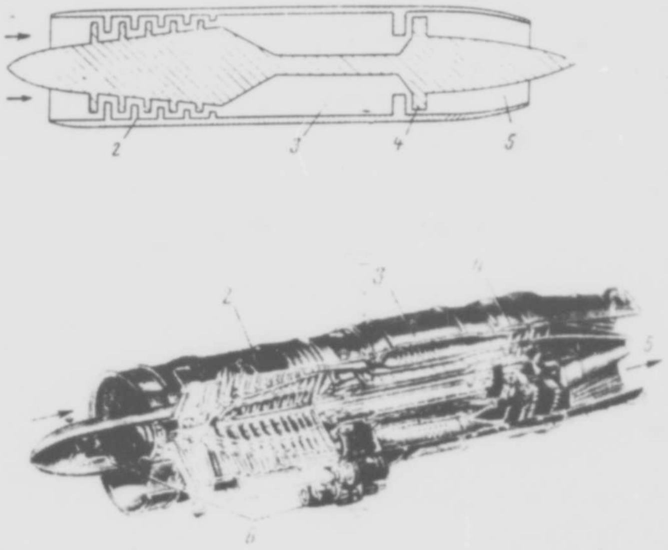


Fig. 8. The main parts of turbojet engine — stations of "conveyer" of changes of state of air (the "Avon" engine, England): 1 — air intake station (No. 1); 2 — conpressor (station No. 2); 3 — combustion chamber (station No. 3); 4 — turbine (station No. 4); 5 — jet nozzle, expansion of air (gases), and acceleration of stream (station No. 5); 6 — regulators and accessories.

How do we answer the previous question? It is obvious that forward-directed (i.e., as is thrust) forces from gas pressure appear in those sections of gas-air duct of engine where pressure is increased and acts on surface of engine so that it seems to push them forward. Thus, for example, is the case in all sections of the duct, which constitute an expanding channel. Conversely, if the channel for flow of gases narrows, the force of pressure of gas flow acts backward, i.e., decreases jet thrust. This figure shows how this is obtained: if from all forces of gas pressure appearing inside

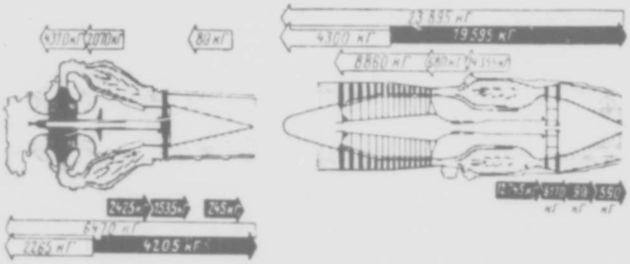
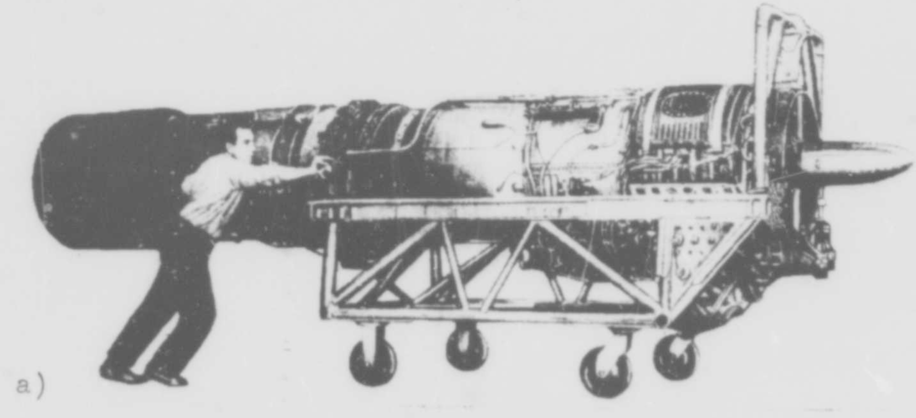


Fig. 9. On internal surfaces of the turbojet engine act forces of pressure of air (and gases) flowing through it, leading to formation of jet thrust (by example of the British "Nene" (left) and "Avon" (right) engines [кГ = kg].

the engine and directed forward, in the direction of flight (such forces appear, in particular, in compressor and combustion chamber), we subtract all forces acting backward, we obtain the exact value of tractive force. Of course, in this complex calculation, as already was mentioned above, is not needed — tractive force is determined in accordance with jet stream.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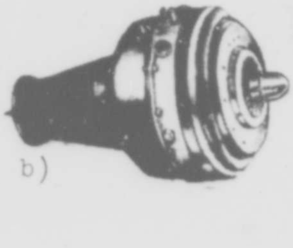

b)

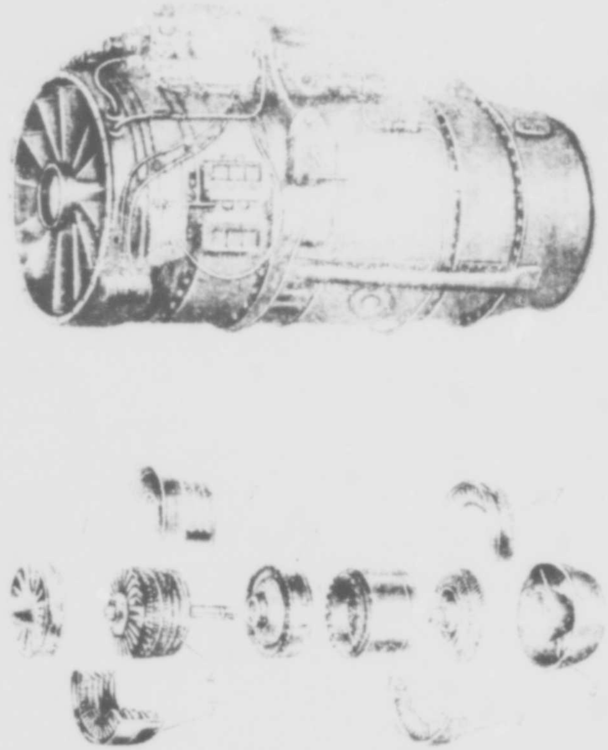
Fig. 10. Contemporary high-power turbojet engine, developing thrust of several tons (a). There also are low-power turbojet engines (that depicted in figure (b) weighs 10.5 kg and develops thrust of 32 kg).

Less than two decades are covered by the short history of the turbojet engine, but in these years it attained high perfection and secured truly remarkable victories.

The contemporary turbojet engines used on military aircraft and passenger liners are able to develop thrust measured in several tons. There are engines with thrust exceeding 10 tons. In the 20 years that have elapsed from the moment of appearance of the first turbojet engine their thrust had increased more than 20 times. And at the same time, on light aircraft – sport, private, and others – are used miniature turbojet engines, whose thrust hardly attains one hundred kilograms, and still less.

Great progress has been made with respect to decreasing the weight of the turbojet engine per kilogram of thrust developed (so-called specific weight). If the first operational turbojet engines had specific weights of more than half a kilogram per kilogram of thrust, it is not rare now to find value of one-quarter kilogram and less. This means that engine thrust is sufficient to lift 4 to 5 or more such engines into the air. There is no need to talk about the importance of maximum possible decrease of weight of the aircraft engine – this is obvious. But it is especially necessary to lighten in all possible ways an engine intended for an aircraft capable of vertical (i.e., without run) takeoff and the same type landing. These aircraft face a great future. Engines for such aircraft will be discussed in somewhat greater detail in Chapter VIII.

At first glance somewhat less impressive but also especially important is the progress of the turbojet engine with respect to improvement of its economy, i.e., decrease of fuel consumption per kilogram of thrust (so-called specific fuel consumption). For the first engines specific consumption exceeded 1 kg of fuel per hour per 1 kilogram of thrust, attaining 1.4-1.5 kg(thrust)/kg(fuel)·h. Now in operation are engines whose specific fuel consumption is about half this.



GRAPHIC NOT REPRODUCIBLE

Fig. 11. Weight of this turbojet engine is approximately 10 times less than the thrust developed by it (the J-85, United States, weighs 136 kg and develops thrust of 1300 kg). Below are shown the main parts of the engine: 1 — intake (air inlet); 2 — rotor of axial-flow compressor (8 wheels); 3 — split compressor chamber with guide-vane apparatus; 4 — adapter between compressor and combustion chamber (diffuser); 5 — annular combustion chamber with 12 burners (flame tubes); 6 — rotor of two-stage axial-flow turbine; 7 — split body of turbine with nozzle blades; 8 — outlet part (jet nozzle).

Reliability of the turbojet engine has become especially high. In this respect in the beginning it was greatly inferior to the piston engine, but it has since outstripped it.

There already are engines that have operated reliably and unfailingly many hundreds and thousands of hours before, in accordance with the strict adopted rule in aviation, in spite of fully apparent efficiency and absence of defects, being removed from aircraft and reconditioned. In the beginning the service life of a turbojet engine was but a few hours, or tens of hours at most! The full period of service of a turbojet engine on an aircraft now sometimes exceeds 100,000 hours.

It is not surprising that the fundamental superiority of the turbojet engine over the piston engine and its such rapid improvement permitted aviation, with its help, to realize truly phenomenal successes.

Immediately accomplishing a jump in flight speed of about 200 kmh as compared to the old piston aircraft, the jet aircraft developed this success rapidly. Soon near approaches to the sound barrier were mastered, and in recent years it too has been taken by storm. Now aircraft with turbojet engines, both piloted and pilotless, fly at altitudes of more than 30 km (although just a few years ago it was considered that their "ceiling" was 20 km) at speeds 2.5-3 times that of the speed of sound. The turbojet engine became truly the sovereign hegemon in aviation.

But, is it really sovereign?

CHAPTER III

WHEN THE TURBOJET ENGINE RELINQUISHES ITS PREEMINENCE TO ITS CLOSE "RELATIVES"

What is the reason for the question with which the preceding chapter was completed? It should have been in this chapter, judging from the title, that the reader is convinced of the fact that the turbojet engine with unprecedented ease subdued aviation, accomplishing a technical revolution in it.

This, of course, is true. And yet the question is founded, since almost immediately after their appearance in aviation the first turbojet engines had to sustain competitory struggle not only with reciprocating engines, but also with engines of another type, essentially born of the turbojet.

The first of such close "relatives" of the ordinary turbojet engine which we will discuss here, the so-called two-shaft engine, differs essentially only in construction – its working process is the same. This engine illustrates one of possible directions of design improvement of the turbojet engine. We will allot certain attention to it also because it is quite widely used abroad. At the same time this will allow us to clarify one of the weaknesses inherent to the simple turbojet engine.

In the preceding chapter, when discussion centered around the compressor of the turbojet engine, it was noted that the higher the compression ratio, the more economical the engine, i.e., the less expenditure of fuel per kilogram of developed thrust (so-called specific fuel consumption). One can understand how aviation is interested in this – engine economy directly determines the flying range of an aircraft or the transported payload possible. Furthermore, in many cases increasing the compression ratio also leads to augmentation of thrust, which further increases the advantage of such increase.

But how is it possible to increase the compression ratio of air in the compressor? One of evident ways consists in increasing the number of stages in the axial-flow compressor. It is not surprising that many engines have very long compressors, from 12 to 15 and more stages. However, the designer selecting this path is threatened by many difficulties. Probably the biggest of them is connected with the problem of operational stability of compressor. This is perhaps the Achilles heel of the axial-flow compressor. Imagine that suddenly (this usually occurs with decrease of thrust, i.e., during transition to partial-power conditions) the normal flow of air through the compressor is distrubed. Pressure in it starts to fluctuate sharply, causing the blades of the compressor to be rained upon by large pulsating loads like the frequent blows of a hammer; the flow rate of air through the compressor (its productivity) sharply decreases in the same way. It is natural that as a result of such phenomenon (called compressor surging) the whole engine ceases to work normally: its thrust drops sharply and starts to vary sharply, and frequently the engine stops altogether. It happens that strong pulsations of pressure lead to breakage of important engine parts and its full breakdown, the more so because during surging temperature of gases in engine also increases sharply. The point here is that with increased number of stages in the compressor the danger of surging increases.

Scientists and engineers have spent and are spending much effort on investigation of surging and development of means of combating it – using, for example, turnable stator blades in compressor, bypass

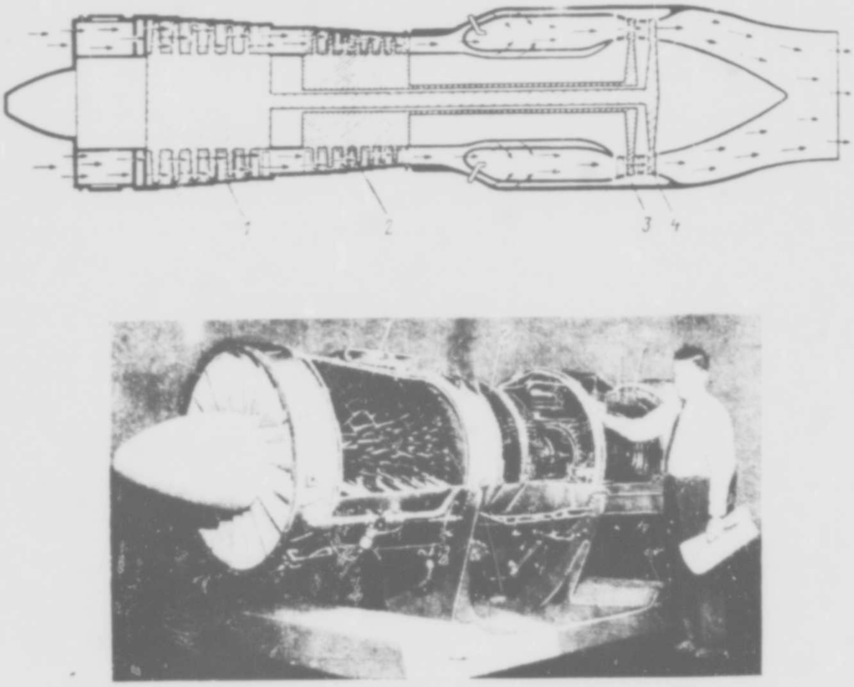


Fig. 12. Two-shaft turbojet engine (or engine with compound compressor). Top — schematic diagram of engine. Below — cutaway engine (civil two-shaft engine JT-4, the United States, thrust about 8000 kg): 1 — low-pressure compressor, 2 — high-pressure compressor, 3 — high-pressure turbine, 4 — low-pressure turbine.

of air from its first stages, and others. One of such means, a very effective one, is used in the engine in question. This engine, as was mentioned above, is called the two-shaft (or two-rotor) turbojet, or the engine with compound compressor. The compressor of such engine has a large number of stages, which with usual construction surely would lead to surging. To prevent this, the compressor is divided into two independent parts so that, essentially, one compressor is as if behind the other. Therefore such compressor is called two-stage: in it compression is carried out in two stages.

Speeds of rotation of the two compressors are different (for the first, i.e., for the low-pressure compressor it decreases more strongly with transition of engine to conditions of decreased thrust), which is most profitable from the standpoint of prevention of surging, which, as was noted above, appears with reduction of thrust and resultant decrease of flow rate of air through compressor. Herein, as a matter of fact, lies the main advantage of the compound compressor. But this advantage leads to complication of engine. In particular, it is obvious that to drive each compressor in this case, a special turbine is required. The low-pressure compressor (i.e., first stage of compression) is also driven by the low-pressure turbine. It is easy to see that this turbine must be located behind the first, i.e., it is the second cascade of expansion of gases. In turn, the high-pressure compressor is driven by the high-pressure turbine, so that the shaft of the low-pressure rotor, connecting low-pressure compressor and turbine, passes through the hollow shaft of the pressure rotor, as can be seen on the engine diagram.

The complexity of the two-shaft engine as compared to the usual turbojet is evident. The fact that it finds rather wide application in those cases when we need a combination of great thrust for flight at high speed and good engine economy (for long range) indicates that this increase of structural complexity justifies itself. It is compensated partially by the fact that the number of compressor stages in this case can be smaller than in the usual compressor with the same compression ratio.

Before discussing the new engine – "relative" of the turbojet – we must look into certain very essential peculiarities of the working process of any jet engine, including that of the turbojet. These peculiarities are characteristic for jet engines, distinguishing them from all other heat engines used in contemporary technology. The peculiarities alluded to here are connected with the stream of gases emanating from the engine.

Do you remember (these were discussed in the preceding chapter), the energy conversions occurring in the turbojet, or in any other thermal reaction engine? First, the chemical energy of fuel, as a result of its combustion, passes into thermal energy of the products of burning, the gases, and then this thermal energy is converted to kinetic energy of gases in the jetstream. It is these conversions that determine the first peculiarity of any jet engine, about which we want to speak.

The peculiarity consists in that the assignment of any jet engine is to produce thrust, which it developes... thrust, but not power, which is characteristic for any other engine – automotive or ship, heat or electrical. We are interested in how many kilograms of thrust are developed by a turbojet engine and not in the horsepower equivalent of its power, in how much fuel it uses per kilogram of thrust and not in that per horsepower, in how much it weighs and not per horsepower, and so forth. All determine engine thrust.

But thrust, as we already know, is equal to the momentum of the jetstream emanating from the engine (mV), i.e., for the same mass of emanating gases it is directly proportional to exit velocity; for thrust to double the amount of increase required of exit velocity. Therefore all basic engine characteristics – thrust, specific fuel consumption, specific weight, etc. – depend on exit velocity. At the same time in examining energy conversions in engine – in particular, during appraisal of its efficiency, i.e., the degree of perfection of engine with respect to efficient use of expended fuel – it is necessary to deal with kinetic energy of gases in jetstream, and this energy is proportional, as it is known, to the square of exit velocity. Therefore, for example, an increase of engine efficiency of, let us say, 20% should produce an increase of 20% not in speed but in the square of exit velocity. Increasing effective engine output (i.e., kinetic energy of jet stream) by four, we increase engine thrust by only two, if this increase is attained as a result of increase of exit velocity. If, however, a fourfold increase of effective output is attained with constant exit velocity, i.e., as a result of a fourfold increase of mass of emanating gases, thrust will no longer be increased by 2, but 4 times.

Here we see the first very important result of the examined peculiarity of the turbojet engine. For the same expenditure of fuel and identical degree of perfection of engine it is profitable to increase mass of emanating gases and to decrease exit velocity as much as possible: this will increase engine thrust and decrease fuel consumption per kilogram of thrust. Large mass and low speed, but not small mass and high speed of outflow are profitable.

What is the practical effect of this on operation of the turbojet engine? We know that in a given engine the mass of gases – this is the flow rate of air through the engine – will not increase, since we consider it as already being the highest possible for engine of given frontal cross section. But then, another situation is possible. By changing the quantity of fuel burning in the engine, i.e., so to speak, enriching or learning the fuel-air mixture, it is possible to change exit velocity and, consequently, engine thrust. Is it profitable to increase expenditure of fuel and, thus, temperature of gases, exit velocity, and engine thrust?

Here we encountered a fact quite unexpected at first glance. Increasing the temperature of gases increases the effectiveness of the working cycle of the engine (its efficiency), i.e., leads to efficient use of all the greater part of energy of the burning fuel. From this standpoint it is profitable to have temperature of combustion as high as possible. However, increase of engine thrust here will lag behind increase of fuel consumption. Roughly speaking, a fourfold increase of fuel consumption results in fourfold increase of gas temperature, while exit velocity and engine thrust only doubles. This means that economy of engine with respect to thrust developed by it will worsen, since for every kilogram of thrust it will expend two times more fuel.

It is true that increase of engine efficiency with temperature increase will correct the situation somewhat, since an even greater part of fuel energy is converted to kinetic energy. And yet, increase of thrust will be less than increase of fuel consumption.

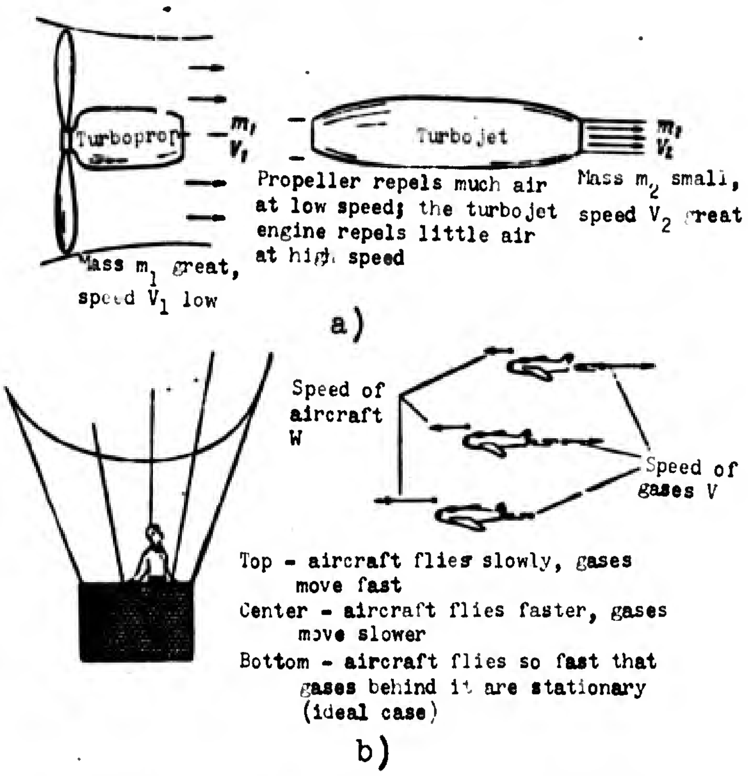
As theory shows, for contemporary turbojet engines it is expedient to increase temperature of gases in combustion chamber to approximately 600-650°C. Until this temperature has been attained the stronger will be the effect of growth of engine efficiency and with an increase of temperature of gases thrust and engine economy also increase. At higher values of temperature its further increase, as before, increases thrust but already worsens economy, inasmuch as fuel consumption per kilogram of thrust increases.

If all contemporary engines operate with higher gas temperatures, approximately 850-950°C, this is due only to the quest for increased thrust, having nothing to do with increased specific fuel consumption. And indeed, who needs an engine developing insignificant thrust, even if it is advanced with regard to fuel consumption? Plus the fact that such engine will not provide the necessary speed of flight (such requires great thrust), it will be very heavy – will have high specific gravity per kilogram of thrust. It is understandable that in every concrete case only by thorough and very labor-consuming calculation can we determine the most advantageous gas temperatures. This calculation shows to what gas temperature corresponds least total weight of engine and of fuel consumed in flight – this temperature will be the most advantageous. It is clear, for example, that the longer the flight must last, the lower the most advantageous temperature, since specific fuel consumption increases here, while the role of engine weight becomes relatively smaller. Therefore for long and relatively slow flights the "cold" engine is more profitable, but for high-speed and short flights, conversely, the "high-temperature" engine is better.

It now becomes clear why in the past, when the speed of flight of aircraft was still very low, application of the turbojet engine was simply unprofitable. It is clear also why in civil aviation on low-speed aircraft reciprocating engines with propellers are still used. The fact is that under these conditions the reciprocating engine with propeller is more profitable and more economical than the turbojet. This is explained very simply, for in such propulsion system the interconnection between power and thrust, characteristic only for the jetstream, is lacking. Actually, combustion temperature in the reciprocating engine is very high, which ensures great engine efficiency, i.e., low specific fuel consumption per horsepower. But this high temperature does not increase the "exit velocity," i.e., speed of discharge of air for creation of thrust, which would be unprofitable, as we already know. The propeller, driven by the engine, throws air back at a much lower speed, but in accordingly greater quantity than is characteristic for the jetstream of the turbojet engine. The propeller of the low-speed piston-engine aircraft throws several hundred kilograms of air back per second at least 10 times more than the turbojet engine of several times greater power!

And is it impossible to use this so profitable method of unique "insulation" of temperature of gases from exit velocity in the turbojet engine too? After all, the temperature of gases could then be as high as engine design would permit, while exit velocity would be as low as possible and profitable. The result would be high engine efficiency and thrust. Such an engine would possess indubitable advantages over the turbojet, at least at relatively low flight speeds. It would also be powerful, i.e., develop great thrust, and economical, i.e., expend little fuel per kilogram of thrust and would be light. Furthermore, it would possess still other merits, resulting from the second feature characteristic for the turbojet, or for any jet engine, connected with the energy conversion taking place outside the engine in its jetstream.

After fuel energy has been converted to kinetic energy of jetstream, is it possible to state that this kinetic energy, determining engine power is, indeed, efficiently utilized? It is



Top - aircraft flies slowly, gases move fast
Center - aircraft flies faster, gases move slower
Bottom - aircraft flies so fast that gases behind it are stationary (ideal case)

Fig. 13. Energetics of the jetstream: a) thrust greater when mass is great and speed of its repulsion is slow (for identical kinetic energy of stream); b) loss of kinetic energy of stream is greater, the lower the speed of flight as compared to speed of stream.

obvious that efficiently utilized energy is only that expended on accomplishment of effective work of moving the aircraft, i.e., that work for whose sake the engine is placed on the aircraft. And only in one ideal case is all kinetic energy of stream wholly utilized. This, of course, constitutes the ideal case.

You will remember the observer in the cabin of the aerostat studying the foggy contrail behind the jet aircraft. This observer helped us in Chapter I to look into the principle of jet propulsion. Foggy streams rushed past him at high speed. At what speed exactly? We now are ready to answer this question. If the exit velocity of gases from engine is equal to V, and speed of aircraft is equal to W, it is obvious that speed of gases in jetstream, recorded by observer in cabin of aerostat, is equal to V - W. Kinetic energy of gases moving at such speed is proportional, obviously, to the square of speed, i.e., $(V - W)^2$. What does this energy indicate? What does it characterize?

It is obvious that gases rushing in the atmosphere no longer accomplish effective work, their kinetic energy disperses uselessly in the air — this is lost energy. Consequently the lower this loss, other things being equal, the greater the effective work accomplished by the jetstream, i.e., work expended on flight of the aircraft. But loss of energy is less the less difference between speeds V and W. Only in that case when exit velocity V is exactly equal to flight speed W is there no loss (see Fig. 13). This is normal, since only in this case will the observer see stationarily frozen gases, left by the flying aircraft, next to him. This will be almost precisely the "track" that appears during flight of a charged particle in the Wilson cloud chamber. It is true that in this case benefit from our observer would be small (not seeing moving gases, he could not help us in elucidation of the prinicple of jet propulsion), but then the biggest benefit would be derived from the gases themselves — their kinetic energy is transmitted to the aircraft, i.e., is expended usefully.

It is true that this case is not characteristic for the turbojet, or for any other jet engine using atmospheric air for its operation. It is not characteristic because in such case the speed of air flowing through the engine, all along its "conveyer," is not changed — exit speed is equal to entrance speed. But then engine thrust is also equal to zero, the engine runs free, by itself. The same case is very real and important for those engines in whose operation atmospheric air does not participate. We will discuss such engines in Chapter VI. Here we need it only to illustrate losses of kinetic energy of jetstream connected with its speed relative to the fixed observer.

Once again we obtain a very important practical conclusion from this second characteristic feature of the jetstream. This conclusion consists in that the lower the flight speed, the less should be the exit velocity; otherwise the greater part of kinetic energy of jetstream will not efficiently utilize. Moreover, lost energy even brings harm, since the greater the speed of gases in the stream, the greater the noise produced by the engine, but the problem of noise frequently is hardly of prime importance. Consequently this is one more argument in favor of the fact that at relatively low flight speeds low exit velocity is profitable.

But how do we ensure that temperature of gases (products of combustion in the turbojet engine) is high and temperature of jetstream is low? In the turbojet engine gases, the products of combustion, exit in the form of a jetstream.

This difficulty is easily surmounted if we apply our "experience" with the propeller-driven propulsion system, i.e., reciprocating engine with propeller. Actually, the propeller is a very good means of repelling large air masses. With relatively large diameter and, consequently, large swept area it is able to repel huge quantities of air. Consequently, it is necessary to use the propeller!

But the propeller requires a great amount of power to drive it. Certain aircraft piston engines developed several thousand horsepower. How can this power be obtained in the turbojet engine?

Obviously, calculation can be only for the turbine. However, as we know, the turbine develops only that power which is necessary for driving the compressor. Will it also be able to rotate the propeller in addition to this?

And why not? Certainly, for this it will be necessary to increase the power of the turbine. It is possible to do this by forcing the gases to additionally give a certain part of their energy to the turbine wheel. It is true, here this expression of gases in the turbine will occur already down to a lower final pressure so that already it will remain somewhat as part of the concluding expansion in the jet nozzle, and exit velocity of gases, and with it also the

Fig. 14. During flight tests of an Il-18 aircraft one of its four turboprop engines is stopped.

jet thrust of the engine will drop sharply. Thrust will be insignificantly small. As usual, a gain in one leads to a loss in the other, but we accepted this consciously. In such an engine thrust is created basically no longer by the jetstream, but by the propeller.

Such an engine is therefore called turboprop (or TVD). The turbine of this engine, which in all its main parts is no different from turbojet, rotates the propeller in addition to the compressor. In connection with this the turbine has a greater number of stages, usually 3-4 and in the front section of the engine is mounted a special pinion gear, the so-called reduction gear, with the help of which rotation from the shaft of the engine is transmitted to the propeller with a reduced number of turns, just as required. Engine exhaust gases emanate as before through the jet nozzle, but their thrust now is already very small and is only a small addition to the thrust of the propeller.

At relatively small speeds of flight (however, quite recently they seemed unattainable, when the only engine in aviation was piston) the turboprop engine turns out to be more profitable than the turbojet. It expends less fuel per kilogram of thrust and ensures less total weight of engine and fuel during prolonged flight.

Turboprop engines were proposed even earlier than turbojet. In particular, in our country a patent for such an engine was issued back in 1923 to engineer V. N. Bazarov. The first turboprop engines were used almost simultaneously with turbojet. However, design difficulties, in particular those connected with the reduction gear and control system for the engine, somewhat delayed the introduction of turboprop engines into operation.

During the last few years turboprop engines have received very wide application in civil aviation in a number of countries. The majority of our new passenger aircraft – the giant Tu-114, Il-18, An-10, and others – are equipped with precisely such engines. In spite of a somewhat lesser speed of flight than for liners with turbojet engines (however, this difference while small is equal to approximately 100-150 km/h) a turboprop aircraft will accomplish a long-range flight, for example Moscow-Khabarovsk, in quicker time. Of course the Tu-104 flies at a greater speed, but expends much more fuel and therefore on this route is forced to make two landings for refueling. The slower Tu-114 (850 km/h – this now is slow!) will carry out the flight nonstop in a little over 8 hours. The turboprop engine has other advantages, for example, in regard to takeoff and landing, noise, and others, therefore it occupies a solid place in aviation. Incidentally, the twin-shaft construction is used with success for the turboprop engine also, where it has additional merits.

Recently great interest was caused abroad, especially in the United States, by the possibility of considerable improvement of economy of the turboprop engine (i.e., decrease of fuel consumption) by means of installing a so-called regenerator on it. A regenerator is a heat exchanger which is mounted on the path of exhaust gases coming out of the engine. These gases are very hot and all their energy is lost irrevocable, while in the combustion chamber of the engine it is necessary to expend a great deal of energy, burning fuel, in order to heat air which is entering the chamber from the compressor. Involuntarily the thought is suggested, is it not possible to use at least part of the heat which is lost with exhaust gases for heating the air before the combustion chamber? This could lead to restoration (heat engineers call it regeneration) of this part of irrevocably lost heat and thus decrease the expenditures of fuel in the engine. Here the regenerator serves this purpose. Gases which are moving through it on the way from the engine to the outside heat the air which is moving from the compressor to the combustion chamber. Certainly the engine is complicated and its dimensions and weight increase, but if the aircraft should accomplish a prolonged flight, then the saving in fuel consumption is great and covers these deficiencies. This is why such so-called regenerative turboprop engines can be used for aircraft used on flights of long distance or duration.

Only one small step from the turboprop engine leads to another close "relative" of the turbojet engine which frequently it is necessary to give priority to, the so-called turboshaft. This not too successful and understandable name pertains to an engine in which, just as in the turboprop, all or almost all useful power is developed by a turbine, but it rotates not the propeller of an aircraft, but the rotor of a helicopter or accessories on board heavy aircraft.

The number of types of such turboshaft engines is very great and their application is increasing continuously. And what distinguishes the turboshaft engine from the gas turbine engine of an electric power station or railroad locomotive — a gas turbine locomotive, without even mentioning a motor vehicle?

Still one more close "relative" of the turbojet engine, which we will speak about in the conclusion of this chapter, is only aeronautical, since it is no longer used anywhere. In aviation all the same it plays an ever increasing role in recent years. This engine occupies as if an intermediate position between turbojet and turboprop and is called two-circuit, although frequently the term turbofan (or TVRD) is encountered.

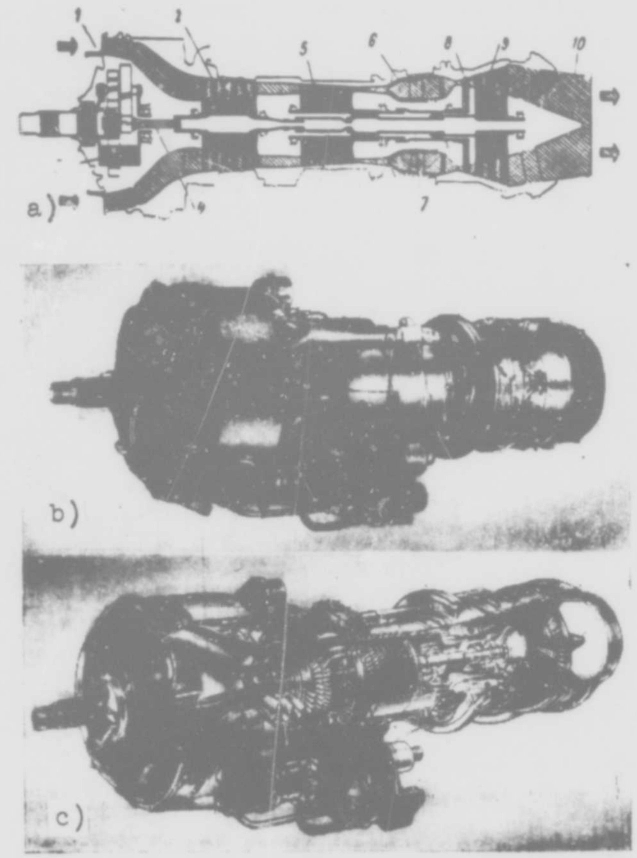


Fig. 15. Twin-shaft English turboprop engine "Tyne" with a power of 6100 hp (of these approximately 5600 hp are due to the propeller and 500 hp are due to the jetstream). Number of engine revolutions is equal to 15,250 rpm: a) diagram of engine; b) external appearance; c) structural arrangement: 1 — air inlet; 2 — low-pressure compressor; 3 — reduction gears, 4 — high-speed shaft for driving propeller; 5 — high-pressure compressor; 6 — combustion chamber; 7 — intermediate shaft; 8 — high-pressure turbine; 9 — low-pressure turbine, 10 — exhaust pipe.

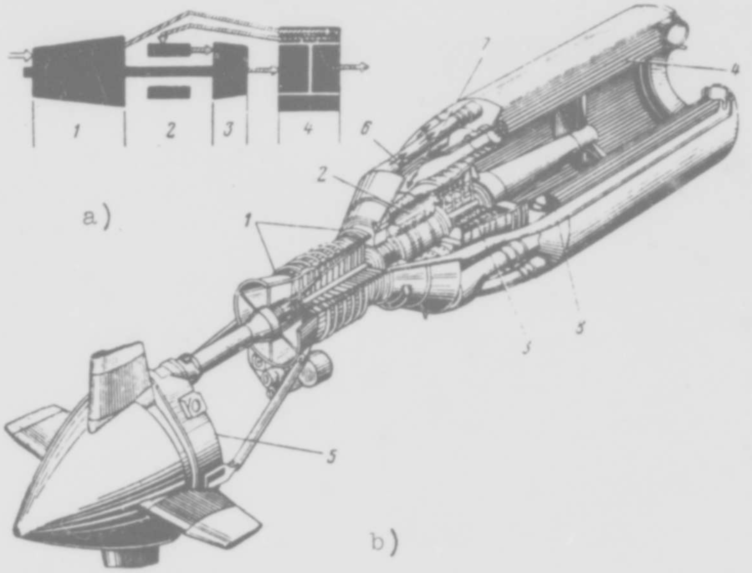


Fig. 16. "Regenerative" turboprop engine. It makes use of part of the usually lost thermal energy of exhaust gases: a) schematic diagram of engine, b) its structural arrangement (engine T-78, the United States). 1 — compressor (14-stage, axial); 2 — combustion chamber; 3 — turbine (4-stage); 4 — heat exchanger-regenerator; 5 — reduction gear driving the propeller; 6 — channel, through which cold air flows from compressor into regenerator; 7 — the same channel for already heated air, proceeding from the regenerator to the combustion chamber; 8 — tube of heat exchanger.

After an explanation of the advantages of the turboprop engine at relatively slow speeds of flight, it should be clear that with an increase of speed these advantages gradually vanish. Certainly, during supersonic flight a turboprop engine is very inferior to turbojet. But how is it possible to present the gradual transition from turboprop engine to turbojet according to increase of speed? What should be the most advantageous engine for these intermediate speeds?

With an increase of flight speed the diameter of the propeller should inevitably decrease, since speed of airflow, flowing around

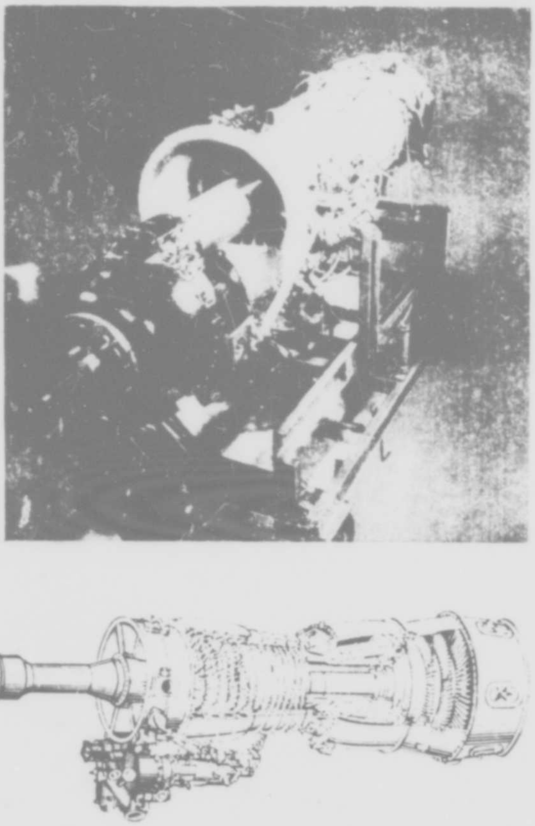


Fig. 17. From the turboprop engine to turboshaft — one step. The turboprop engine T-64 (the United States) with power of approximately 2600 hp (from above) can be easily converted into a turboshaft (below). It differs by the absence of a reduction gear and therefore is somewhat lesser in weight (400 kg instead of 490 kg) and slightly greater in power (by approximately 80 hp).

the ends of the propeller blades, attains the speed of sound, and then exceeds it. This is connected with a sharp decrease of efficiency of the propeller and a loss of its basic qualities. Such a decrease of propeller effectiveness at supersonic flow around is explained by the same reasons as for the increase of drag of an aircraft during approach to the "sound barrier" (this was spoken of in Chapter I).

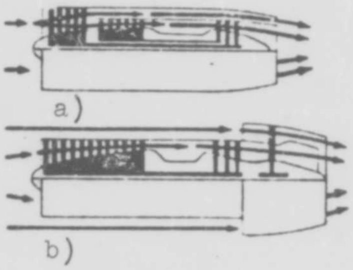


Fig. 18. Diagrams of two-circuit turbojet engine: a) bypass (twin-shaft construction): b) turbofan (with rear location of fan).

But if the diameter of the propeller decreases, then there is a decrease in the section of airstream rejected by it, as a result of which the velocity of rejection should increase, otherwise the quantity of rejected air and power of the propeller will decrease. An increase of velocity of rejection is generally connected with an increase in the number of revolutions of the propeller. Thus the turboprop engine makes the first step in the direction of turbojet.

Several more such steps and the propeller is transformed, essentially, into a high-speed fan (simultaneously it becomes multivaned) very similar already to the wheels of the first stages of an axial-flow compressor. Similarity increases yet until such a propeller is hidden away usually in a special "tunnel," i.e., it is placed in a cylindrical housing (this increases the effectiveness of the propeller), and this fan is even made to two-stage, i.e., with two wheels. Well, what further? Obviously, further it is necessary to go already to a compromise step – it turns out to be profitable to decrease power of turbine which is running the fan so that part of the energy of gases is used again in the jet nozzle. It is true, exit velocity of gases will be at first relatively small, to increase it strongly is still unprofitable. But then the velocity of gases emanating through jet nozzle should gradually increase and, accordingly, will gradually decrease the quantity of air rejected by the fan. This will lead to a gradual increase of average or effective rate of rejection so that every increased value of flight speed will have its own corresponding most advantageous value of this average rate of rejection.

Certainly it is impossible to develop an engine which would automatically reorganize its work in such a way, by adjusting in the most advantageous manner to every given flight speed. But then it is possible to develop an engine which is most profitable in a definite, quite narrow range of change of flight speed. There is such an engine and it is called two-circuit (or double-circulating). Air in it flows not along one, but along two parallel "conveyers." One of these "conveyers," or circuits as is customarily said, is the basic "engine" circuit; it is described in the preceding chapter. The other is the secondary "fan" circuit. The greater the speed of flight and less its duration, then the "more modest" this secondary circuit is. The less air flows through it, then the less, as they say in these cases, the "coefficient of bypass" (this coefficient constitutes the ratio of mass consumption rates of air through the "fan" and "engine" circuits). Incidentally, from this point of view the conventional turboprop engine can be viewed as two-circuit with a bypass coefficient equal to 200-300. For conventional bypass engines this coefficient fluctuates most frequently with the limits of 0.5-1.5.

Bypass-turbojet engines are made differently. Sometimes the first stages of the engine compressor are equipped with extended blades so that airflow beyond these stages is divided in two: internal flow moves through the remaining stages of the compressor and further along the "motor" circuit, and external flows along the annular "secondary" circuit. Then both these flows are either mixed in a common jet nozzle (similar engines are usually called bypass), or emanate outside each through its own special nozzle, as in the case of the turbofan engine. In principle the first path is more profitable, but more complex.

Sometimes a turbofan engine is developed from a simple turbojet. This is done simply by adding to the latter, sometimes in front and sometimes from behind, a short "fan" unit — a ring embracing the engine in which a 2-3-stage fan revolves. This fan is run either from the compressor of the engine if it is placed in front, or from

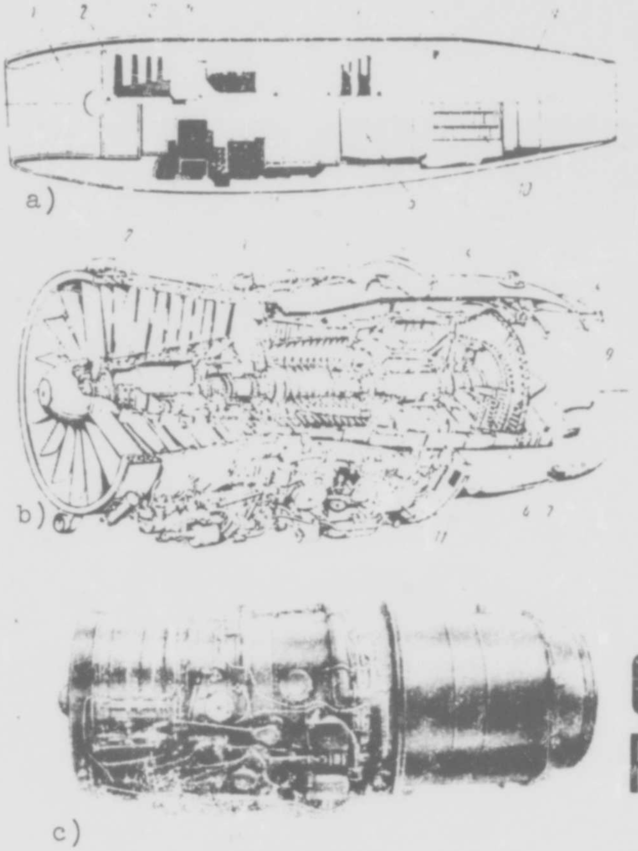


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Fig. 19. Two-circuit (bypass) English turbojet engine "Spey" (twin-shaft construction, thrust approximately 4500 kgf): a) diagram of engine; b) its structural arrangement; c) external view: 1 — general air inlet; 2 — low-pressure compressor; 3 — high-pressure compressor; 4 — bypass channel (2nd circuit); 5 — combustion chamber of tubular-annular type; 6 — high-pressure turbine; 7 — low-pressure turbine; 8 — mixer; 9 — general exhaust pipe; 10 — thrust reverser (this will be spoken of in the following chapter); 11 — aggregates of the engine.

its turbine — in a rear location. In the latter case drive is usually carried out from an independent turbine wheel, not connected with basic turbine of engine which is running its compressor.

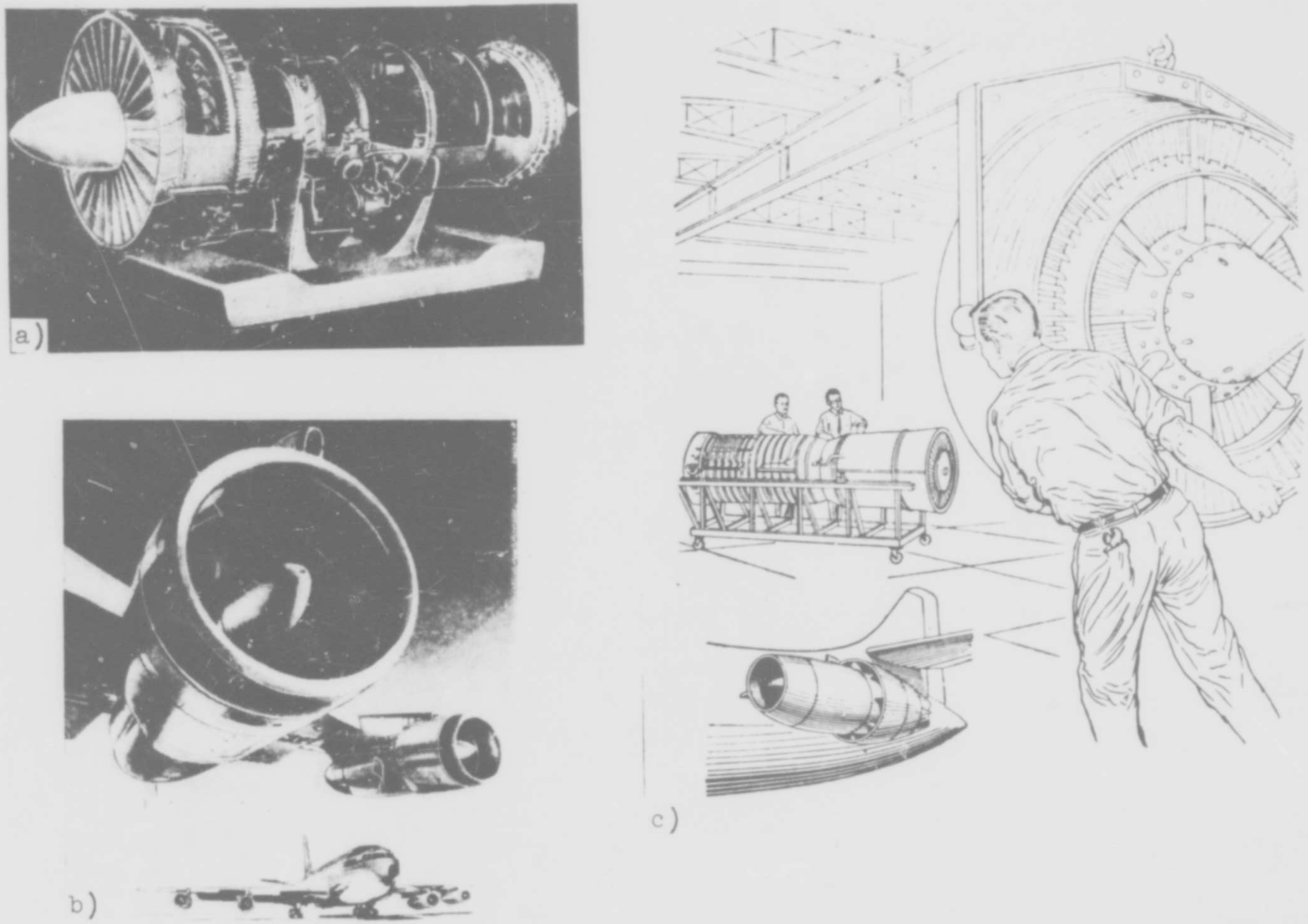

Fig. 20. Turbofan engine (the United States): a) profile of engine with front location of fan (thrust 7760 kgf); b) external view of gondola with engine on passenger jet aircraft Boeing 707; c) installation of rear turbofan attachment on turbojet engine and external view of gondola with engine (thrust 7300 kgf) with rear location of fan on French passenger jet aircraft "Caravelle."

At speeds of flight in the range from 0.7 to 1.2 times the speed of sound bypass engines are more advantageous than turbojet due to their greater economy, i.e., lesser specific fuel consumption, achieving approximately 0.6 kg/h for each kilogram of thrust and even less, while for the best turbojet engine it is equal 0.7-0.8 kg/h per kilogram of thrust. Two-circuit engines are also more suitable in respect to the noise which they create during operation, but the problem of noise of a turbojet engine turns out to be very complex, as we will learn from the following chapter. Bypass engines possess certain other merits also. This explains their more extensive application in contemporary aviation.

The fate of the bypass engine is interesting. This idea was expressed by K. E. Tsiolkovskiy long before development of the first aviation jet engines. The first bypass engines appeared almost simultaneously with turbojet, but they did not find application. This was explained by their relatively greater complexity. In the first stage of development of jet aviation it was most important of all to develop reliable and simple turbojet engines. All other problems, engine economy in particular, were then secondary. And only in recent years, when it was possible to finish the construction of a bypass engine and simple and reliable turbofan engines appeared, they received general acceptance and began to be used in a number of countries.

They are used especially widely in civil jet aviation, in which considerations of economy are very naturally important. It is not surprisingly that on the majority of new jet passenger liners primarily such engines are used. In particular, in our country we have turbofan engines mounted on the new passenger aircraft which were designed by A. N. Tupolev — the Tu-124 and Tu-134, which are flying on Aeroflot routes. Abroad in the United States, in particular, turbofan engines are mounted on certain passenger aircraft instead of the earlier simple turbojet engines — this increases the distance of nonstop flight and payload.

In this chapter we met several cases when the simple turbojet engine gave in to its own "relatives," gas turbine engines of another type, basically at relatively low subsonic flight speeds.

And what happens when the speed of flight exceeds the speed of sound, when it becomes supersonic? Do turbojet engines preserve their positions in this case?

We will talk about this in the following chapter.

CHAPTER IV

THE GAS TURBINE AND SUPERSONIC FLIGHT

The turbojet engine was predestined to break the "sound barrier" and lead aviation into the spaciousness of supersonic speeds of flight. In the process of this attack the turbojet engine did not remain the same; it was changed and developed, or expressing it somewhat more freely – it reached maturity in the struggle. And ahead of it still greater progress is waiting; still more considerable changes are forthcoming. What are they connected with?

If one were to talk about the engine, then for increasing the speed of flight it is in need, first of all, of an increase of thrust with the minimum increase of weight and dimensions, primarily of the frontal area. It is doubtful whether it is necessary to explain again why this is so, after all such an affirmation by itself is sufficiently clear, and was already spoken of above.

What possibilities does the designer of the engine have here?

Several of them were mentioned in the preceding chapter, however, not all of them are suitable in the case of high-speed, supersonic flight. Thus, for example, at relatively low flight speeds it is advantageous to increase thrust by means of transition from the turbojet engine to turboprop or bypass turbojet. However, such benefit is preserved only at subsonic speeds. It is true, when using all possible means and designs specially for supersonic flight speeds the advantage of such engines is also preserved in a certain portion of the spectrum of supersonic flight speeds. However, introduction of them in this area turns out to be very small – it is concluded at flight speeds which are approximately 20-30% greater than the speed of sound (i.e., at M number = 1.2-1.3, where M number is the ratio of speed of flight to speed of sound).

Another possible means of augmentation of thrust of a turbojet engine was also mentioned in the preceding chapter – this is an increase of temperature of products of combustion, i.e., transition to a "hotter" engine. It was already noted then that this means is unprofitable at relatively low flight speeds since it leads to a worsening of economy of the engine, i.e., an increase of fuel consumption per 1 kilogram (force) of thrust, but with an increase of speed the position is changed for the better.

Increase of thust with an increase of temperature of effluent gases is explained, as this was already mentioned, by an increase of escape velocity (proportional to the square root of temperature). Therefore, in general a dilemma appears before the designer; where to burn the additional fuel for increasing the temperature of gases – in the combustion chamber, i.e., in front of the turbine, or beyond it, i.e., before the jet nozzle? After all any method and even a combination of both of them is possible. They are possible because in an ordinary turbojet engine, as it is known, far from all the oxygen from the air flowing through engine is used for combustion of fuel. Almost 3/4 of all oxygen is still found in the effluent gases and, of course, can be used for the burning of an additional amount of fuel. But nevertheless where should it be burned, before or after the turbine?

The first method, i.e., burning of additional fuel before the turbine (injection of it into the combustion chamber), as can be seen, is more preferable from the point of view of engine economy than the second. Actually, in this case if engine economy worsens, then it is to a lesser degree than in the second method; specific fuel consumption will increase less. This is not surprising. Thermodynamics teaches that the supply of heat to gas in the cycle of a thermal engine is carried out more profitably under as high a pressure as possible. In this case more effective work is accomplished by the gas during subsequent expansion. The increase of effective work in this manner considerably exceeds the increase of work on compression of gas up to the greater pressure.

Indeed, if additional fuel is burned in the combustion chamber of the engine, then gases which are already hotter will be expanded in the turbine. But this means that the power, necessary for drive in rotation of the compressor, can be developed by the turbine with lesser expansion of gases. Consequently, the increase of temperature of gases before the turbine will lead to an increase of pressure of gases beyond it. Since the temperature of gases beyond the turbine also will increase, then, naturally, there will be a strong increase in the efficiency of gases. As a result the speed, which the gases obtain during expansion in the jet nozzle (i.e., escape velocity), will also increase strongly, and, finally, for this reason engine thrust will also increase.

If, however, additional fuel is burned not before the turbine, but beyond it, in the exhaust pipe of the engine, then this will have no effect on the operation of the turbine. Consequently, pressure before the jet nozzle no longer will increase, as previously, and escape velocity will be increased only as a result of an increase of temperature of gases due to the liberation of heat during combustion of the fuel. It is obvious that the resulting augmentation of engine thrust during burning of the same quantity of additional fuel will be less in this case. And this means that engine economy will drop more strongly; the engine will consume more fuel for each kilogram of thrust.

Thus, the advantage of increasing thrust by means of burning additional fuel in the combustion chamber of the engine is evident. It is true, we should not forget the fact that this method of increasing thrust is profitable only relatively, i.e., as compared to the other method - burning of fuel beyond the turbine. And although it is indeed comparatively more economical, nevertheless at flight speeds which are less than the speed of sound or just a little faster than it the increase of temperature of gases even before the turbine of specific fuel consumption, i.e., worsening of engine economy.

But what can one do if an increase of flight speed requires the augmentation of engine thrust? There is nothing surprising about the fact that this augmentation of thrust must be paid for by impairment of economy. However, again it is necessary to remember that with an increase of flight speed the situation changes: the greater the speed, then the more advantageous the escape velocity of gases from the engine. But, this means there is a corresponding increase in the most advantageous temperature of effluent gases, since escape velocity depends directly on it. Actually, at high supersonic speeds of flight, exceeding the speed of sound by 2-3 times, even a considerable increase of temperature of gases before the turbine, as compared to characteristic values for ordinary turbojet engines (i.e., equal to approximately 850-950°C), leads no longer to an increase, but to a decrease of specific fuel consumption. Moreover, if the situation concerns a comparatively short-term augmentation of engine thrust (such an increase is usually called boosting the engine), then even a certain increase of specific fuel consumption does not present a great danger. After all for a short time the overexpenditure of fuel will be insignificant. Meanwhile, engine boost frequently turns out to be necessary in flying operations of an aircraft, for example, during acceleration, climbing, and so forth. It is absolutely clear that creation of a turbojet engine with increased temperature of gases before the turbine, although in the first case for a short time, is of great practical interest. Why did it turn out this way? Probably such engines were designed long ago and are installed on aircraft.

But the situation is far from this. Essentially, during a period of almost fifteen years which have passed since the appearance of the first turbojet engine, the problem of increasing the temperature of gases before the turbine never could be solved but not because little work was done on it, but because the difficulties standing on this path were very great. Only very recently the first serial high-temperature, as they are called turbojet engines appeared, for example, the English engine "Avon" and others.

The main stumbling-block turned out to be the turbine, more exactly its blades, both nozzle and, especially, moving. However, if one were to look deeper, there was nothing unexpected in this. After all it was precisely due to the turbine, due to its blades, that the very birth of the gas turbine was delayed. Its fundamental advantages over the steam turbine and the piston internal combustion engine were determined by scientists almost a century ago. Creation of an efficient gas turbine with reliable blades was a very difficult task due to the unusual and severe conditions of operation of these blades.

In fact the blades revolve with tremendous speed together with the turbine wheel (diameter about one meter), on the circumference of which the blades are attached. With such violent rotation the blades naturally strive to separate from the wheel, as a stone is torn from a sling which is holding it. The pull which is exerted on the blades exceeds by tens of thousands of times their own weight. The result of being on such a "merry-go-round" is clear without further words.

But, it turns out that for a blade this is not the most important and, in any case, surely not the only test. Such durable blades could still have been made, although such a task is far from simple, if one considers that every blade essentially constitutes a long, thin strip of metal which is twisted intricately along its longitudinal axis and having in a cross section a profile similar to the arc of an aircraft wing. Inasmuch as in the engine there are many hundreds and even thousands of compressor and turbine blades, then the quantity of such aerodynamic profiles inside the engine is incomparably greater than that on the aircraft. After all, the blade is found on the crown of the turbine wheel not just for the purpose of revolving around with it. Its mission is to change the direction of the swiftly rushing gas flow in such a manner that the force which this flow exerts on the blade creates the maximum possible torque on the wheel, since only this way will the turbine develop maximum power. The force of the gases on the blade is very considerable and, what is worst of all, if the first force mentioned by us stretched the blade, then it bends, i.e., creates a very unpleasant tension in it. Still worse is the fact that this force does not act constantly and continuously, but only if the blade during its rotation passes past the channel formed by each two neighboring nozzle blades. It is from this channel that the swift gas flow is pulled outward, thus striking against the moving blade. When the revolving blade turns out to be as if in a shadow behind the nozzle, then for an instant the flow is interrupted, so that it then strikes the blade with new force. Naturally, such a gas "hammer" is shifted by blade much worse than if the force acted constantly. It forces the blade to vibrate tensely and to oscillate, and such a load is difficult to sustain.

However, even this is still not all. The gas flow has a temperature of many hundreds of degrees. It is natural that the thin fin of the blade (as they usually call the part of the blade protruding from the wheel in contrast to the root part which is in the wheel) is heated up almost instantly. And such a red-hot blade has to withstand and sustain all loads.

It is understandable what difficulties arise before the designer of a gas turbine and before the metallurgist called to produce the material for manufacturing the blades. As can be seen, in this case the ordinary, even the highest strength, steel alloys are no longer useful, since not only is strength required from the material of the blades, but also heat resistance - strength at very high temperatures. If one were to consider that in that temperature range in which the turbine blades have to function an increase of operating temperature by only 1° usually leads to a decrease of strength by 1%, then it becomes clear that a complex problem is faced by the metallurgist and designer. Usually an increase of temperature by 5% reduces the period of service of the blade by 10 times.

But it turns out that even this is not all. The fact is that a heated and strongly loaded blade can be sufficiently durable, i.e., it will not break and will not go out of order during operation, and yet will not be suitable for use. It turns out that during prolonged and continuous influence of some tensile force on a part (and it is exactly such a force which acts on the blade, pulling it from the turbine wheel during rotation) this part starts to stretch and is extended. After the load is removed this deformation does not vanish, the lengthening is preserved. This property of metal, to slowly inconspicuously be extended under the impact of a permanent load, has been given the name of creep. Creep is manifested especially strongly during heating of a metal. This is why the turbine blades are gradually stretched as the engine is working even more hours; they become longer and longer. Is this dangerous? It is very dangerous. First of all because there is simply nowhere for the blade to extend. The turbine wheel revolves in its encompassing body in such a way that between the blades and this body only a very small clearance remains. Anything else is impossible - through a large clearance much of the gas would overflow besides the turbine blades and its energy would not be used in the turbine - this would be an uncompensable loss. It is understandable that a blade which is extended from creep will brush against the body as it is broken. But even if one were to increase the clearance, in principle the situation does not change; only the moment of breakdown of the blade will be extended somewhat. And even if the clearance was very great, all the same the blade would break because its cross section would be weakened from the lengthening.

This is why it is not enough to make the blade from ultraheat-resistant alloy; this alloy should also have little creep. The labor of metallurgists in creating such alloys which are nonexistent in nature perhaps, based on merits, can be called a creative feat. These alloys consist of many unusual and rare metals - tungsten, vanadium, cobalt, tantalum, niobium, and others. And still even they made it possible only to produce a turbojet engine, but not in a condition to ensure the necessary operational efficiency of turbine blades during a further increase of temperature of gases.

Does this mean that a high-temperature turbojet engine - an engine for supersonic flight - will not be produced? Of course not.

Scientists and designers are investigating new and promising materials, in particular a combination of metals with ceramics. However, the first real success was gained on quite another path.

If up until now it has not been possible to produce a turbine blade from material which is able to sustain increased operating temperatures, then maybe it is possible to increase the temperatures of the gases which are expanded on the turbine blades without increasing the temperature of the blades themselves.

At first glance such an assumption seems paradoxical. In fact, it is known that usually the temperature of the blade differs comparatively somewhat from the temperature of gases; it is lower by more than 100°. Is it possible to bring this difference to 400 or 500°? Is it not possible for this purpose to cover the blade on the outside with some kind of thermal insulation?

Of course not, it is doubtful if thermal insulation will help here, but the problem is resolved more successfully and simpler in another way. The blade is heated by obtaining heat from hot gases. If it does not acquire their temperature, then it is only because in its turn it gives the heat to the turbine wheel. It is natural that the stronger this heat transfer is the less will be the temperature of the blade itself. And the thought comes to mind here of the possibility of additional artificial cooling of the blade. For this it is possible, for example, to make it hollow and pass some coolant, a liquid or gas, through it; true it will be necessary to remove very large quantites of heat - for all blades this quantity is such that it would be sufficient for the evaporation of several hundred kilograms of water per hour. It is simplest, of course, to use air for this purpose, after all it flows through the engine in huge quantities.

It is possible to remove a relatively small portion of air from the compressor of the engine without special labor, although, of course, this will lead to a certain impairment of engine economy (after all the work of compression of air in the compressor is lost), but in return the temperature of the blades will drop and this will make it possible to considerably increase the temperature of the gases, and together with it the thrust of the engine.

Recently turbine wheels with air-cooled blades and with the same nozzle blades have been put into practical application. This made it possible to produce a high-temperature turbojet engine with the temperature of gases before the tubine increased up to 1000 and even 1100°C. In particular such engines have been developed and are already being exploited, for example, in the United States – the J93 engine, in England – the "Avon" engine, and others. And this is only the beginning. It is obvious that in the future newer and newer engines of such a type will appear. It is possible that they will become the basic type of turbojet engine for supersonic flight.[1]

However, pioneers in this respect turned out to be turbojet engines of another type. These were already mentioned above. These are engines in which the second method of increasing temperature is used, i.e., additional fuel is not burned before the turbine, but after it, in front of the jet nozzle. While it is extremely difficult to increase the temperature of gases before the turbine, behind it this does not present particular difficulty up to 2000° abs. It is true that such a method is connected with a large overexpenditure of fuel, but then this permits simply the carrying out of short-term augmentation of thrust, or boosting of the engine. Therefore, arrangements for such a burning of fuel in the exhaust pipe of the engine have been given the designation of afterburners.

Comparative simplicity and low weight (although not all small dimensions) of the afterburner were the reasons that the first engines with such a chamber appeared long ago. And exactly such an engine was predestined to be the first to break the sound barrier; this was the first engine of the era of supersonic aviation. It is true that already prior to this a flight at supersonic speed was accomplished in an aircraft with an engine of another type – a rocket, however this was a unique flight, an experimental flight, and performed under special, artificial conditions; this flight and

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[1] No less, if not more, important is an increase of temperature of gases for "relatives" of the turbojet engine – turboprop and bypass engines.

Fig. 21. Cooled turbine blade from one of the new English turbojet engines. The blade contains channels for passage of the air coolant.

the engine which made it possible will be dealt with in Chapter VI. Regarding, however, the mighty army of contemporary supersonic jet aircraft, then both the first of its representatives, and also the latest generally have turbojet engines with afterburners. With the help of an afterburner it is possible to almost double engine thrust; it attains 11-12 and even 15 t.

Incidentally, an afterburner can be attached not only to a simple turbojet engine, but also to a bypass engine. In it the

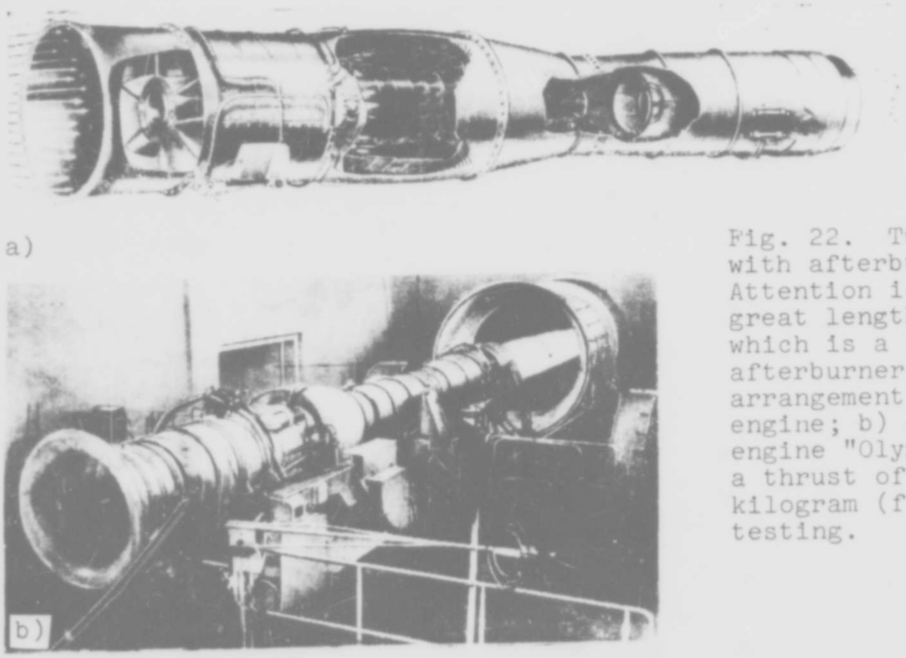

Fig. 22. Turbojet engine with afterburner. Attention is drawn to the great length of the engine which is a result of the afterburner: a) – arrangement of a typical engine; b) – English engine "Olympus" with a thrust of 11,000 kilogram (force) during testing.

afterburner can be mounted either in the main circuit, i.e., as this is done in the usual turbojet engine, or in the secondary circuit behind the fan. Of course, it can also be in both circuits, which makes it possible to increase thrust even more.

It is interesting that an afterburner in the second circuit during high supersonic flight speeds turns out to be an even more profitable method of augmentation of thrust than such a chamber in the main circuit. After all, pure air flows through the secondary circuit, and not products of combustion, as through the main engine "conveyer," so that in this circuit a greater quantity of fuel can be burned. Furthermore, the air in the secondary circuit is colder than the gases behind the turbine, which is also important. In regard to pressure, which for effectiveness of work of an afterburner should be sufficiently high, then in supersonic flight, as we now see, it is also ensured in the secondary circuit without the help of a compressor.

So that this important circumstance becomes clear, we will become acquainted in greater detail with the peculiarities of operation of a supersonic engine. Back in Chapter II it was noted that many main parts of a turbojet engine endure very radical changes when the engine is designed for supersonic flight. The time has arrived to look into why this occurs and what these changes consist of.

It is natural, of course, to turn for this purpose to the very beginning of that "conveyer" of continuous changes in the state of air which is the turbojet engine. This is all the more appropriate when the speed of flight exceeds that of sound. Then it is exactly here where the most radical, probably even dramatic, changes in the work regimen of the engine occur.

When we first became acquainted with the turbojet engine in Chapter II, we started this acquaintance with station No. 1 of the "conveyer," from the air inlet, i.e., that part of the engine in which atmospheric air arrives. However, we cannot turn to it; we are interested in what happens to the air before this station.

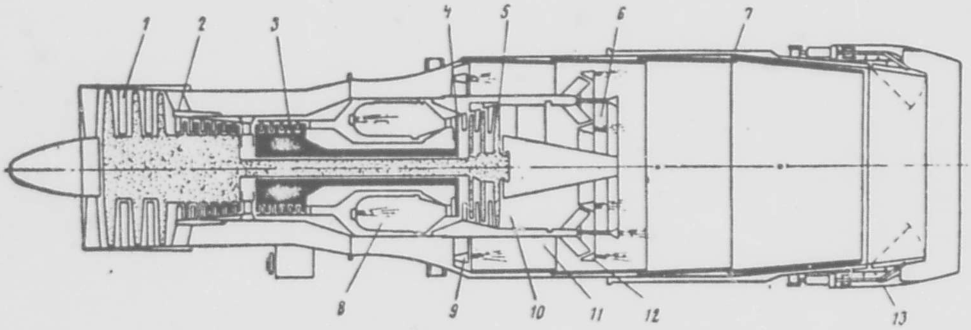

Fig. 23. Diagram of a bypass turbojet engine with an afterburner in both circuits (engine TF-106, developed in France): 1 – fan; 2 – low pressure compressor; 3 – high pressure compressor; 4 – high pressure turbine; 5 – low pressure turbine; 6 – main afterburner; 7 – cooling "jacket"; 8 – combustion chamber of engine; 9 – injection of fuel into airflow of fan circuit; 10 – main gas-air duct ("conveyer") of engine; 11 – fan circuit; 12 – injection of fuel into afterburner; 13 – variable-area jet nozzle.

But does this really mean in front of the engine? Does it seem that changes in the state of air begin before it enters the engine, while it is still in the atmosphere? How is this?

And although it is so at first glance it seems unexpected and even, probably, paradoxical. It is here in the atmosphere, outside the engine, in front of it, and, even more exactly, before the flying aircraft important changes in the air are starting to take place. Incidentally, this reservation about the aircraft is extremely significant – usually station No. 1 of the "conveyer," i.e., the air inlet, constitutes part of the aircraft itself, and not the engine. Such an organic merging of the aircraft and its powerplant is very characteristic mainly for jet aviation, in the past it did not exist.

But if changes in the air, which started already in the atmosphere, occur prior to "station No. 1," then, obviously, in accordance with our nomenclature this should be another – "zero" – station of the "conveyer." And although this post is invisible it nevertheless actually exists and, moreover, sometimes plays, as we will learn below, a very large role in the work of the entire "conveyer." Certainly the appearance of such a station is connected with the engine and with its operation, but by itself the "zero" station does not have any visible real connection with the engine. What is this mysterious "outpost" of the engine in the atmosphere?

It is necessary to note that the "zero station" appears not only in the case of supersonic flight; it exists always, but only supersonic flight makes its role extraordinarily important. That is namely why we did not mention it in Chapter II, although we had every right to do so.

The appearance of the "zero station" is explained by the fact that through the turbojet engine, which is working under certain constant conditions, only a strictly defined volume of air can flow every second. This consumption, thus, does not depend on flight speed of the aircraft. Nevertheless, as we will see blow, if one were to talk about the air inlet of the engine, then through it at various flight speeds a different quantity of air should flow. Thus on essential contradiction appears between "behavior" of the engine and its air inlet during a change of flight speed. But inasmuch as the engine has to function with fully-limiting air inlet, then such a contradiction has to be smoothed out, it has to be eliminated. Here this function is fulfilled by the "zero station." In contrast to all the other "stations" of the engine "conveyer," each of which fulfills a strictly specific function, the "zero station" behaves by far not so specifically. Nature as if supplied it with a whole set of functions, so that this station not only appears automatically when it is necessary, but also in the same way automatically fulfills this or that role, depending on necessity.

Work of the "zero station" is so important for the entire working process of the engine that it is worth alloting it somewhat greater attention here. First of all, let us note tha the requirement of constancy of volumetric flow rate of air through the engine is equivalent to the condition of constant airspeed in the entrance mouth of the air inlet. Actually, after all the volumetric flow rate of air is nothing other than the product of speed of airflow by the area of cross section of this flow. Since the air inlet has a fully determined section, then the speed in it is thereby fully determined. Let us assume, for example, in a given air inlet the airspeed is equal to 100 m/s. If the speed of flight is precisely equal to the same value, i.e., 100 m/s, then obviously counter airflow which is incident on the aircraft and, consequently, entering the air inlet of the engine, will enter the air inlet in a wide river, moving at exactly the shown speed. As we can see, in this case there is no need for a "zero station." This is a unique case in flying exploitation of aircraft when the "zero station" does not function.

It is worthwhile though to somewhat change the velocity of flight, as now the picture of phenomena at the entrance to the engine becomes different and "zero station" will enter into action. Let us assume that the speed of flight is decreased and becomes equal, let us say, to 70 m/s. This means that precisely at such a speed the atmospheric air is incoming on the aircraft. But in the entrance mouth of the air inlet the speed should still equal 100 m/s. It is easy to see that unavoidably in this case the following should occur: obviously, while still outside the air inlet of the engine the speed should be increased from 70 to 100 m/s. Here the work of reorganization of incident flow is accomplished by the "zero station." How does it do this?

When air moves at subsonic speed, then it behaves in general just as any imcompressible liquid, water for example. This is explained by the fact that at such relatively low speeds of movement the changes of pressure in moving air are so small that they do not lead to any noticeable compression of air; this was already spoken of before, in Chapter II. In the case of flow of an incompressible liquid the following evident law operates: the greater the speed the less the section of channel which is required in order to pass a given quantity of liquid. Therefore, for acceleration of a flowing liquid the section of channel should be decreased, and for its deceleration – increased. The same obviously pertains also to air at subsonic speed.

In our example with the engine the speed of airflow, incident on aircraft, should still be increased from 70 to 100 m/s in front of the entrance to the engine. Consequently in this case the airflow should flow through a narrowing tube. Certainly it would have been possible to place such a tube in front of the engine, but it is easy to see that this would not resolve the problem, after all every speed of flight should have its corresponding special tube with a various ratio of sections at the inlet and outlet, sometimes convergent and sometimes divergent. Certainly it is possible to create such a tube, but it is far from simple. Fortunately, however, there is no necessity for this, since the invisible "zero station" copes with this problem without any participation of man and even better than this would be done by any adjustable tube.

Unfortunately, in the transparent and colorless air the work of the "zero station" is invisible. But if the air suddenly became visible, as this was spoken of in Chapter II for example, then before our eyes a remarkable picture of the functioning of the "zero station" would appear. When the speed of flight equaled airspeed in the air inlet, i.e., 100 m/s in our example, then we would see entering the engine on air stream with a constant section in the form of a round cylindrical tube or pole, formed in the surrounding atmospheric air. As soon as the speed of flight started to decrease, for example, decreased to 70 m/s in our example, immediately instead of a cylindrical a convergent conical, more exactly, funnel-shaped tube would appear. In it acceleration of air from 70 to 100 m/s would take place. Conversely, with an increase of speed of flight, up to 130 m/s for example, the cylindrical tube would be replaced by a divergent funnel-shapped one – in it the air would be slowed down from 130 to 100 m/s. In spite of the fact that these tubes do not have any walls, we could observe their border very clearly.

Let us imagine for a minute what it would be like if the atmosphere did not possess the remarkable property to create such flexible invisible "tubes" in front of the engine. In this case the change of speed should take place by a jump in the very entrance mouth of the engine – such a process is always connected with losses of energy and this means that it is less profitable than a smooth

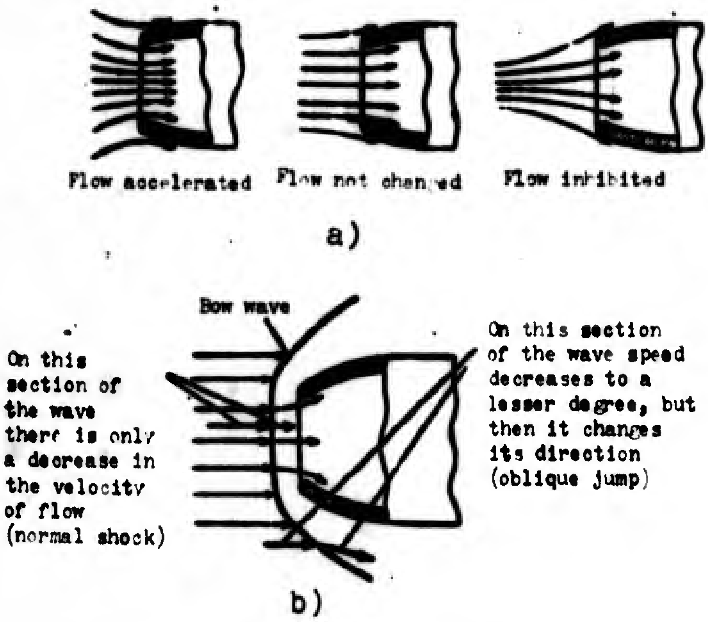

Fig. 24. Changes in the state of air start already in front of the engine, in the atmosphere: a) – "zero station" of the conveyer during subsonic flight; b) – the same air inlet in supersonic flight.

change. Therefore, a change in the state of air occurring outside the air inlet at the "zero station" is an important factor for increasing the effectiveness of the engine.

But if this is true even in the case of flight at subsonic speed, then it is immeasurably more true and important during supersonic flight. And this is because processes of deceleration of supersonic airflow (obviously, in this case incident flow should certainly have to be slowed down, its speed is considerably greater than in the air inlet of the engine) are considerably more complex (or more capricious if the reader desires). At the same time the value of kinetic energy of supersonic flow is so great (after all it is proportional to the square of speed) that loss of this energy can also be very great based on absolute value. It is necessary to have the true wisdom of the scientist and talent of the designer in order to effectively, without excessive losses, inhibit supersonic flow.

The main difference between supersonic flow and subsonic, as was already mentioned in Chapter II, is that disturbances (i.e., local increases of pressure) in it, which as is known are spread with the speed of sound, cannot be spread more against flow, they are carried away by it. On the other hand, these disturbances become much stronger, i.e., local increases of pressure can become very considerable. But this means that the air can no longer be viewed as an incompressible liquid. The effect of compressibility strongly changes the picture of flow.

In our case this has effect first of all in the fact that during deceleration of supersonic flow its section is no longer increased, but is decreased.[1] Consequently, here already for deceleration it is required to have a convergent tube such as was required earlier for acceleration of subsonic flow. Theoretically, therefore, deceleration of supersonic flow should occur in a tube which at first converges and then again starts to diverge. It is understandable why this is so. While the flow remains supersonic, the tube for deceleration should be converging. And here, finally, the flow rate in decreasing reaches the speed of sound. Now further deceleration obviously requires a divergent tube since the flow in it is subsonic.

Well, to construct such a tube is not really so complicated. It is known that the reverse process of acceleration of gas from low subsonic to a high supersonic speed, which obviously should occur in the same convergent-divergent tube, is being carried out successfully in practice. Such Laval nozzles,[2] as they are called, are used extensively in steam and gas turbines, jet engines, and other machines.

It was unfortunate, however, that what was easily realizable in the case of a nozzle turned out to be practically impossible in the attempt at creation of a similar diffuser (a diffuser is a device for deceleration of gas, i.e., having an assignment which is reverse to the assignment of a nozzle). Theoretically everything is true, but here all the attempts of scientists and engineers to realize these theoretical possibilities in practice until now have usually ended in failure. What then is the matter here?

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[1] This is explained by the fact that during deceleration air density increases as a result of its compression faster than speed decreases.

[2] The nozzle is a device for acceleration of gas, and it is called Laval because this Swedish engineer was the first to propose and put into practical use such a nozzle.

It turns out that it is not so easy "to lure" the flow into such a diffuser. Practically always already at the inlet to it or at the very beginning a subsonic flow is established; deceleration from supersonic speed to this subsonic is carried out outside the diffuser, in front of it. Again the same "zero station." However this time it is working quite differently. If subsonic deceleration outside the engine (in the atmosphere) was carried out smoothly in an invisible tube, then in the case of supersonic flow smooth deceleration in the atmosphere, outside the air inlet (in it itself smooth deceleration is not realized; we already know this), does not occur also. Instead of it there is a sharp uneven deceleration of flow with the corresponding compression of air (see Fig. 24). This deceleration is usually called compression shock or shock wave, which was already mentioned in Chapter II. The thickness of the layer of air in which such a jump occurs is commensurable with the length of free path of molecules, i.e., under usual conditions is insignificantly small (only during strong rarefaction does the situation change). This was truly an instantaneous jump!

In Chapter II it was mentioned that shock wave, as also any blow, is energetically uneconomical. It is connected, as it is said, with irreversible, i.e., unrestorable, losses of kinetic energy of flow (converted into heat). Therefore, deceleration in shock does not permit the complete conversion of kinetic energy of incident flow into potential energy of the delayed air - the pressure of this air will be less than in the case of an ideal, smooth compression without losses. After all it is absolutely evident that the goal of deceleration of air before the engine is the maximum possible increase of pressure, since this pressure directly determines thrust and economy of the engine - the higher it is then the greater the compression of air. It appears that in supersonic flight the "zero station" does not work quite so well.

This is true, but what can be done if such is the nature of supersonic flow. It remains only for the designer to endeavor as far as possible to decrease the loss in shock. But then here before him is opened the widest spaciousness for creativity in respect to selection of configuration and nature of jumps, which it turns out are never the same.

When a body which is moving at supersonic speed has a dull nose, then in the air in front of it, as tests show, a compression shock wave appears which is similar in form to the breaker forming before the bow of a cutter which is moving rapidly through the water (see Fig. 3). Directly in front of the bow itself this shock wave is most intense (below will be explained the detailed meaning of this term) and its front is perpendicular to the direction of motion of the body. Then on both sides of the moving body the wave weakens and is bent so that it passes into two straight "runners." These are inclined to the direction of motion at a strictly specific angle, the value of which depends only on the speed of sound, i.e., on the Mach number. The higher the Mach number, the sharper the angle and the closer the wave "runners" adjoin the moving body. This is what takes place in the case of waves on water which are diverging from a cutter. Incidentally, when such a wave "runner" from an aircraft flying at supersonic speed reaches the earth then at that place resounds the "supersonic boom," which sounds like a shot from a cannon and is already familiar to many.

But what precisely is meant by the term "intensity of wave," which was used by us above? Inasmuch as in a shock wave (or compression shock) a deceleration of incident flow of air occurs, i.e., there is a decrease of its speed relative to the moving body, then it is logical to characterize the intensity of the wave by the magnitude of this deceleration, or the relation of speed in front of the wave to speed behind it. When the wave is intensive, then this ratio of speeds is great, it is considerably larger than a unit; in a weak wave it is close to a unit. In such a weak wave as sound the relation of speeds practically does not differ from a unit. It is interesting here that the greater the flow rate prior to the jump, the less it is after it, i.e., the more intensive the jump. Consequently, "strong" jumps take place only in a flow of very high speed.

This is why directly in front of a body which is moving at high speed the flow rate is changed sharply, and on the "runners," where the wave is less intense the change of speed becomes less and less considerable, so that on the very ends of the "runners" it practically already corresponds to a simple sound wave. But the matter is not limited to intensity of wave, to a change of velocity in it. It turns out that on various sections of the wave there are various changes in the direction of speed.

Directly before a moving body, in the very front section of a bow wave, airspeed does not change its direction at all, there is only a decrease (and the strongest, as was already mentioned) of velocity. Inasmuch as such a wave, or compression shock, is disposed at a right angle to the direction of flow rate, then it is usually called normal shock.

What occurs with speed of airflow on other sections of the bow wave, there where this wave is disposed no longer at a right, but under a slanting angle to the direction of speed (therefore such a shock wave is usually called oblique)? As theory and experiment showed, in an oblique shock the flow rate, inclined to the plane of the shock, is as if decomposed (based on the well-known rule of decomposition of speeds, or rule of parallelogram) into two components, one of which is perpendicular to the plane of the shock, and the other - parallel to it. During passage through the shock the first component changes value just as this occurs in the usual normal shock (not surprisingly, after all for it the jump is as if direct), without changing its direction. The second component, parallel to the shock, does not change either in value or in direction - it simply does not feel the shock, it does not seem to exist for it, inasmuch as speed in this case is directed along the shock.

To what then is the flow rate beyond the oblique shock equal to? Obviously it is equal to the geometric sum of both components behind the shock. But inasmuch as the first (perpendicular to the shock) component behind the shock became less than before it, and the second component remained the same as previously, then it is easy to see that their sum behind the shock will be less than before it, and, furthermore, the resultant velocity will turn somewhat in direction to the shock so that its angle with the shock will decrease. It appears that an oblique shock is weaker than normal. The weaker it is the more it differs from normal and the "more slanting" it is.

In this difference between direct and oblique shocks lies the essence of those possibilities of control over the nature of deceleration of air before an engine which turn out to be in the hands of the designer. The designer is in a position to assign a "program" of work for the "zero station" of the conveyer so that it is most advantageous during those conditions of flight when this is most important, and changes depending upon conditions of flight also in a sufficiently suitable manner. The science of physical processes which accompany the flow of gas at high supersonic speeds, or the so-called gas dynamics, places in the hands of the designer the theoretical bases for such "programming." How can it be realized?

We will give only one example which clearly illustrates those methods which the designer uses in the development of the air inlet for a supersonic turbojet engine. It was stated above that normal shock is less profitable than oblique shock. Consequently, it would be profitable to dispose an oblique shock directly in front of the opening of the air inlet, and not direct, which appears ahead of any dull body, which the air inlet essentially is. It is simple to replace normal shock?

The secret of such a possibility is connected with the fact that if a moving body has a sharp, and not a dull, nose, then on the very tip of it divergent obliques shocks develop. Therefore, it is sufficient that some pointed object be extended forward from the air inlet of the engine - needle, cone, wedge (this so-called central body is a characteristic distinction of supersonic air inlets), as now oblique shocks will develop on its point (designer would say "will sit"). Flow rate behind these shocks will naturally decrease, although it will remain supersonic, and then the normal shock, appearing directly in the entrance mouth of the air inlet, will be

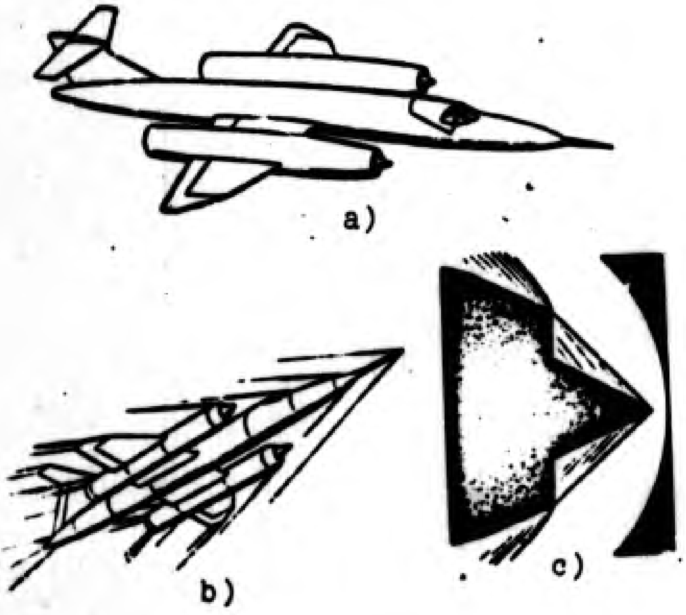


Fig. 25. Oblique shock waves "sit" on the prominent point during supersonic flight: a) – the English supersonic research aircraft the Bristol 188, calculated for flight at M = 2-2.5, has a needle in the nose of the fuselage and a peaked central body in the air inlets of its two turbojet engines; b) – such a system of oblique shocks is formed during the flight of this aircraft; c) – photograph, obtained in a wind tunnel of oblique shocks on the central body of the air inlet.

much weaker. Theory shows that such a system of shocks – "oblique plus direction" – at a sufficiently high speed of flight, specifically faster than Mach 2, may be considerably more profitable than a simple normal shock. But this means that the work of "zero station" will be much more effective, air pressure in the engine will increase.

Still more profitable at higher speeds of flight can be a complex system of shocks in which air at first is slowed down consecutively in two oblique shocks and then in a concluding normal shock. A quite detailed theory has been developed for such multi-shock systems. This makes it possible for the designer to select the most economical system for every given case.

Now it is not difficult for the reader to establish the difference in the work of the "zero station" of a subsonic and supersonic engine. When the speed of flight is less than the speed of sound, then the only influence which the designer can have on the work of "zero station" is the selection of that speed of flight at which the "station" does not work. Such a selection sets the velocity of airflow at the mouth of the air inlet; the larger the entrance mouth, then with other things being equal the less the speed of air in it and, consequently, the less the speed of flight at which the "station" remains unemployed – these speeds equal each other exactly. At all other speeds of flight the work of the "zero station" is regulated absolutely automatically, the designer does not interfere in it. The "station" itself "decides" when it is necessary to brake and when to accelerate the airflow before the air inlet and by precisely how much.

The supersonic engine is another matter. Here in addition to a change in the area of the entrance mouth of the air inlet the designer has at his disposal other means of influencing the work of "zero station." One such means was spoken of above – the designer designs the system of shock waves in the flow before the air inlet. It is understandable that he achieves this by means of changes in the construction of the actual air inlet, as was already spoken of.

But the difference is not restricted to this. Here, for example, is one more. While in a subsonic engine the "zero station" does not work at all at one specific speed of flight (we will call it calculated), then in the case of a supersonic engine such a speed does not exist. Under all conditions of supersonic flight complex physical phenomena occur in the airflow in front of the air inlet – "zero station" works with a full load.

Certainly if the flight is performed at that comparatively low subsonic speed at which the entrance mouth of the air inlet was calculated, then the "zero station" of a supersonic engine will cease its work. But, of course, this in no way is that speed for which the designer calculates the working of a supersonic engine. In this case the calculated speed is that high supersonic speed at which the system of shocks planned by the designer in front of the air inlet is established, i.e., "zero station" is working according to the program assigned by the designer. Here the effectiveness of work of the air inlet is most advantageous; that is why calculated speed should correspond to the conditions of flight which are most important for the given aircraft, when maximum speed or ultimate range of flight is required.

But what happens when the speed of flight no longer equals calculated speed? How does the "zero station" work on such so-called uncalculated conditions?

This question is not so simple to answer without examining in detail the construction of the air inlet. One statement can definitely be made – in all cases when the speed of flight is greater or lesser than that for which the system of jumps is calculated, i.e., calculated speed for the air inlet, its functioning grows worse. Appraisal of the functioning of the air inlet is made according to how it ensures the inhibition of air, i.e., what portion of kinetic energy of flow which is incident in flight is expended on compression of air and what is the head resistance of the air inlet.

In an ideal case, when there is no loss of energy, obviously the greatest pressure of air in the air inlet is attained. In all real cases true pressure naturally turns out to be less than ideal. Here this ratio of pressure obtained to ideal usually serves as the basic criterion of perfection of the air inlet.

A lessening of operational effectiveness of the air inlet under nonrated conditions, leading to a decrease of pressure in it comparative to the maximum possible, i.e., ideal, is caused by various reasons. First of all, it is connected with the position of normal shock which locks the system of shocks. In the most advantageous case this normal shock is disposed in the smallest section (duct) of the air inlet, usually coinciding with the entrance section. Sometimes this shock shifts forward during flight and then it is established before the air inlet, or as it is said, "is disconnected" in the same manner as this takes place with an ordinary head wave. Here the functioning of the air inlet worsens, pressure in it drops, external (frontal) drag increases, and pulsations of flow develop. If, conversely, normal shock advances deeper inside the air inlet, where its cross section is already larger, then the intensity of the shock increases, which naturally is also uneconomical, and in this case pulsations of flow frequently appear. Such pulsations can damage components of the air inlet and cause surging of the compressor.

Another important factor determining the quality of operation of the air inlet in supersonic flight is the location of oblique shock. In the best case it should intersect with the fairing of the air inlet in its front point, otherwise its drag will be increased and quality of work worsened.

Such changes of operating conditions of the air inlet can be caused either by a change of speed of flight or of operating conditions of the engine, i.e., flow rate of air through it.

Is it possible to avoid a worsening of operation of air inlet under nonrated conditions? One possibility obviously was to change the geometry of the air inlet in such a way that the calculated geometry of the system of shocks is restored. For this in a number of cases it is sufficient, for example, to move the central body of the air inlet with its point back or forward, with a corresponding change of position of oblique shocks forming on this point. Sometimes, however, this turns out to be insufficient and it is required to bypass a certain portion of air from the air inlet outside, into the atmosphere, through a special valve. Another time it is necessary to transfer the front section of the air inlet backwards or forward, changing its position in respect to the point of the central body. Other forms of adjustment of the air inlet are also used - change of angle of conicity of the central body and others. In all cases the goal of such adjustment is the same - to coordinate the amount of air passing through the air inlet and engine in such a way as to ensure the greatest possible pressure of air entering the engine with the least drag of the air inlet.

It is obvious that to force a pilot to manually control the system of regulating the air inlet is irrational perhaps even impossible. Certainly automation should be brought to the help of man in this case. It can incomparably faster and more precisely cope with the problem of adjustment. It is true that such automatic regulators are very complex and frequently include cybernetic computers. But this by no means is the only example of the use of automation and cybernetics for the service of jet engineering - such use is being expanded with every day.

We saw that the air inlet of an engine during transition to supersonic flight speeds endures radical changes indeed. From a simple thin-walled pipe it is turned into a complex unit of fixed and moving parts and units connected by a common automatic control system. Then what is the fate of the following, the second station of the "conveyer" – the compressor of the engine?

On the one hand, as it is easy to see, it should become considerably more simple. Actually the very assignment of the compressor is to compress air which is entering the combustion chamber, to increase its pressure. But in supersonic flight this function is taken on by the air inlet. If in subsonic flight the compression of air in the air inlet (this includes the "zero station") is very minor, so that the pressure of air is increased only by a hundredth part of an atmosphere, then supersonic flight is quite another matter. Kinetic energy of incident flow of air at supersonic speed is so great (let us remember that it increases proportionally to the square of speed) that during the complete use of it in the process of deceleration of airflow for compression of air its pressure can become very great.

Here are only some characteristic figures. With a flight speed at the ground exceeding the speed of sound by 2 times the maximum pressure of air reaches approximately 7 at, at 3 times the speed of sound 36 at, and at 4 times the speed of sound – 150 at!

Under these conditions the air inlet is in a state to take on a considerable portion of that work which usually in a turbojet engine is performed by the compressor. In the compressor the pressure of the air is usually increased by approximately 10 times, so that in supersonic flight the air inlet decreases this necessary increase of pressure to 2-3. This means that in a supersonic engine the compressor can have only a few stages. And this is how it is in a supersonic engine. A low level of compression is a characteristic feature of the compressor of a supersonic turbojet engine.

But this does not mean at all that supersonic flight brings only alleviation for the compressor. Unfortunately, impact pressure of air which is incident on the engine, which as we saw, so strongly unloads the compressor, at the same time very strongly loads it. There is no paradox here, since if easing the conditions of work of the compressor is connected with an increase of pressure of airflow during its slowing down, then such a slowing down also has a reverse side - the strong heating up of air, and this is very thoroughly, complicates the work of the compressor.

That compression of air is accompanied by its heating is a generally known fact. Air which is coming out of the compressor of a turbojet engine usually has a temperature of 300-400°C and higher. This is why the blades of the last stages, especially of high-pressure compressors of engines, frequently are no longer made from light alloys (it is clear that such alloys are profitable - weight of the blade should be minimum, then the load on it will also decrease in the same way), from titanium, or even steel. But if the speed of flight becomes supersonic, then even before the compressor the air becomes hot as a result of its compression in the process of slowing down. How high the temperature of the air is here can be seen from the following: with ground speed equal to that of sound it reaches approximately 70°C, at twice that speed - 245°C, and at five times the speed of sound - already approximately 1450°C. This means that at high supersonic flight speeds the air in the compressor turns out to be almost as hot as the gases before the turbine of an ordinary turbojet engine and even hotter. It is not surprising that in such compressors the temperature of the air causes a great deal of trouble for the designer. It is particularly understandable that aluminum alloys are no longer suitable as structural material for the manufacture of compressors.

Regarding the combustion chamber, then it probably endures the least changes during transition to supersonic flight in comparison to the remaining elements of the engine. This is understandable - after all it is isolated from external conditions, it is separated from the surrounding atmosphere by other parts of the engine - the air inlet and compressor on the one hand, and turbine and nozzle on the other. And this is a natural advantage of the middle, as they say, internal station of the "conveyer." Certainly this does not mean that the chamber never "senses" supersonic flight - it appears first of all in an increase of pressure and temperature of gases in the chamber, which naturally complicates its work.

But the next station - the turbine - changes perceptibly during transition to supersonic flight speed. This is not surprising since the assignment of the turbine is to revolve the rotor of the compressor, and the compressor, as we already know, becomes different in many respects. First of all the number of its stages and compression ratio decrease strongly. But such a compressor uses significantly less power, and this means the power of the turbine should be less. Therefore in this case the turbine usually is single-stage (more are not necessary). The rotor of the engine - its compressor and turbine - are simplified when the speed of flight becomes supersonic (true, we have to remember the necessity of increasing the temperature of gases before the turbine in a supersonic engine), but then the air inlet is complicated. The last station of the "conveyer" - the jet nozzle - is also complicated. It is just as thoroughly complicated as the air inlet. Pay attention to the fact that during transition to supersonic flight the extreme stations of the "conveyer" - the air inlet and nozzle - are changed most of all, then to a lesser degree both of the following - compressor and turbine, and least of all - the central station, i.e., combustion chamber. In the following chapter we will return to this peculiarity.

Whatthen are the changes which differentiate the jet nozzles of the supersonic and ordinary turbojet engines? Remember that in an ordinary engine the nozzle constitutes a simple convergent tube, i.e., a channel of gradually decreasing cross section. In such a tube, as was already mentioned above, subsonic gas flow is accelerated, but its speed cannot exceed that of sound. In order for it to become greater than the speed of sound, it is necessary that after the section, in which the speed became equal to that of sound, the tube again be expanded. Such a convergent-divergent nozzle has the name Laval, as was already mentioned. But in a subsonic engine a Laval nozzle is not used, there is no need for it since the problem is resolved with the help of a simpler subsonic nozzle. This is explained by the fact that the exit velocity of gases in a subsonic engine usually does not exceed or somewhat exceeds that of sound (a high exit velocity at relatively low speeds of flight is unprofitable, as we already knew).

Supersonic flight is another matter. In this case the exit velocity of gases should increase and become supersonic, which is necessary for production of greater thrust and profitable from the point of view of increasing engine economy. But, consequently, the pressure of gases before the nozzle in this case should be so high that for their full expansion a Laval nozzle will already be needed. Such a nozzle is one of the most important parts of a supersonic turbojet engine.

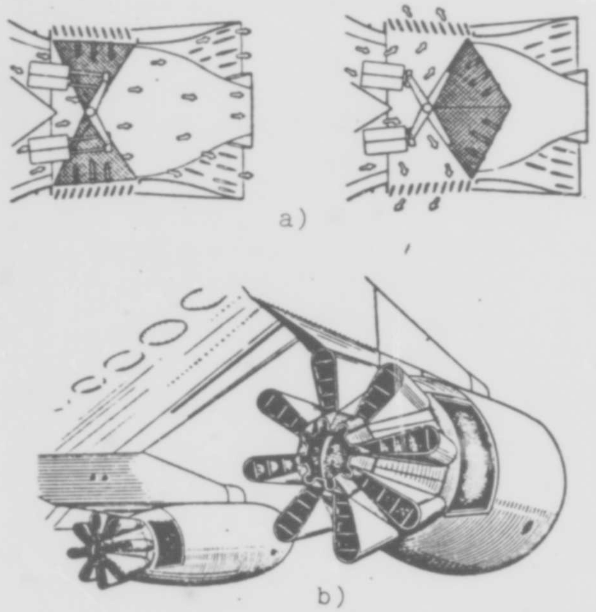
But to create a Laval jet nozzle is not at all so difficult; it is exactly the same profile as the air inlet. If the problem amounted only to this, it would not be so complex. True, difficulties arise when it is necessary to consider changes in the operating conditions of the engine. Under one condition (we will call it rated) the nozzle works excellently. But then the conditions changed and consequently became unrated. This means that the quantity of gases flowing through the nozzle each second and (or) their parameters, i.e., pressure and temperature, were changed. How will our nozzle work under these new conditions?

When the discussion concerns a subsonic nozzle, i.e., a simple convergent cap – a tube, then such a change of operating conditions is not terrible for the nozzle, it as if automatically adjust to it. Another matter is the Laval nozzle. During work under unrated conditions its features are greatly worsened, which naturally worsens the performance of the entire engine. In order that such impairment does not occur, during a change of operating conditions of the engine the geometry of the nozzle should be changed, in particular the cross section of its narrowest part – the throat, and the nozzle exit section. It appears that here a complex automatic control system is needed. Remember what difficulty there was with this problem in regard to the air inlet and it will become clear that here there is still considerable difficulty – after all it is not cold atmospheric air which is flowing through the nozzle, as in the air inlet (true, in supersonic flight the air is already far from cold), but heated gases.

Difficulties in the creation of a Laval jet nozzle are still more complicated when the engine is equipped with an afterburner. After all, in this case the inclusion of the chamber and change in the value of the afterburner additionally change the operating conditions of the nozzle, which obviously strongly hampers the problem of its adjustment. Furthermore, with incorporation of the afterburner the temperatures of gases passing through the nozzle are increased sharply. What is necessary in this case for elements of nozzle construction which these gases flow around is complex due to the necessity for adjustable geometry! After all, the afterburner, as was already mentioned above, is definitely an obligatory element of a supersonic turbojet engine.

There is one more circumstance which also does not facilitate the working conditions for the jet nozzle of a supersonic engine. It is connected, as a matter of fact, not even with one but immediately with two peculiarities of performance of such an engine. One of them, probably the main one, concerns the noise, created by gases emanating from the engine. This was spoken of in the preceding chapter. This noise increases very sharply when the velocity of effluent gases increases (based on experimental data proportional to the 7th or 8th degree of exit velocity), and becomes so strong that it creates significant practical limitations on the possibilities of application of supersonic engines. Obviously it is necessary to take special measures for decreasing the noise of the stream. Methods of such damping of noise are well-known and continue to be developed. This problem is subjected to intense investigations, as it is important. Usually for decreasing the noise of an engine (even an ordinary subsonic one) a special device is attached – a muffler which is fastened directly to the jet nozzle (thus appears one more "supernumerary" station on the "conveyer"). In principle of arrangement mufflers are various, but most frequently their idea is connected with ensuring a smoother mixing of the emanating gases with the air. But it is easy to see that the attachment of a muffler on the engine worsens work conditions for the jet nozzle: it obtains an additional load – mechanical and thermal.

Similar impairment takes place, when another device is joined to the nozzle of the engine, the so-called thrust reverser (sometimes it is joined with the muffler). The purpose of the reverser should be understandable from its very name: it reverses, i.e., changes, the direction of thrust of the engine. But why is this necessary and in general it is necessary, after all thrust is intended to accelerate the aircraft, why should it be deflected from its natural direction? It turns out to be very necessary. It is necessary mainly because thrust does not always have to accelerate an aircraft, sometimes with its help it is necessary to brake an aircraft. This occurs during landing of an aircraft. Landing speed of supersonic aircraft turns out to be greater than for subsonic – after all the greater the minimum speed of flight, the less should be the wing of the aircraft. But this strongly hampers landing and requires a much longer landing strip. In order to facilitate the problem the thrust reverser is used – with its help gases are released not back, but forward, and their reaction brakes the aircraft. It is true, the purpose of the reverser is not only this. Probably no less important is something else. When the aircraft is making a landing, then engine thrust is decreased to the minimum. It is impossible to turn off the engine completely, and what if the landing cannot be accomplished and the aircraft has to again gain altitude immediately? Here there is no time to turn on the engine and increased thrust has to be developed instantaneously. But, it turns out that even if one did not turn off the engine but only switched it to so-called low gas, then frequently it is still not possible to increase thrust sufficiently rapidly. It is easy to see that the reverser solves this problem – after all with its help a change of direction of thrust of the engine which is sufficiently great based on its absolute value can be carried out in calculated instants. However, even a reverser, for the same reasons as the muffler, complicates the making of a supersonic nozzle with adjustable geometry.



a)

b)

Fig. 26. One of the thrust reversers used abroad – sound suppressors: a) diagram of arrangement and action of reverser (on the left – normal thrust, on the right – reversed); b) reverser-muffler on an aircraft.

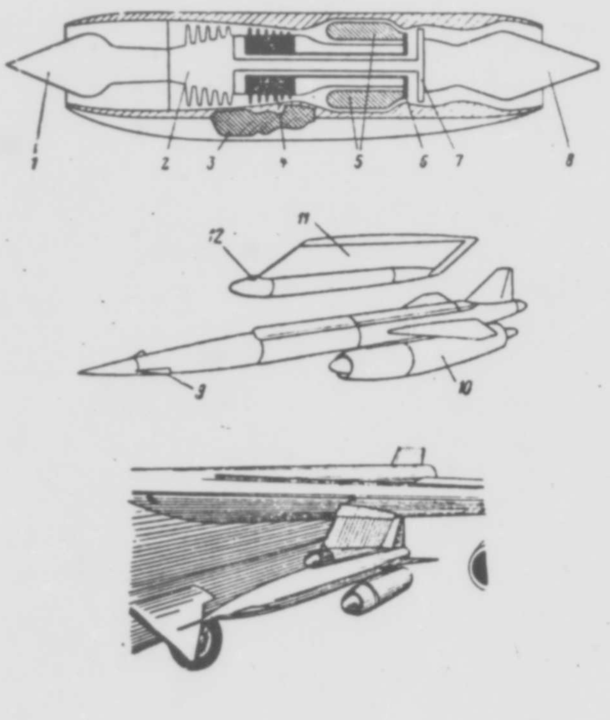


Fig. 27. Diagram of the arrangement of the supersonic twin-shaft turbojet engine J-52 (the United States) used on the "Hound Dog" quided missile. Below – diagram of the missile and its appearance (missile is suspended under the wing of the aircraft): 1 – moving central body; 2 – low pressure compressor; 3 – engine accessories (pumps and others): 4 – high pressure compressor; 5 – combustion chamber; 6 – high pressure turbine; 7 – low pressure turbine; 8 – variable – area jet nozzle with central body; 9 – controls (elevators); 10 – turbojet engine J-52; 11 – pylon for suspension of missile on aircraft; 12 – astronomical guidance system.

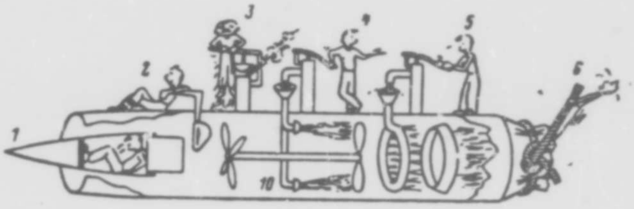


Fig. 28. A supersonic turbojet engine should have a complex automatic system for control of geometry (air inlet, compressor, nozzle), fuel feeding, and other parameters. On the figure are represented only certain necessary forms of control: 1 – adjustment of air inlet (position of central body and others); 2 – turning of compressor guide vanes; 3 – bypass of air from compressor; 4 – fuel feed in combustion chamber; 5 – fuel feed in afterburner; 6 – adjustment of jet nozzle.

This of course does not mean that such a nozzle is impossible to make. It undoubtedly will be made; a number of such constructions already exist since without such a nozzle it is impossible to have a supersonic engine with optimum characteristics. Operational use of such an engine is only a matter of time, inasmuch as it is possible to think that in the speed range of flight from 2 to 4 times the speed of sound a supersonic turbojet engine with afterburner and complex adjustable geometry will be the best propulsion system for aircraft, both piloted and pilotless. In particular, in the United States such an engine is already being used on the pilotless winged missile "Hound Dog." It has been proposed for the English-French supersonic civil aircraft the "Concord" and others.

Similar engines will find application both in civil and in military aviation. But this will probably be the corona of successes for the gas turbine in aviation. At still higher speeds it has no place – we will talk about this in the following chapter.

CHAPTER V

"FLYING FURNACES" AND "BURNING WINGS"

The fact that the turbojet engine is inapplicable at great supersonic speeds of flight, it is doubtful whether the reader will be surprised after what was said in the preceding chapter. In fact, already at relatively low supersonic speeds, 2-3 times greater than the speed of sound, the turbojet engine starts to be changed very much. These changes are extraordinarily characteristic, as you will remember what was said about them in the preceding chapter. The air inlet and nozzle, with respect to accessories of the subsonic engine are here advanced in the first plan, and the most important parts of the subsonic engine — compressor and turbine — become clearly secondary.

Such a change in the relative role of parts of the engine with a growth in the speed of flight is quite regular. As a result of this growth an ever greater part of processes of the change in the state of air in the engine making up its working cycle is transferred from the compressor to the air inlet, if the question is about compression and from the turbine into the nozzle, inasmuch as expansion is considered. Therefore, the rotor of the engine is reduced in dimensions, and its role becomes progressively less.

It is not difficult to see that with a further increase in speed of flight, in general, there is no need in the compressor and turbine — the engine can manage without them. But then what is left of the engine — the air inlet, combustion chamber and nozzle? What kind of gas turbine engine is this if in it there are not the most important parts of such an engine — the compressor and turbine?

Thus the turbojet engine "degenerates" and is converted into an air-breathing jet engine of the compressorless type, the so-called steady-flow (or ramjet engine PVRD).

The first engines of such kind appeared when the turbojet engine did not even exist and, consequently, they were not the result of "regeneration" of gas turbine engines. They were intended for flight at relatively low subsonic speeds. In them there were no compressor and turbine and, at the same time, the engines successfully operated, developing a thrust necessary for flight. In our country the ramjet engines were developed approximately 30 years ago by Yu. A. Pobedonostsev, I. A. Merkulov and other researchers and designers. The first takeoff of a small rocket with the ramjet engine of I. A. Merkulov was carried out, in particular, in May of 1939, and the first test of such an engine on an aircraft was in January of 1940. However, these were experimental models of the engine, and at that time there was no application for them. The practical use of the ramjet engines belongs to a much later time, essentially, only to recent years when developed flight speeds considerably increased.

During the years of the war there was practical application of compressorless ramjet engines of another type. These were the so-called pulsejet engines, which were installed then on the first German pilotless winged missiles "Fau-1" [V-1].

Thousands of such small aircraft with a loudly thundering pulsejet engine and explosive charge on board crossed the English Channel carrying death and destruction. Their speed was relatively low, and they flew at a low altitude so that the British rapidly learned to destroy them in the air with help of aircraft and antiaircraft guns.

At present pulsejet engines find very limited application on guided missiles and as a propulsion system of jet helicopters.

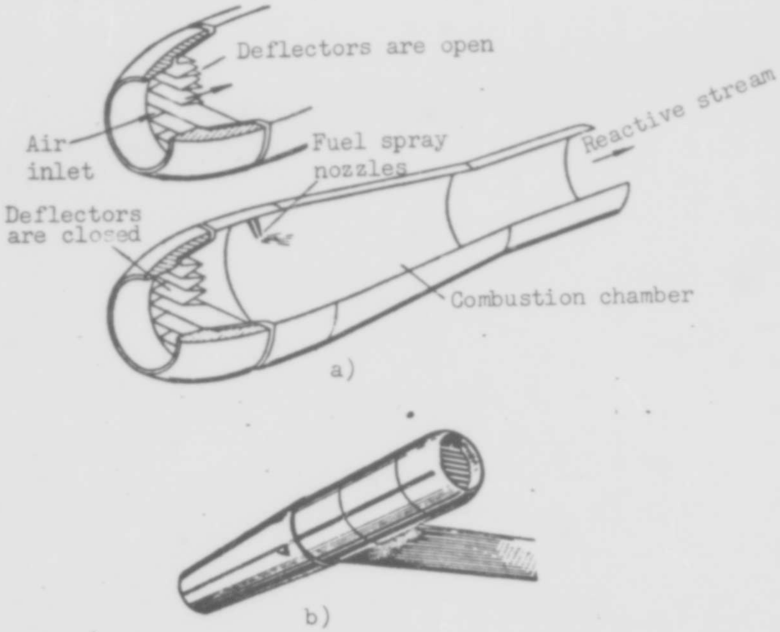


Fig. 29. Pulsejet engine: a) diagram of the engine; b) installation of the engine on the blade of the rotor of the helicopter (United States).

They are installed directly on ends of blades of the rotor of helicopters, eliminating the need in its mechanical drive. The thus obtained simplification and facilitation of the helicopter together with great simplicity and unpretentiousness of pulsejet engines explain the causes for which they find a certain application, in spite of considerably lesser economy, i.e., greater fuel consumption in comparison, for example, with gas turbine engines. It is true that they do not have great prospects here.

The fact that the economy of a pulsejet engine is very low is not unexpected and is easily explained by peculiarities of its working process. In a pulsejet engine, just as a compressorless engine, the compression of air should be carried out by some other method, and the impact pressure of the counterflow of air in this case is insufficient. Such compression is carried out with the use of pulsations of pressure in the engine, which operates not continuously, as a steady-flow or gas turbine does, but periodically. But by this method it is possible to compress the air only very insignificantly, and this is why the whole cycle of the engine is uneconomic. Operation of the engine is provided with the help of valves located in the front section of the engine, which has the appearance of a long pipe. When the valves are open, inside the engine there proceeds fresh air, and when the mixture of fuel with air ignites inside the engine the valves are closed and forming gases of raised pressure flow out through the nozzle of the engine backwards, creating a thrust. It is interesting that in small pulsejet engines it is possible to manage entirely without valves, by selecting in an appropriate way the geometry of the engine. In such engines there are created oscillations of pressure of an acoustic character, as in a standard pipe organ, and as a result of similar oscillations the gases flow out primarily backwards, which is required for the creation of thrust.

In a ramjet engine there are no valves, but there are also no intentional pulsations of pressure and they operate on a continuous, steady state. The compression is carried out as a result of impact pressure of incident flow of atmospheric air, and since at low subsonic speeds of flight such a compression is very small, the engine is extremely uneconomic. Therefore, subsonic ramjet engines did not find practical application, if one were not to consider certain jet helicopters (reasons of their use in these cases are the same as the above-mentioned for pulsejet engines). Nevertheless, we will begin the story about the arrangement and work of ramjet engines from subsonic as the simpler.

The first part of the ramjet engine, station No. 1 of the "conveyer" of the continuous change of the state of air in it is, as in a turbojet engine, the air inlet. Of course, everything said in Chapter IV about the "zero station" is completely applicable here; and here this "station" exists outside the engine, in the atmosphere before it. Regarding "station No. 1," in the case of the ramjet engine, it, probably, is not quite true to call it an air inlet, although, indeed, here the air first of all proceeds from the atmosphere. The fact is that if the air inlet of the turbojet engine usually only feeds air to the compressor, and the state of the air in it is almost not changed or is changed insignificantly (air can either somewhat accelerate, or, on the other hand, be braked in the air inlet), then in the ramjet engine this is not so. Here the first part fulfills immediately two functions, obligations immediately of the first two stations of "conveyer" of the turbojet engine — air inlet and compressor. It is not surprising that for this reason "station No. 1" of the ramjet engine obtained the name of diffuser — so called the pipe or channel in which compression of air or other gases is carried out.

When subsonic flow is braked, then, as was mentioned in Chapter IV, the diffuser should constitute an expanded pipe. Thus this is exactly how the diffuser of a subsonic ramjet engine looks — in any such engine in front it is possible to see a long conical gradually expanded pipe. It appears long not accidentally; this is explained by the fact that the angle of coincity should be small, usually only several degrees, i.e., the pipe should be indeed expanded gradually. It is worth violating this rule and shortening the diffuser (at those same values of the inlet and outlet sections it is sharply expanded), as now the pay for the thus obtained decrease in dimensions and weight will be a sharp impairment of operation of engine. It appears the deceleration of flow without losses here becomes impossible, since the flow is detached from too steeply divergent walls, and in it eddies appear, on the formation of which there is expended a considerable part of the kinetic energy of flow. As a result there is a decrease in the compression pressure, so small in this case, with a corresponding decrease in thrust of the engine and impairment of its economy.

The next station of the "conveyer" (as before we will consider it the third in order , considering that Nos. 1 and 2 are united in the diffuser) is the combustion chamber. Although it is mostly similar to the combustion chamber of the turbojet engine, nevertheless here there are very significant distinctions. One of them is quite obvious and, probably, the most important: once in the ramjet engine there is no turbine, then, consequently, there are limitations of maximum temperature of gases connected with it. This is why here in combustion there can participate not a smaller part of air flowing through the engine but all of it. Accordingly, there could be more thrust of the engine if there were not reduced pressures in it. It is understandable that the absence of the necessity in the mixing of products of combustion with cold air simplifies the combustion changer, for which there remains, essentially, only one problem - stabilization of the flame, i.e., the providing of stable burning. It is true that the increase in temperature of the gases simultaneously complicates the problem of the creation of a reliable chamber, since all its parts coming into contact with the gases have a considerably raised temperature.

Somewhat different appearance is found in the combustion chamber of engine if instead of liquid fuel it operates on solid fuel. With engines of such kind experiments were conducted in Germany as early as during the years of the war, later from time to time patents appeared on different designs of similar engines. Usually in this case solid fuel, for example, carbon, is disposed in a layer near the walls of combustion chamber, thereby ensuring their shielding from the direct effect of hot gases. However, such engines are not yet in operation.

The final station of the "conveyer" of the ramjet engine again should have a double number, 4th and 5th, since it combines the function of both these stations in the turbojet engine. Actually, the process of the expansion of gases, which in the turbojet engine occurs in two stages and in two different parts of the engine, turbine and jet nozzle, is carried out here only in the nozzle; the ramjet engine does not have a turbine. And inasmuch as the engine is subsonic, the jet nozzle has the form of a simple convergent pipe. This pipe is shorter than the diffuser - the expansion of gases does not require such a smooth slow change of the section of flow as that of compression.

Thus, the subsonic ramjet engine is extremely simple in own external outlines and construction. It consists of only three main

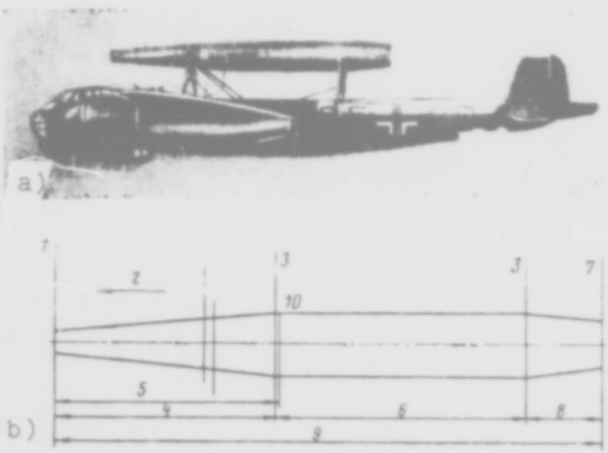


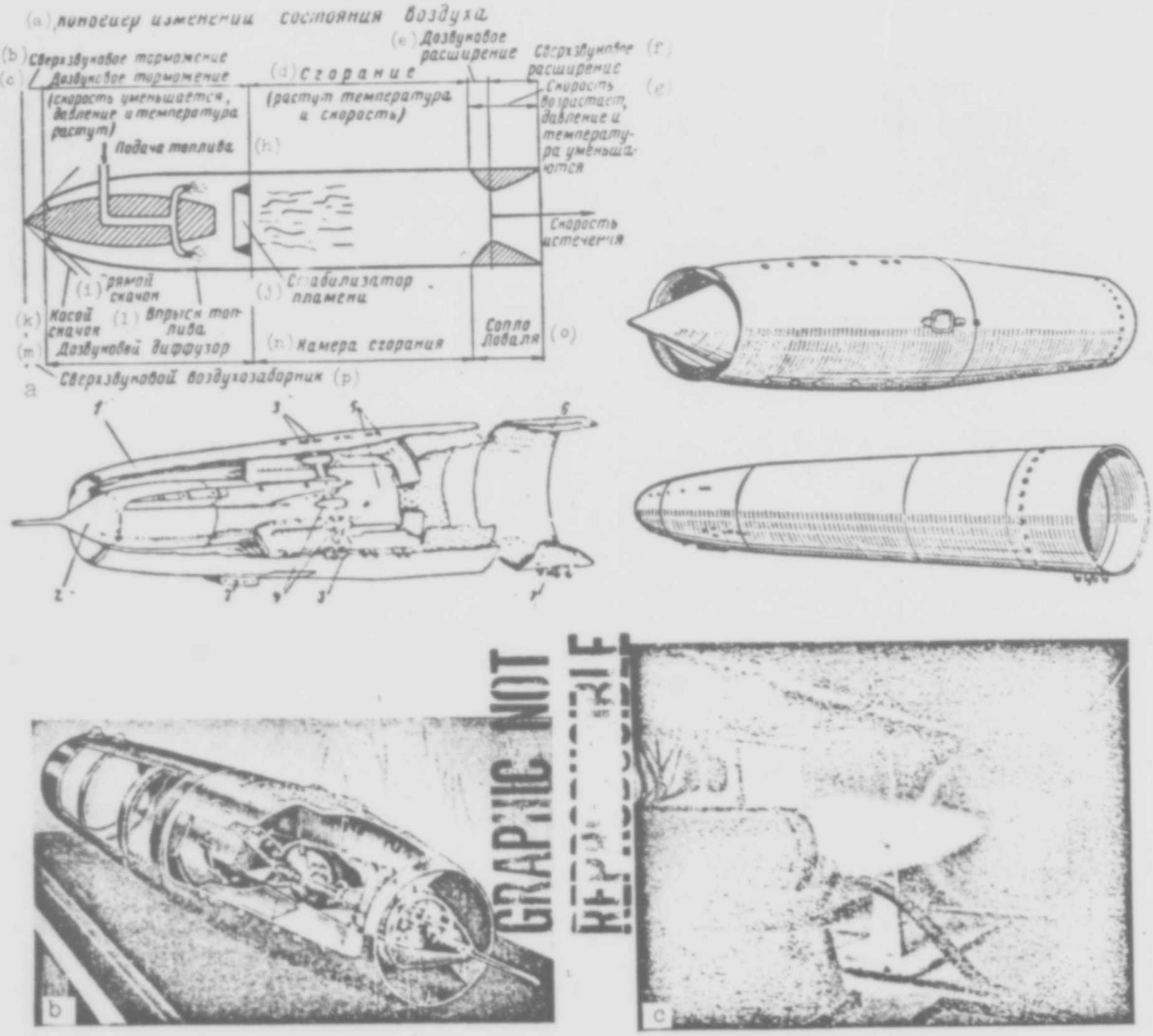
Fig. 30. Subsonic ramjet engine: a) flight test of the engine on an aircraft (Germany, 1944); b) diagram of this engine. 1 – diameter of inlet section, 397 mm; 2 – direction of flight; 3 – diameter of combustion chamber, 999 mm; 4 – length of diffuser, 3421 mm; 5 – distance from inlet section to the plane of injection of fuel through injectors, 3454 mm; 6 – length of combustion chamber, 3996 mm; 7 – diameter of outlet section, 751 mm; 8 – length of jet nozzle, 1209 mm; 9 – total length of engine, 8626 mm; 10 – plane of the location of fuel spray nozzles.

parts: middle – cylindrical (this is the combustion chamber) and two outer – conical (diffuser and nozzle). Of course, the engine should possess other parts and systems, for example, for the fuel feed into the combustion chamber, ignition of this fuel, stabilization of the flame, etc. But still its design simplicity as compared to the turbojet engine is striking. Essentially, this is a simple segment of the pipe, one furnace for the burning of fuel but a "flying one"; it is able not only to fly by itself but also to force an aircraft on which it is installed to move. It is clear that a similar "flying furnace" proves to be very light. The only trouble is that such a furnace burns much fuel, and it is extraordinarily uneconomic. But here the trouble is not in it but in the speed of flight. So long as the speed is low, there is little kinetic energy of incident flow of the atmospheric air, and, consequently, there are low pressures in the engine. It immediately becomes clear that the situation can be radically changed with a transition to supersonic flight.

In one respect the ramjet engine will not be helped, obviously, by the most high-speed flight. The question is about operation of the engine on the test stand, i.e., during takeoff of the aircraft. It is obvious that in these conditions, when the impact pressure of the counterflow of air is absent, i.e., speaking simply, such a flow does not exist, and the engine is not able to work. It is possible, of course, to feed fuel into its combustion chamber on stand and even to ignite it, but gases formed during combustion will flow out forward and backwards, and the engine will not develop thrust. The combustion will immediately be ceased because of the absence of the feed of new portions of fresh air. It is obvious that for takeoff some other engine will be needed. And only if the speed of flight will increase up to a certain minimum (at least 200-300 kilometers per hour), will the engine be able to start to operate. For the same, in order to ensure flight, i.e., to develop sufficiently great thrust, the speed should still considerably increase. In order for the work of the engine to become profitable, so that it expends little fuel, less than other known engines during a high-speed flight, the speed should increase more and become supersonic. Here is where the spaciousness for using all the remarkable properties of the ramjet engine appears, the very nature intended for high-speed flight.

It is understandable that the supersonic ramjet engine will have the same three main parts as that of the subsonic. But there will be preserved the former, essentially, only one name – construction of these parts will be radically changed, and the working processes in them will be changed. They have much more in common than similar parts of the supersonic turbojet engine, and the characteristic influence of supersonic flight is thus affected.

Everything that was said in Chapter IV about the "zero station" and air inlet of a supersonic turbojet engine completely pertains to the diffuser of a supersonic ramjet engine. Here there is a system of shocks in front of the input into the engine and the peaked central body and a control system of geometry – movement of the



GRAPHIC NOT REPRODUCIBLE

Fig. 31. Supersonic ramjet engine: a) diagram of the engine; b) cross section of English supersonic ramjet engine "Thor"; c) outer view of the engine "Thor" and its bench test: 1 – body of the engine 2 – central body; 3 – igniters; 4 – fuel spray nozzles; 5 – flame holder; 6 – jet nozzle; 7 – bracing support of the engine.
KEY: (a) "Conveyor" of the change of the state of air; (b) Supersonic deceleration; (c) Subsonic deceleration (speed decreases, pressure and temperature increase); (d) Combustion (temperature and speed increases); (e) Subsonic expansion; (f) Supersonic expansion; (g) Speed increases, pressure and temperature decrease; (h) Fuel feed; (i) Normal shock; (j) Flame holder; (k) Oblique jump; (l) Fuel injection; (m) Subsonic diffuser; (n) Combustion chamber; (o) Laval nozzle; (p) Supersonic air inlet.

central body or front section of the cowling (body), etc. Just as in the case of a subsonic ramjet engine, in a supersonic engine there is a simple conical divergent diffuser. In this respect the supersonic engine does not differ from the subsonic in anything surprising - in the diffuser itself after locking normal shock, the air speed is subsonic. The air inlet of a ramjet engine has even still more stringent requirements with respect to the effectiveness of its operation than does that in the turbojet - here there is no compressor, and all compression is carried out in the air inlet and diffuser. In particular, for a ramjet engine especially profitable is the application of such central body which creates a system from an infinite set of weak oblique shocks (its profile is obtained curvilinear here). In this case the pressure, created by the air inlet, can theoretically be greater, which explains the attention manifested to such an air inlet.

Regarding the combustion chamber of the supersonic ramjet engine, then it is worth saying something about it in somewhat greater detail. Remember what was said above in Chapter IV about the combustion in airflow of great speed.

The ignition of fuel in such a flow and the supporting of combustion in it is connected with very great difficulties and requires engineering skill and even true art. It is easy to see that with an increase in flow rate these difficulties increase. This is why the airflow incident on the engine in flight must be braked to such a low speed that the difficulties connected with the combustion chamber proved to be practically surmountable. But something must pay for this. What?

So that the answer to this question becomes obvious it is sufficient to recall what was mentioned above about the diffuser. In the diffuser deceleration of the counter airflow occurs and the necessity in a smooth deceleration forces us to extend greatly the diffuser. If it were possible to decrease the deceleration, i.e., to increase the terminal velocity of air in the diffuser (with this speed the air abandons the diffuser and enters into the combustion chamber), then, naturally, the diffuser would be shorter. Furthermore, this would decrease the losses of energy inevitably accompanying the deceleration of flow and would lower the temperature load of parts of the engine, i.e., decrease the influence of those factors essentially determining the limit of speeds of flight at which still the application of ramjet engines is profitable. This is why the requirement of the highest possible deceleration of flow rate in the combustion chamber is equivalent not only to the complication, increase in dimensions and loading of the engine but also to the limitation of possibilities of its use.

It is not surprising that scientists and designers do not cease working on the problem of a possible increase in flow rate in the combustion chamber.

To be free completely of the long subsonic diffuser would be especially profitable, i.e., to try to carry out combustion in the supersonic airflow. But the solution to this problem, in spite of the intensive investigations, is still a matter of the future. Different possible methods of its solution are studied (for example, by means of the injection of fuel before the intense shock waves in such a manner that in these shocks as a result of great compression the fuel-air mixture would ignite, i.e., with the help of the so-called stabilized detonational combustion[1]), problems of providing stability of supersonic burning are investigated and so on. If these problems are solved, and it is possible to assume they will be, then the supersonic ramjet engine will become considerably smaller in length and lighter and effective at increased flight speeds.

The jet nozzle of the supersonic ramjet engine also does not differ in principle from the nozzle of the supersonic turbojet engine. Here there is a Laval nozzle, and here there is controlled geometry. But, of course, there is undoubtedly one distinction – the temperature of gases expanded in the nozzle are consideralby higher. However,

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[1] This phenomenon of continous detonation, noticed for the first time in the USSR, is subjected at present to investigation in the Siberian Department of the Academy of Sciences and abroad for the purpose of designing combustion chambers of such type.

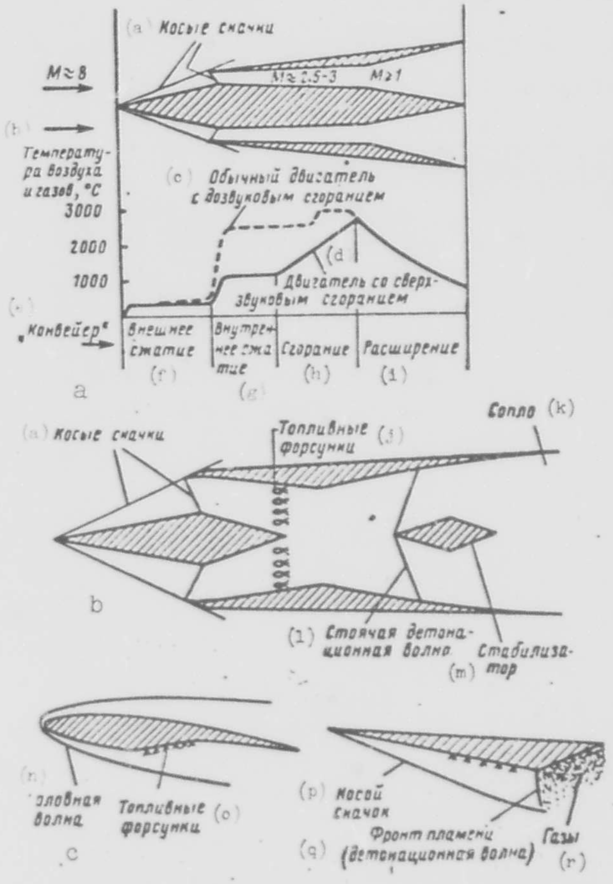

Fig. 32. Ramjet engines with supersonic (detonation) combustion: a) engine with combustion in supersonic flow (the change in temperature of gases in this engine as compared to the standard is shown); b) engine with combustion in a standing detonation wave; c) engine with external detonation combustion in a standing wave ("burning wing").
KEY: (a) Oblique shocks; (b) Temperature of air and gases; (c) Standard engine with subsonic combustion (d) Engine with supersonic combustion; (e) "Conveyer"; (f) External compression; (g) Internal compression; (h) Combustion ; (i) Expansion; (j) Fuel spray nozzles; (k) Nozzle; (l) Standing detonation wave; (m) Stabilizer; (n) Head wave; (o) Fuel spray nozzles; (p) Oblique shock; (q) Flame front (detonation wave); (r) Gases.

if the topic of discussion is about a turbojet engine with afterburner, then this distinction is absent. Incidentally, there is great interest in connection with high temperature of gases in attempts to create the so-called aerodynamic jet nozzle.

In this case the control of geometry of the jet, i.e., the change in its section and profile, is carried out in the nozzle of the fixed, constant geometry by means of putting air into the jet. The air is supplied in such places in such quantity and at such speed so that its influence on the stream leads to its assigned change. It is clear as to what advantage there is in such a method, as it eliminates the need for a complex system of mechanical control of the nozzle, working in contact with gases of very high temperature. Such nozzles of the aerodynamic type possess a great future.

As can be seen, the supersonic ramjet engine, althought it is extremely simple in its basic configuration, it is not quite as simple as compared to the subsonic engine of the same type. If one were to consider the presence of very constructively complex adjustable elements, the diffuser and nozzle, also complex control systems and other auxiliary systems (how to accomplish, for example, actuating the pump of fuel feed if the engine does not have a revolving shaft?), then one should recognize that in reality such an engine will not be at all simple but rather the opposite. But this, of course, in no way decreases its potential possibilities of use for supersonic flight and its advantages over other possible engines of this assignment. These advantages are such that specialists unanimously consider the ramjet engine the basic engine of aviation of great supersonic speeds of flight approximately corresponding to the Mach number M = 4 - 6.

One of the fundamental advantages of the ramjet engine over the turbojet is the considerably great freedom of choice of its geometric forms. It is easy to see how this is important for the designer of an aircraft. Regarding the turbojet engine, its geometry first of all is determined by the presence of revolving parts – compressor and turbine. The natural form is therefore a solid of revolution; it is not surprising that all well-known turbojet engines have the form of a cylinder.

The ramjet engine is not related to such limitation. And although until now basically there were constructed engines reminiscent in their forms of turbojet engines, this is never obligatory; there are already engines of other forms. In particular, for example, it is possible to construct engines of rectangular cross section, flat, which it would be possible to place in the wing of an aircraft. It is possible to imagine even a wing-engine, i.e., a wing for which the whole internal cavity constitutes a ramjet engine. Here very interesting possibilities are revealed.

But, probably, even more interesting are possibilities of quite another kind. In order to discuss them, it is necessary to start somewhat from afar.

Let us assume that before us is a supersonic ramjet engine of rectangular section, the engine being without a subsonic expanded diffuser, i.e., with supersonic combustion. Consequently, this engine consists of a rectangular channel of approximately constant section and nozzle. The nozzle will be considered only divergent, i.e., as if a Laval nozzle with the first convergent section cut from it. It proves to be possible to do this, and this is why. In the cylindrical combustion chamber the gas flow with its heating up gradually accelerates, its speed increases, where, as the theory shows, this speed, if in the beginning it was subsonic, can reach (but by no means exceed) the speed of sound. We consider that in our case the speed of gases at the combustion chamber outlet is equal to the speed of sound, and this is why further acceleration of gases should be carried out already in the divergent nozzle.

Thus, here we will take the following, at first glance, unexpected and even senseless decision; we will cut absolutely literally, our engine in half by the horizontal plane, passing through geometric axis of the engine. Let us cut and then simply remove the lower part, leaving the upper. There appears the question: if we will carry out this our risky operation of cutting the engine during its operation will it cease to work?

It seems that such a question is absurd. How, in fact, can this upper half of the engine operate (however, with the same success it was possible to leave the lower half and be concerned with the upper half), if all of it is as if open outside, and its internal surface is directly in contact with the atmosphere? In the engine the state of the air should undergo great changes, and its pressure and temperature cannot fail to differ considerably from the atmospheric. Can this be in our case?

And why not? In fact this at first glance only appears that the distinction in value of pressure requires the presence of some solid limiting walls.

However, this is true but only in the case of fixed gas, i.e., for static conditions. Quite another matter is motion; it is enough to remember already the well-known "zero station" of the motor "conveyer." The same pertains, for example, to the case of the wing in flight: as is known, the pressure on its surfaces differs from atmospheric, otherwise flight would be impossible. Even simpler and clearer is the question of temperature - the presence of heterogeneities of temperature is well-known, and it is enough to remember at least a burning match.

Does this mean our half of the engine can work? Yes, it can. Of course, there is no need for proof of this to cut the engine in half. It is possible to proceed differently: to construct such a ramjet engine for which there would be only one limiting surface. But such a surface, as it is easy to see, reminds one of the profile of a standard aircraft wing. Perhaps it is possible not to construct a special ramjet engine but to use as such an engine the existing wing of an aircraft?

The theoretical analysis and available experimental data show that there is such a possibility indeed. The wing of an aircraft can become a ramjet engine and, in the case of supersonic flight, can develop thrust necessary for its realization. For this on the lower surface of wing it is necessary to feed fuel through injectors and ignite it. This surface as if protected by a flaming armor, and such a burning wing (it is clear that combustion will be carried out in supersonic flow) begin not only to support the aircraft but rush it at enormous speed. Here there will probably be needed special quick-burning fuels, but fuels will be discussed later, in Chapter IX which is specially devoted to them.

At present such a ramjet engine with "external combustion" is only an assumption, but the real possibility of its creation is indubitable, and in this direction intensive works are being conducted. Inasmuch as such an engine possesses definite advantages as compared to the standard ramjet engine, it is possible to consider just as indubitable its probable use in aviation of the future.

But let us return to ramjet engines of the more usual type. What is their place in the aviation of today and tomorrow?

If the topic of discussion is about the subsonic engine, then, as was already said above, their application is very limited; essentially, such engines are installed, and even that in a small number of cases, only on blades of rotors of helicopters. Another matter is that of supersonic ramjet engines. Already at present they have obtained abroad a rather wide application as the propulsion system of pilotless winged missiles and rockets. Thus, for example, according to source material, in the United States the "land-to-air" pilotless missiles are well known, i.e., interceptors, "Bomarc" with two sustainers (this means operating for a long time in flight) Marquardt ramjet engines with a weight of 223 kg and thrust of more than 5 T with a flight at M = 3, pilotless missiles Navaho with ramjet Curtis Wright engines (thrust of 18 T during flight at M = 3-3.5, length of 3500 mm, diameter of 1200 mm) and others. In England there are rockets of such "Bloodhound" design with the ramjet engine Thor (thrust during flight near earth at M = 3 is equal to 6800 kgf, length of the engine – 2400 mm, diameter – 400 mm).

These rockets possess a speed of 2-4 times that of the speed of sound. There are no doubts that similar application will be found on supersonic ramjet engines in future both on operational rockets and on pilotless aircraft of peaceful assignment – postal, cargo and so forth.

Regarding piloted aircraft, at present there are still no such aircraft in operation but individual experimental models have already flown. Thus, for example, French experimental aircraft Leduc 021 with a ramjet engine is well-known, the body of which serves as the fuselage of the aircraft, and in the central body a cockpit is placed. For takeoff, climb and acceleration this aircraft was set on another, the heavy aircraft Langedoc, which thus served as the carrier. In the following modification of the aircraft, Leduc 022, besides the pilot in the central body there was a turbojet engine so that the aircraft could accomplish an independent takeoff and acceleration. In the more recent French aircraft "Griffon" [spelling not verified] with a ramjet and turbojet engine they already are combined into a single combined propulsion system; similar, very long-term installations is the subject of Chapter VIII.

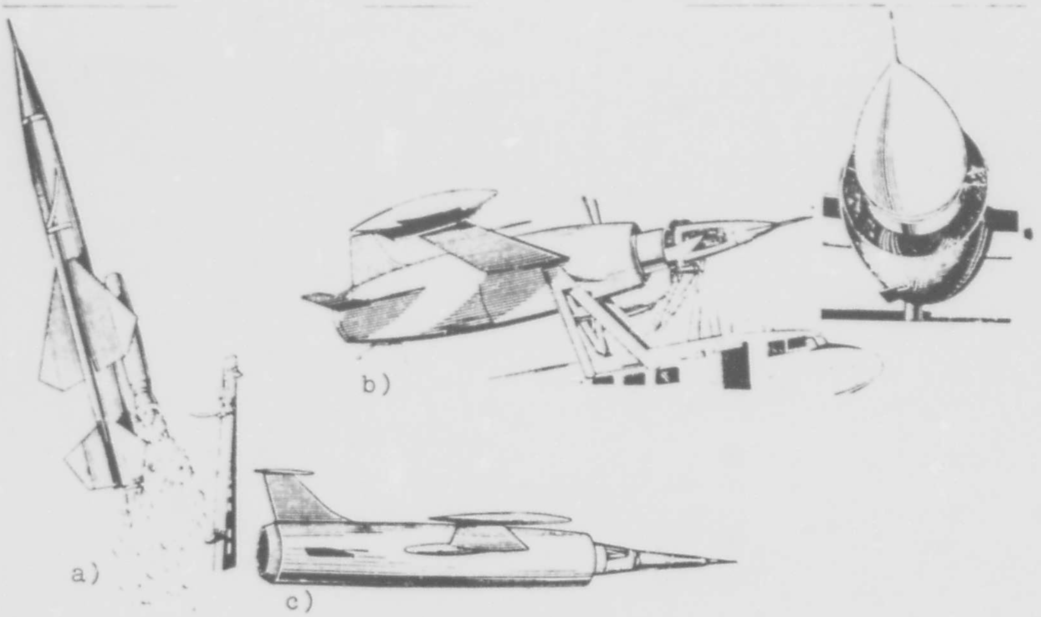

Fig. 33. Supersonic ramjet engine on an aircraft: a) takeoff of pilotless antiaircraft winged missile Bomarc with two ramjet and one assisted takeoff rocket engine; b) aircraft Leduc 021 [spelling not verified] with a ramjet engine on the carrier aircraft Langedoc [spelling not verified]; c) aircraft Leduc 022 in flight.

In the future, according to the most widespread opinion of scientists, the ramjet engine will receive wide application in supersonic aircraft, both military and civilian. Aircraft with such engines (of course, in combination with engines of another type, inasmuch as ramjets not able to provide independent takeoff) will fly at speeds 3-6 times that of the speed of sound. In this speed range not another engine can compete with the ramjet with respect to specific thrust (i.e., thrust per 1 kg of its weight) and specific fuel consumption per 1 kgf of thrust. During flight with a speed three times greater than the speed of sound, the ramjet engine with a middle section of 1 m^2 is in a state to develope a thrust of tens of tons and effective power of hundreds of thousands of horsepower at a record-breaking low weight and specific fuel consumption. Ramjet engines can find application in astronautics, in particular, on carrier rockets, and also for flight in atmospheres of other planets, for example, Mars and Venus.

Incidentally, hydrojet ramjet engines, similar in design, can find application in the future for high-speed underwater transport. In this case the water should serve as one of the components of fuel, reacting with the other component. A number of such engines was tested in Italy.

However, why is the range of supersonic speeds in which the application of the ramjet engine, is promising limited to the value M, approximately equal 6, i.e., the speed is 6 times greater than the speed of sound? Is it that at high speeds the ramjet engine is no longer in a state to operate?

No, this is not so. Of course, at higher speeds the ramjet engine is fully in a state to develop the thrust necessary for flight. It is in the state, but still ...it is not able. There is no paradox here, but simply a number of circumstances does not permit realizing potential possibilities of the ramjet engine at such great (they are usually called hypersonic) speeds of flight. What are these circumstances?

Remember what was said above about the heating of air during its compression, about the fact that with deceleration of the airflow possessing great supersonic speed its temperature is many hundreds of degrees. At quintuple the speed of sound the temperature of the braked air can reach almost 1500°C. It is not surprising that with an increase in speed of the flight there is attained such an air temperature entering into the engine that the construction of engine and materials from which it is made is no longer in a state to sustain such a temperature. Even the cooling of the walls of the engine by external air, widely used in engines, for example, of automobiles or aircraft, at lower speeds of flight is not able to help here. In fact, the temperature of the external air flowing around the walls of the engine will be precisely the same height – at the wall itself this flow is braked! It is obvious that there is some terminal velocity of flight at which the engine still preserves its efficiency. At greater speed it can no longer be used.

But it appears it can be used not only at a greater speed than this maximum permissible from considerations of heating but even at a considerably lower speed. The secret here is simple. The temperature of the air proceeding into the engine is never the maximum operating temperature in the engine. As a result of the combustion of fuel there will be formed gases whose temperature is certainly higher than the initial temperature of the air; otherwise the engine will not develop thrust. This means that the temperature of air will not be limited, but the temperature of gases will, so that at the maximum given operating temperture of gases the temperature of the braked air, and accordingly, the speed of flight should be even less.

Thus, when the speed of the flight greatly increases, then the temperature of the air entering into the engine increases, and with an increase in speed there is attained such a value of it when the limitation of the maximum operating temperature of the walls of the combustion chamber and nozzle of the engine compels decreasing the heating of gases in the combustion chamber, i.e., the fuel feed into it. But this means that the thrust of the engine decreases. It appears that although at these high speeds the engine continues to remain very economic, i.e., uses relatively little fuel per kilogram of thrust developed by it; and the magnitude of the thrust itself rapidly decreases. This finally makes the engine unfit for operation. Thus, there appears the above-indicated speed range of the flight in which a ramjet engine can be effectively used. At flight speeds exceeding the speed of sound 6 times, the greatest, 7 times, there appears an invisible "temperature border," over which the ramjet engine is not able to cross. But this engine is the most "high-speed" of all the known airbreathing-jet engines. Consequently, the indicated border determines the limit of possibilities of all airbreathing-jet engines. It is true that certain authors examine the possibility of using ramjet engines even up to $M = 8$-10,[1]

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[1] In particular, for testing hypersonic ramjet engines at $M = 8$ the well-known high-altitude aircraft X-15 is reequipped (journal "Problems of Rocket Technology," 1964, No. 8) and others.

and 15. However, these, as they are called, hypersonic engines (the term hypersonic refers to flight at a speed exceeding the speed of sound by more than 5 times when the high temperature of the braked air already changes its physicochemical properties) require the application of not as yet existing structural materials, methods of cooling, etc. Therefore, usually the border of the speed of flight for airbreathing-jet engines is assumed to be M = 5-6.

To what kind of jet engine is this border not dreadful? This will be discussed in the following chapter.

CHAPTER VI

ONE LIQUID BURNS INTO ANOTHER

If the maximum speed of flight at which there can still operate any air-breathing jet engine is limited by properties of the air (its stagnation temperature), then, obviously, the engine which could overstep this limit should not depend in its operation on air and should not use it. We know engines possessing this fundamental peculiarity; in contrast to the air-breathing jet, they are called rocket engines.

It is known that the rocket engine was the first of all jet engines created practically by man. This was a solid-propellant rocket, i.e., a solid-propellant rocket engine. But it is easy to see that in aircraft (and also for using it in space flight), such an engine has little use and at the present level of its development is never useful. This is explained by the fact that once launched the solid-propellant engine continues to operate until all the fuel is burned, and also by the fact that the thrust of engine practically does not yield to control. It is understandable that an engine with such properties cannot satisfy aviation and astronautics – the flight of an aircraft or spaceship should be controlled and occur in various conditions. It is true that very recently there have been attained definite successes in the control field of operation of solid-propellant rocket engines.

There exists, however, a rocket engine of another type, operating not on solid but on liquid fuel and fully meeting the complex requirements of aircraft and space propulsion systems. This is the so-called liquid-propellant rocket engine (or ZhRD).

But what does this mean – liquid fuel? The turbojet or ramjet engines also operate on liquid fuel. What then is the distinction here, and is there one generally?

Yes, such a distinction exists and is so fundamental that it should be given attention. In fact, the fuel for a turbojet engine is, of course, liquid, but for its combustion oxygen from air is still necessary. Thus, in the combustion participate in this case two equal-rights components, only one of which is liquid and the other – gaseous. In a liquid rocket engine the gaseous component is completely absent, and in this case both fuel components are liquid.

But is it possible that one liquid burns into the other?

Indeed, it is well-known that the combustion of fuel always occurs with the participation of atmospheric air. Thus was and then when man built a bonfire for the first time. Thus occurs now everywhere where fuel burns – in an iron stove or a cylinder of an internal-combustion engine, furnace of a boiler or combustion chamber of a turbojet engine. But is this the only possible form of burning?

It is possible to perform a small experiment. Let us throw a piece of metallic potassium or sodium into water. Immediately there will start a stormy chemical reaction accompanied by the liberation of a great quantity of heat, and the air in it clearly does not participate. But, it is possible to retort that, this is nevertheless not combustion, since there is no flame characteristic for combustion. Let us assume that there is combustion so that a flame can be obtained. For example, nitric acid is splattered on a saucer, into which another liquid, aniline, is poured and now the saucer will be enveloped by a flame. What happens? Combustion. But here not only does the liquid fuel in air burn, but one liquid fuel into the other. Such examples can be given arbitrarily.

In many cases the simple contact of liquids does not cause burning; for example, if the same nitric acid were poured, into a saucer with kerosene, then a flame would not appear. It is enough, however, to ignite this mixture, as the combustion, once started, will occur very vigorously. What is surprising here, in case of the usual combustion there is required, as a rule, ignition and a match is needed. Without it the burning of gasoline, alcohol and other conventional propellants will not start.

Fig. 34. One liquid burns into another.

But when one liquid burns into another, what burns into what? Which of these liquids is the fuel, the nitric acid or aniline?

When a conventional propellant burns in air, this question does not appear, although, in fact, we have full right to say that the air (more accurately, of course, oxygen from air) burns into the gasoline, but not inversely. The role of both these substances participating in combustion is equally important, neither one of them can manage without the other. This is all the more true, obviously, in case of combustion of one liquid into other; here both substances participating in the combustion are not different even in their aggregate state. Therefore, they both have the full right to be considered fuel. Thus, nitric acid and aniline for example, are called rocket fuel, more precisely, components, i.e., component parts of this fuel. The combination of both components constitutes rocket fuel or a fuel combination.

But although both fuel component play an equally important role, qualitatively their roles, of course, cannot fail to be distinguished. This is so in the case of the combustion of gasoline in air. Combustion constitutes a chemical reaction of oxidation, where the fuel (gasoline) is oxidized and the oxygen from air serves as the oxidizer. It is in exactly the same way in the case when both fuel components constitute a liquid; one of them is oxidized, and the other is the oxidizer (this is established by chemistry according to the character of the change in electron shells of atoms and molecules of both reagents). In order to stress this distinction, it is accepted to call one of the components of the rocket fuel <u>fuel</u> (it is oxidized) and the other, the <u>oxidizer</u>. Here it is now already clear, for example, that nitric acid is the oxidizer and aniline or kerosene, the fuel. Both of them together are rocket fuel.

Thus, if for all air-breathing jet engines – turbojet, ramjet and others, as, however, for reciprocating engines, one component of the fuel, the combustible (it is often called in this case fuel) is on board the aircraft, and the other component – oxidizer – is borrowed from the atmosphere, then in the case of a rocket engine both components must be on the vehicle. Therefore operation of the rocket engine does not depend on the atmosphere, and it can operate in space vacuum or provide flight in the atmosphere theoretically at any arbitrarily great speed. The compression of air in such a flight will no longer affect more the work of the engine, as takes place in the case of air-breathing jet engines. There will not, therefore, be the limitations mentioned in the preceding chapter connected with temperature – such limitation will only exist with respect to shell and construction of the vehicle itself.

This is why the rocket engine is a natural record holder with respect to both the already attained and, all the more so, possible speeds and altitudes of flight. This never means that in the whole possible speed range, up to the speed of light in a vacuum, the predominate force will be any one type of rocket engine. In the struggle for flight speed there will be used all possible rocket engines; each of them will be used in those cases when it gives the best results as compared to all other engines. In subsequent chapters we will meet with certain already developed types of rocket engines and also with those which as yet are only being investigated. Here the discussion will only be about the engine to which now records belong with respect to speed, altitude and flying range – the liquid-propellant rocket engine.

How is this engine installed, and how does it operate?

The fundamental diagram of a liquid-propellant engine is very simple, just as the ramjet engine; common for these engines is that they do not have moving parts and possess very low specific weight (weight per 1 kgf of thrust). Therefore, both are called flying furnaces with sufficient basis. But further this conditional similarity (conditional because the true arrangement of the engine is immeasurably more complex than the fundamental diagram) common for both engines, is of course, small.

We already know that the liquid-propellant rocket engine operates on fuel consisting of two different and separately stored liquids. There are indeed such engines in which the fuel constitutes one liquid, which is either a mixture of both components necessary for combustion – fuel and oxidizer, or does not burn in the engine and liberates heat and forms gases as a result of disintegration or dissociation on simpler substances. However, engines of this type occupy as yet a very modest place, and probably, this will always be the case. Therefore, we will consider only engines with a so-called separate fuel feed.

Any liquid rocket engine should include at least two obligatory parts: a system of fuel feed (and sometimes a system governing the quantity of fuel fed) and a thrust chamber, as it is frequently called. In its turn, the thrust chamber consists of a head with injectors of the supply of components of fuel, a combustion chamber and a jet nozzle. Of course, besides these main parts there are usually others, for example, a system of the ignition of fuel with the starting of the engine, a system of cooling and so forth; the design fulfillment of the engine can be most diverse.

Let us become acquainted with the arrangement of the basic above-mentioned parts of liquid-propellant rocket engine and physical processes occurring in them.

Our story about the liquid-propellant rocket engine will start from the thrust chamber, in which the whole working process of the engine occurs. As any other jet engine, for example, the turbojet or ramjet liquid-propellant rocket engine is as though it is a "conveyor" of continuous changes of the state of the working substance on which the engine operates. Only in the turbojet or ramjet engines, which was discussed above, such a substance is air; we observe the change of its state when we discussed the working process of these engines. At this same time there is no air, and fuel moves along the "conveyer."

Station No. 1 of the conveyer, from which there start the "mishaps" of fuel, is located in the head of the thrust chamber. The components of fuel are fed here without change in its state with the help of an additional "conveyer" - a fuel system which will be dealt with below.

Components of fuel proceed separately into the head; their first encounter occurs already inside the combustion chamber. It is clear why this is so: a similar encounter of components can lead to a very stormy reaction the place of which is only in the combustion chamber.

The task of the head of the thrust chamber is to introduce the fuel component into the combustion chamber so that the chemical reaction occurring in it occurs as rapidly as possible and as full as possible. This means that into the reaction there should enter the total quantity of components of fuel introduced into the chamber, and the reaction itself should occur up to full liberation of the potential chemical energy of the fuel. To achieve this it is necessary to provide as much as possible the full contact components of fuel in the combustion chamber so that in the ideal case every molecule of fuel encounters a molecule of oxidizer. This consists of the basic task of the head.

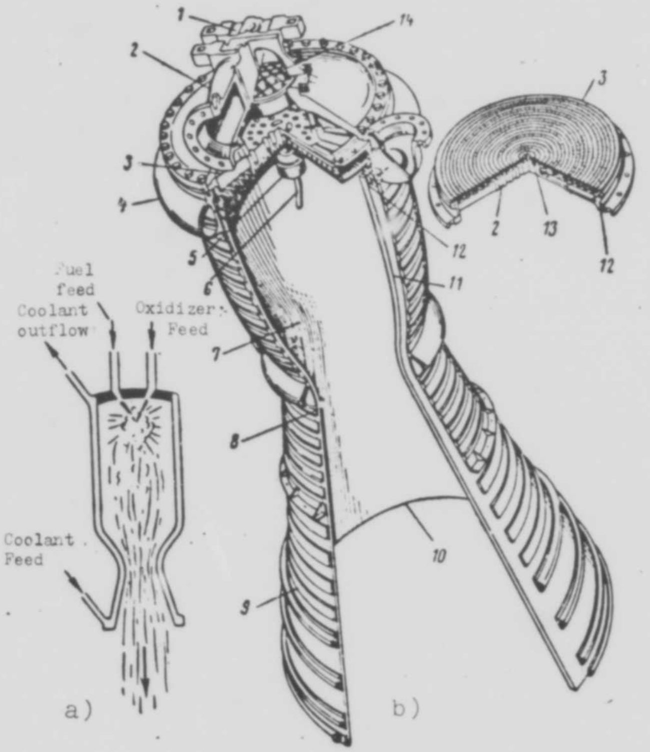


Fig. 35. Thrust chamber of a liquid-propellant rocket engine: a) schematic diagram; b) construction of the chamber of the English engine RZ-2. Thrust of the engine is 62-68 t, it operates on liquid oxygen and kerosene, is installed on the rocket "Blue Streak": 1 — Cardan suspension of the chamber allowing its turn for a change in direction of the tractive force; 2 — supply of oxidizer (liquid oxygen); 3 — head of the engine (injector plate); 4 — pipeline of the supply of fuel (kerosene); 5 — pyrotechnic igniter; 6 — electrical conductor to the igniter; 7 — combustion chamber; 8 — throat (minimum cross section); 9 — ribs providing the necessary strength and rigidity of the chamber; 10 — jet nozzle; 11 — walls of the chamber from separate tubes through which the cooling kerosene flows; 12 — feed of fuel (kerosene); 13 — feed of priming fuel (for ignition); 14 — grid for the rectification of flow of liquid oxygen.

This task is not very simple. Every second through the head flow hundreds of kilograms, and for the most powerful engines, even tons of fuel, and all of this fuel must be prepared for combustion in a very short time and on very small path inside the chamber. Otherwise the whole "conveyer" will appear very long, and the dimensions and, consequently, weight of the engine intolerably increase.

In order to ensure thin mixing of fuel components in the combustion chamber, in the head there is usually a very large number of holes - injectors, through which fuel injection is produced in the chamber. These injectors are alternately located so that around every injector for the oxidizer usually several injectors for fuel are located.

The most profitable position of injectors is determined in each separate case. Sometimes the injectors are disposed along alternating concentric circles (one circle for the oxidizer, the other for fuel), and sometimes they will form different geometric figures reminniscent of kaleidoscopic patterns.

In the case of an engine of very great thrust the construction of the head, having many hundreds of small holes - injectors for the injection of fuel, is very complex and expensive. Therefore, interest in investigations of heads of the simple type, all with several injectors of large diameter is clear. The creation of such heads would considerably facilitate the development of powerful engines.

The fuel fed by injectors into the combustion chamber should be well atomized, mixed and then vaporized. Therefore, it is impossible to be limited to only one successful location of the injectors, and the head designer must solve many other problems. Thus, for example it is not very simple to find the correct feed pressure of the fuel - it changes depending upon the quantity of fuel flowing through the injectors, i.e., operating conditions of the engine and can appear either too small, which will worsen

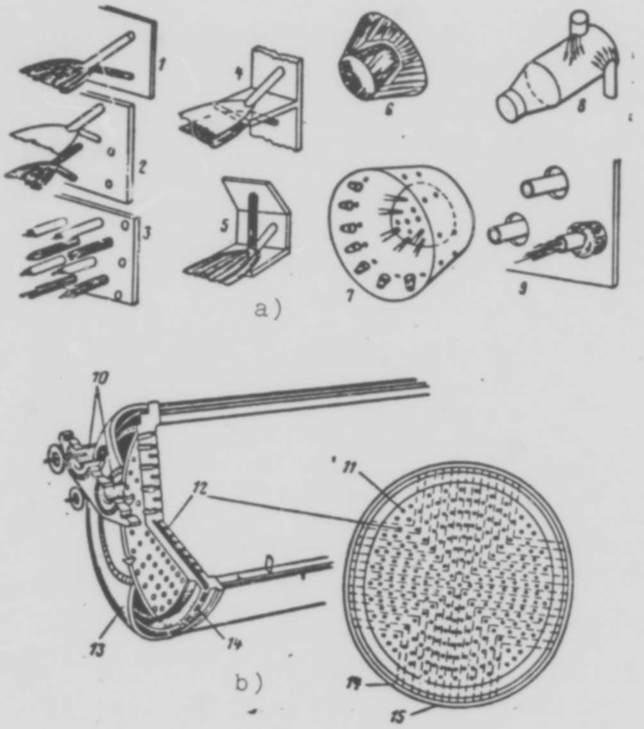


Fig. 36. Certain methods of fuel injection used in the combustion chamber of a liquid-propellant rocket engine (a). Head of the engine of rocket "Nike" (United States) — (b): 1 — colliding jet of both components of fuel; 2 — colliding jets of the same component of fuel; 3 — non-colliding streams (shower head); 4 — jets directed towards spraying plate; 5 — streams are mixed on the plate; 6 — streams form two cones, convergent and divergent; 7 — conical "rosette" (engine of the rocket "Fau-2" [V-2]) with a supply of oxygen in the center and alcohol on the periphery; 8 — supply of preliminarily mixed components of fuel; 9 — coaxial streams (one inside the other); 10 — hole for apportioned mixture; 11 — hole for fuel feed; 12 — hole for oxidizer feed; 13 — subassembly of the head; 14 — lateral holes for oxidizer feed; 15 — bottom of head (plate, top view).

the spraying and lower the economy of the engine, or excessively large, and this will lead to an increase in losses of energy in the engine and therefore again to the impairment of its economy. Frequently the designer locates the injector in such a manner so that the stream of fuel collides, and with this their atomization is improved; here it is necessary to find the best angle between the streams, distance between the injectors and others. How important all these problems are can be seen from the fact that most frequently the successful construction of the head determines the success of this engine.

But here the fuel is injected into the combustion chamber. Now it is necessary to ignite it. Upon starting the engine for this purpose there are special firing devices, for example, electric detonator spark plug, pyrotechnic fuse and so forth, located at the very beginning of the following, i.e., second station of the engine "conveyer." Thus, as in a turbojet engine in this place of the basic "conveyer" it is as if connected by the other auxiliary "conveyer" of the system of ignition. Only in one case is the necessity dropped in such an auxiliary "conveyer" – when the engine works on so-called hypergolic fuels. Let us recall the above-mentioned example with ignition of analine in the saucer when into this saucer there was poured strong nitric acid. It is clear that with operation on this or other similar components of fuel there is no need in a special ignition: the components of fuel self-ignite immediately after their contact in the combustion chamber. Incidentally, sometimes for the ignition of non-self-igniting fuels upon starting the engine in the combustion chamber through special injectors there are injected small quantities of special self-igniting components. As a result there will be formed a starting flame, which already ignites the basic fuel components. Such a system of ignition is usually called chemical, in contrast to electrical or pyrotechnic.

When the engine already started operating, then for the igniting of the following next portions of fuel, continuously injected into the combustion chamber, no special system of ignition is necessary. However, as this is already well-known to us, so it is in any gas turbine or ramjet engine - this ignition is carried out by a flame permanently existing in the combustion chamber.

Remember how much concern there is of stabilization of the flame, i.e., the providing of stable burning in turbojet and ramjet engines? For this different special stabilizing devices are used - registers. If a similar register was necessary in the combustion chamber liquid-propellant rocket engine, then the position of designer would be simply desperate, probably, even hopeless. Of course, such a register was washed by gases with a temperature almost twice higher than in the turbojet engine, sometimes attaining and even exceeding 3500°C.

Fortunately, in this case the register is not needed. The register is necessary only when combustion occurs in a gas flow of high speed; here there is no airflow, and the speed of fuel vapors injected into the chamber before the beginning of combustion is low. Only, when as a result of combustion the temperature of the gases becomes very high does the speed of the gas flow greatly increase. However then the combustion is practically finished.

But, unfortunately, the problems connected with the stabilization of combustion in a liquid-propellant rocket engine are not exhausted. Very frequently in the combustion chamber of the engine in the course of the process of burning pulsations, oscillations of pressure of the hot gas flow appear. Sometimes these pulsations become very strong, which leads to considerable impairment of the whole operation of the engine. Harmful consequences of such kind, as it is usually called, of vibration burning can be most diverse from a decrease in thrust and impairment of the economy of operation of the engine up to the appearance of local overheatings and even burnouts or putting the engine out of operation for other causes connected with considerable vibration loads in its construction. Pulsations in powerful engines of great dimensions are especially strong and are dangerous.

Investigation, both as theoretical and experimental, show that the causes of the appearance of intense pulsations, just as their frequency, can be different. Sometimes they appear as a result of oscillations in the system of fuel feed in the engine (these usually low-frequency oscillations change also the quantity of burning fuel), sometimes they have an acoustic character, i.e., similar to oscillations appearing, for example, in an organ pipe (these high-frequency pulsations are usually the most dangerous), sometimes they are connected with peculiarities of the combustion itself.

Usually high temperatures of gases in the combustion chamber of a liquid-propellant rocket engine lead to one more unique distinction in the process of combustion in this engine from the combustion in any air-breathing jet engine. It is known that when the temperature of some gases becomes very high the molecules of these gases cease to be stable. Atoms making up the molecule start to oscillate inside them so greatly that finally they break the intramolecular bond, and the molecule disintegrates. This process, which is called dissociation, is characteristic for a liquid-propellant rocket engine, since in a turbojet and even ramjet the temperature of the gases is insufficiently high for dissociation to become noticeable, although it starts there. Inasmuch as the process of dissociation occurring in the combustion chamber is connected with the splitting of molecules of products combustion into simpler (for example, initial reagents), then it inevitably leads to a loss in chemical energy and corresponding lowering of the temperature of gases forming during the reaction. Actually, in the presence of the dissociation the temperature of the gases is always smaller than without it. Therefore, for example, the increase in pressure in the combustion chamber leads in these cases to the increase in temperature of the gases, inasmuch as it is easy to see with the growth in pressure the dissociation is hampered, and the molecules become as if more durable. It would have been possible to assume in connection with this that the phenomenon of dissociation very harmfully affects the operation of the engine, decreasing at the same expenditure of fuel the exit velocity and, consequently, thrust (exit velocity, as was already mentioned above, is proportional to the square root of the temperature of the gases). Fortunately, however, the situation is not quite so, inasmuch as in the situation the next, third station of the "conveyer," jet nozzle of the engine interferes.

Since in the combustion chamber there occurs a process of the conversion of chemical energy of the fuel into thermal energy, then the problem of locking the "conveyer" of the jet should be, obviously, the conversion of thermal energy into kinetic energy of the jet, as takes place in any other jet engine. For the sake of correctness it is necessary to note that partially this conversion also occurs in the combustion chamber, since there in the course of combustion with an increase in temperature and volume of the gases their speed increases. However, as the theory shows in a combustion chamber of cylindrical form the speed of the gases can be increased only up to a definite limit, exactly to the speed of sound in gases. Inasmuch as the exit velocity of gases from the nozzle of a liquid-propellant rocket engine exceeds the speed of sound several times, and the kinetic energy, as is known, is proportional to the square of the speed, then, as it is easy to see, the part of thermal energy turning into kinetic in the combustion chamber itself is very small as compared to the same transition in the nozzle.

As we already know, in order to accelerate the gas flow up to supersonic speed, the nozzle should have the form of convergent-divergent channel characteristic for the Laval nozzle. Such a form is found in nozzles of the majority of the constructed liquid-propellant rocket engines where the convergent section of the nozzle is usually very small as compared to the divergent. It is not surprising that already at the combustion chamber outlet the speed of the gas flow is very close to being sonic; if it was equal to it, then in general the convergent part of the nozzle was absent, and the cylindrical combustion chamber immediately turned into a divergent conical nozzle.

Incidentally, the fact that a supersonic jet flow out of the engine can be judged not only with respect to the form of the nozzle. A characteristic peculiarity of the supersonic jet, all the same, whether this pertains to a liquid-propellant rocket, turbojet or any other jet engine, is its nonuniform structure. In contrast to a subsonic jet in a supersonic, it is always possible to see alternating brightly luminescent and darker spots and a unique fire dashed line. Its origin is connected with the propagation in a supersonic jet of strong waves of pressure and rarefaction - in zones of increased pressure the temperature of the gases is increased, and this is why they start to gleam more brightly.

The acceleration of gases in the nozzle is accompanied by their expansion with a corresponding decrease in pressure and temperature. But the cooling of gases is inevitably connected with the process of reverse recombination of molecules, dissociating in the combustion chamber; this process is usually called recombination. The thermal energy expended on dissociation is thus separated in the nozzle again. However, this never means that losses of energy connected with the dissociations are eliminated. First of all, the recombination of molecules in the nozzle never occurs to the end - the temperature of gases in the nozzle is still very high. Furthermore, this process requires a certain, let us assume, short time, and the speed of gases in the nozzle is so great that molecules are in the nozzle for already a very short time. This is why the true expansion in the nozzle has as if an intermediate character between the two boundary cases: when recombination succeeds in being carried out completely (of course, in accordance with the temperature level), and when it does not occur at all. It is easy to see that the first case of outflow through the nozzle (it is called equilibrium outflow - in each section of the nozzle the recombination accurately corresponds to the temperature of gases) powerfully more favorable than the second (it is called "frozen" - the composition of gas in the nozzle is not changed). Actually, in the second case the energy of dissociation is never separated.

GRAPHIC NOT REPRODUCIBLE

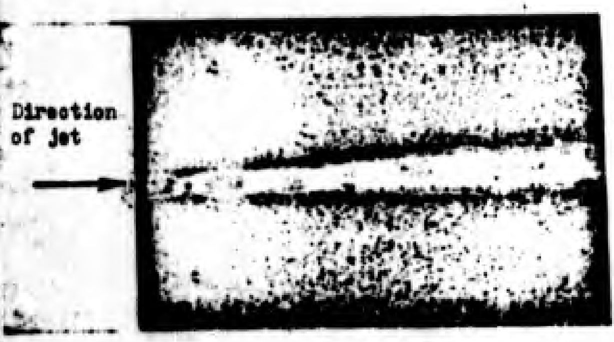


Fig. 37. In a supersonic jet zones with greater and smaller glow are alternated; this fire dashed line is the characteristic peculiarity of a supersonic engine.

But, it appears that the interference of station No. 3, which does not allow dissociation to worsen catastrophically the operation of the engine, is not limited by the phenomenon of recombination. The fact is that the exit velocity depends not only on the temperature of the gases but also on their molecular weight. The peculiarity of the process of outflow of gases through the jet nozzle is the fact that the velocity of outflow proves to be dependent on the ratio of both of these values - temperature and molecular weight (more accurately, it is proportional to square root of this ratio). But it is easy to see that dissociation, in decreasing the temperature of the gases, simultaneously decreases their molecular weight: the dissociation is the process of splitting of complex and massive molecules into simpler and lighter. Therefore, precisely as a result of dissociation, even if the exit velocity decreases, it does so insignificantly. In reciprocating engines, for example, where the dissociation is less significant, its harmful action can appear more considerable.

How successfully the nozzle is designed, in many respects, is governed by the effectiveness of the whole engine, since in the nozzle, as was shown above there occurs one of the most important working processes of the engine. Fortunately, the acceleration and expansion of gases can be carried out practically incomparably more simply than can compression and deceleration.

There are no fundamental difficulties, for example, those connected with the designing of supersonic air inlets, in the creation of the nozzle of a liquid-propellant rocket engine. It is necessary to observe only that the section of the nozzle (least in the throat and the largest outlet) be optimum in value, so that the walls of the nozzle inside are sufficiently smooth and its contours provide the minimum length of the nozzle and the smoothest expansion of flow. This means that in the flow inside the nozzle eddies should not appear, and at the outlet of the nozzle speeds of all the gas particles should have identical direction; otherwise the thrust of the engine will decrease. It is understandable that the designer tries to solve these problems with the help of a nozzle of the least possible length and weight, since the weight of the nozzle is a very considerable part, sometimes of the order of $\frac{1}{3}$ of the total weight of the engine.

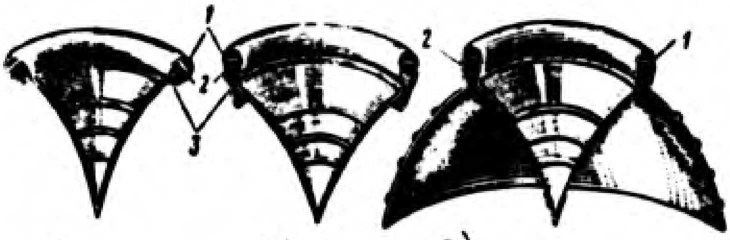
However, the situation changes most radically if the thrust of the engine must be changed or if the engine operates in a great range of altitudes of flight and, consequently, with greatly changing outlet pressure from the nozzle, which can always take place, for example, in the case of installation of the engine on an aircraft or space aircraft. In order, let us assume, that the thrust of the engine is decreased, it is necessary to decrease the quantity of gases flowing from the engine through the nozzle, i.e., obviously, to decrease the fuel feed in the combustion chamber of the engine. It is easy to see that the pressure of gases in the combustion chamber will inevitably decrease, because the flow area of the nozzle throat remains the same. The speed of the gas flow in the nozzle throat with a change in flow rate of gases through it is not changed, and it remains as before equal to the speed of sound. Consequently, a decrease in flow rate can be obtained only as a result of a decrease in density of gas flow, i.e., a decrease in its pressure.

But a decrease in pressure in front of the nozzle changes the whole condition of its operation, makes it, so to speak, off-design, and in particular, in the nozzle exit section the pressure of gases will also decrease (it is always smaller than the pressure in front of the nozzle in a strictly definite number of times corresponding to the expansion area ratio). This so-called overexpansion of gases always worsens the economy of operation of the nozzle and whole engine, i.e., leads to an increase in fuel consumption per 1 kgf of thrust. The same occurs with an increase in pressure in the combustion chamber of the engine higher than that to which the nozzle is designed. In this off-design case the nozzle starts to operate with the so-called underexpansion, i.e., with increased pressure in the outlet section, which also increases the specific fuel consumption.

Analogous off-design conditions will appear and with a considerable change in atmospheric pressure, i.e., altitude of flight. When the altitude increases, the nozzle operates with underexpansion, and when it decreases, with overexpansion.

Obviously, there would not be such impairment if changes in thrust would have been possible to reach with changed pressure in the combustion chamber, and with a change in altitude of flight the pressure in the nozzle exit section was changed accordingly. But this requires changes in the cross section of the nozzle throat and its outlet section. But the creation of such a nozzle is still more complex than that for turbojet or ramjet engines, and the temperature of the gases in the nozzle in this case is incomparably more!

It is not surprising that in spite of the numerous inventor proposals and patented designs, there is one engine with a similar nozzle in operation abroad as yet. But then recently engines with nozzles considerably differing in design from the usual Laval nozzles have appeared abroad. It is considered that these nozzles possess indubitable advantages and prospects of further application and improvement. In particular, they permit improving the operation of the engine in off-design conditions, simplify the possibility of the creation of so-called clusters of engines - a combination of several thrust chambers for the augmentation of thrust (such clusters will be discussed in greater detail later), lead to a decrease in weight and simplification of construction of the engine in respect to the fact that their length can be decreased almost half as compared to standard nozzles.



a) b) c)

Fig. 38. Diagrams of nozzles with a central body: a) completely external expansion of gases; b) partially internal, partially external expansion; c) completely internal expansion. 1 - head of the engine; 2 - combustion chamber; 3 - nozzle throat.

These new nozzles differ in that essentially they are not... nozzles in the usual meaning of the word, i.e., channels or pipes in which the expansion and acceleration of gases occur. This sounds paradoxical, but we now will see that the principle on which the operation of similar nozzles is constructed is already familiar to us.

The new nozzles are called sometimes nozzles with a certain body (true, such nozzles are possible with a central body for which there are external walls of the nozzle, i.e., they still constitute a pipe). Indeed, along the axis of this nozzle there is located a special body, usually conical or a shape close to it, in the form of a cone, frequently truncated, with a summit along the flow (in certain types of similar nozzles the central body looks like a mushroom). The base of the cone is located exactly where the nozzle throat is assumed to be, so that the throat area becomes annular in this case.

Moreover, the whole combustion chamber is also annular shaped, in the form of a ringed-shaped roll or torus, located around the throat. Of course, the throat diameter must be increased respectively, and now gases flow only through the narrow annular slot. This slot is made so that gas jets are directed not only along but also toward the axis of the nozzle. They flow around the central body, forming in space a fire gas flame, and its external outlines repeat the contours... a Laval nozzle! It appears that this divergent nozzle nevertheless exists, but only without external walls which limit the gas flow. Until now we knew of such invisible walls appearing in the atmosphere before the air inlet of a turbojet or ramjet engine. We now encounter (they were mentioned earlier in connection with the problem of an aerodynamic nozzle) similar invisible walls created already behind the engine and this time by the will of the scientist and designer, using the laws of nature. Thus there is obtained a nozzle with a completely external expansion, although there can be created similar nozzles with combined, half external, half standard internal, expansion.

Experience has shown that nozzles with a central body possess high economy, i.e., induce very small losses of energy. At the same time, they themselves, without any special regulating mechanism, are rather well adapted to off-design conditions of operation of the engine. With the installation of a number of separate segmental combustion chambers on the ring it is possible to change the fuel feed in separate chambers in such a manner that the symmetry of the jet is disturbed, and it is turned at a certain angle, which is very important for flight control of the rocket. Control of the cross sectional area of the throat in this case with desire is also less complexly accomplished and it is sufficient to move the central body along axis of the engine. True, the

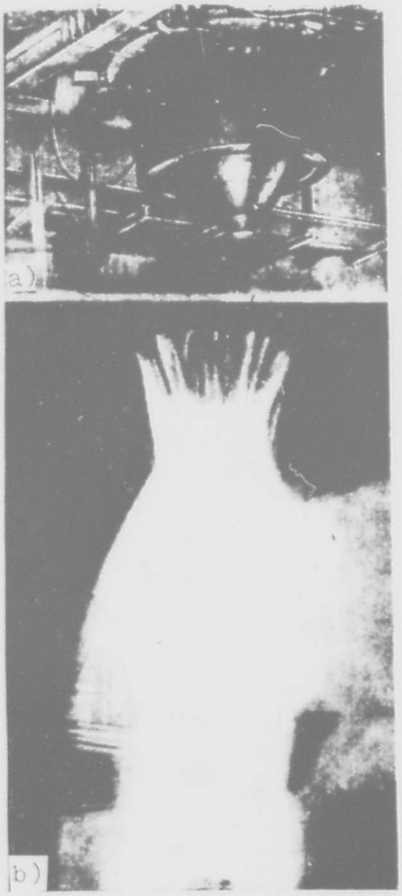


Fig. 39. Liquid-propellant rocket engine with a thrust of more than 22 t, having a nozzle with a central body (United States):
a) engine on a test stand;
b) test firing of the engine.

conditions of operation of this body are not quite at all simple, but rocket technology is able to cope with this difficulty. It is assumed that nozzles with a central body will find wide application in the future, especially for engines of very great thrust. Incidentally, this principle can be used and is even being used for nozzles of supersonic turbojet engines.

In order to complete our story about the thrust chamber of the liquid-propellant rocket engine, it is certainly necessary to say something about the most important problem appearing during its designing, the problem of cooling. In fact, we already know that the speed of gases relative to the walls of the chamber can

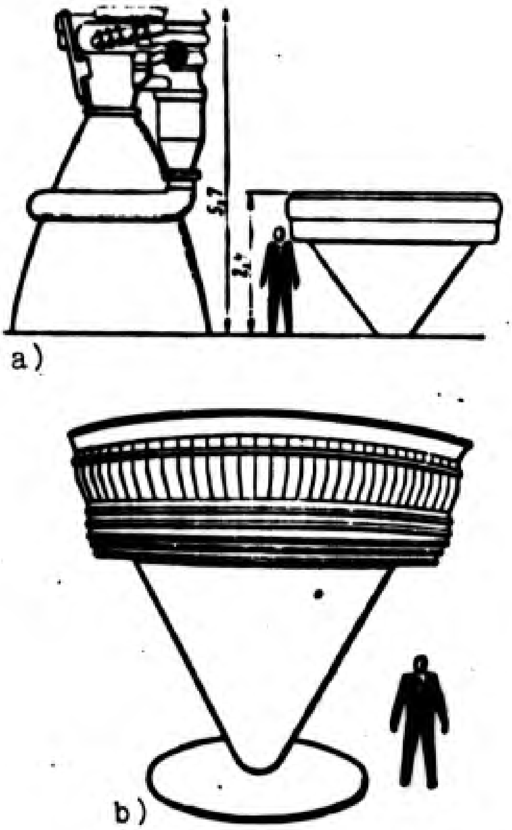


Fig. 40. Nozzle with a central body radically changes the appearance of the liquid-propellant rocket engine: a) figures of the appearance of the standard engine (on the left) and engine having a nozzle with a central body with an identical thrust (of the order of 450 t); b) photograph of a full-scale mock-up of an engine, having a nozzle with a central body, thrust at approximately 1100 t, developed in the United States. The engine has 13 separate small combustion chambers located about the ring (segmental). Height of the engine – 4.6 m, diameter – 3.5 m.

exceed the speed of sound several times, and the pressure and temperature of the gases can reach, respectively, tens of atmospheres and more than 3000°C. It is easy to imagine what enormous heat flow should flow from gases to the walls of the chamber if one were to consider that the temperature the walls themselves should not exceed several hundred degrees and, in the worst case, in no way higher than 1000°C. At a similar temperature any metal loses so much of its strength that it is not able to sustain considerable stresses appearing in walls of the chamber.

It is obvious that these enormous heat flows must be removed from the walls; otherwise, the latter for short instants will be fused, and the engine will break down. Here is where the cooling system is important. One of the most frequently used methods of cooling and, incidentally, one of the oldest – it was proposed by the inventor of liquid-propellant rocket engine by

K. E. Tsiolkovskiy - is the method of so-called regenerative cooling. The term "regeneration" denotes restoration, and it reveals the essence of this method of cooling, which is included, in order to restore, i.e., use repeatedly, again putting into the gas flow emanating from the engine that heat which the gases returned to the walls. It is understandable that such restoration of lost energy improves the economy of the engine. But the popularity of regenerative cooling is explained not so much by this as the relative constructive simplicity.

In order to carry out regenerative cooling, one of the components of fuel prior to the injection of it into the combustion chamber washes on the outside the walls of the thrust chamber (usually the combustion chamber and nozzle are made together). For this the walls are made double, i.e., are supplied, so to speak, with a jacket - in the clearance between walls and the jacket, usually in special channels, the cooled liquid flows. Then this already heated liquid injected into the combustion chamber - this is why the heat of cooling obtained by it is not lost. But, of course, this is only a scheme, and is in reality the matter is far from being so simple. Thus, for example, it is not easy to decide what the clearance for passage of the liquid coolant should be. If the clearance is great, the liquid flows slower and cooling worsens, and the walls are overheated. If, however, the clearance is excessively small, the speed is increased, but the necessary pressure increases for pushing the liquid through the clearance; it is clear that this is unprofitable. In an ideal case the flow area for the liquid coolant in this clearance should be variable on various sections, depending upon what the heat flow is from gases through the walls on this section. In particular, for example, near the nozzle throat where the heat flow is maximum, the clearance had to be minimum.

Here is one of the constructive methods widely used abroad. The body of the thrust chamber is not machined beyond one integer and is not welded from separate parts but is composed of a great number of thin metallic tubes located close to one another along the engine and welded to each other for the obtaining of a monolithic construction. The tubes are bent along the length for the giving of proper outlines of the combustion chamber and nozzle and are also flattened for decreasing the width in the narrow sections, in particular, at the nozzle throat. Thus an approximation to the most advantageous form is attained.

However, in spite of all these devices, the regenerative system of cooling appears not able to cope with the colossal heat flows, which characterize the contemporary powerful engines. It is necessary, therefore, to use other methods of cooling, usually jointly with the regenerative system. For example, there is used the so-called film cooling, by which in the walls of the thrust chamber there is drilled a large number of small holes, through which inside the chamber under pressure liquid coolant is fed. This liquid covers inside the walls with a thin layer, thus protecting them from the influence of heated gases. The temperature of the walls decreases as a result, but then the fuel consumption is increased - since not the whole quantity of the liquid coolant (this is the fuel!) succeeds in burning in the engine. Film cooling possesses other deficiencies.

Development of the idea of film cooling is the method of cooling which obtained the name of penetrating. Another name of the same method encountered in literature - "sweat cooling" - reveals its essence. In this case holes for introduction inside of liquid coolant, as is done during film cooling, are not drilled. Instead of them in the walls there will be formed myriads of insignificantly small, microscopic holes by means of the use of methods of powder metallurgy, i.e., the manufacture of walls by sintering from grains of metal. Through these micropores the liquid coolant is pressed so that the whole internal surface of the walls is covered by its microscopic drops and layer of vapor - as if it "sweats." This method of cooling provides the least temperature of the walls but requires even further improvement. In particular, by the method of sintering it is possible quite reliably to prepare only comparatively small surfaces, for example, walls of the nozzle near its throat.

In conclusion one should mention such a possibility as the creation of never cooled thrust chambers - experimental engines of similar kind are created abroad. Of course, such engines are useful only for relatively short-term and, usually, single-time action, which is characteristic for rockets. In this case the walls of the thrust chamber are covered from within by a special substance, usually, ceramic, which with operation of the engine is gradually melted and evaporates, protecting the walls from the direct influence of gases. Similar, ablative cooling, as it is called, is used both with metallic walls of the chamber and with plastic, in particular, from reinforced glass fiber. However, similar uncooled chambers are used much more frequently in solid-propellant engines, and these will be discussed in greater detail. The advantages of ablative cooling are clear. They are simplicity and low weight (in one engine with a thrust of 1500 kgf the weight of the chamber is equal to only 13.5 kgf); the change in the flow area of the nozzle throat because of removal from the walls of part of the protective substance in the process of operation can be considered beforehand. Sometimes the same ablative covering is combined with the standard regenerative cooling.

Somewhat alone in this connection is the uncooled thrust chamber from... a transparent material. As the authors who proposed such a chamber in the United States consider, the temperature of its walls will be much lower than that in the uncooled chambers in view of the fact that they pass thermal radiation of flame and gases.

From all other elements and systems of the liquid-propellant rocket engine, besides its traction chamber, we will here discuss only the fuel systems, i.e., the system of fuel feed in the combustion chamber of the engine. As was already stated above,

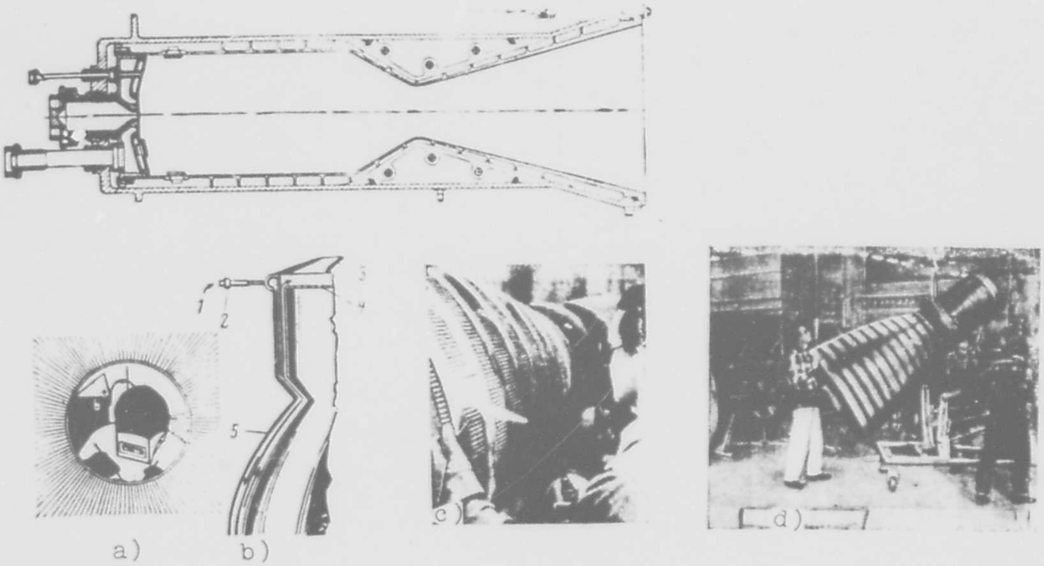
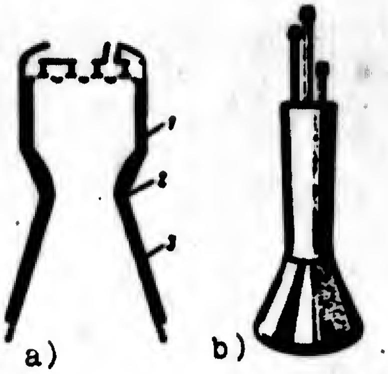


Fig. 41. Cooling of the thrust chamber – one of the basic difficulties in the creation of a liquid-propellant rocket engine. Above – cross section of thrust chamber of an English engine with regenerative cooling (in the cross section spiral channels for the passage of cooling fuel are shown). Remaining figures show a thrust chamber made from tubes through which the liquid coolant (fuel) flows: a) welding of tubes of rocket engine Titan (view through the nozzle), b) schematic section of the chamber, c) soldering of tubes of the rocket engine Thor, d) external view of this chamber. 1 – supply of fuel; 2 – flow valve of fuel; 3 – head of the engine; 4 – injectors of fuel injection; 5 – tubes.

the fuel and oxidizer are stored on a rocket or aircraft in separate tanks and should be fed from them in strictly definite quantities into the thrust chamber, more accurately, to its head. How is this supply carried out?

Various methods are possible here. The simplest is the so-called pressure feed system. As name itself implies, it consists in the fact that in the fuel tanks raised pressure is created, which forces out fuel from the tank so that it is fed into the head of the engine. Increased pressure can be created in the tanks, for example, with the help of any compressed inert gas, let us assume,



a) b)

Fig. 42. Walls of the thrust chamber can be uncooled if the duration of operation of the engine is short and ablative (i.e. expended) or ceramic coating is used: a) diagram of thrust chamber with ceramic heat-resistant covering from within; b) outer view of thrust chamber formed by a winding from an impregnated plastic glass fiber. The chamber of engine with a thrust of 1000 kgf is not cooled and has from within an ablative covering and the engine operated more than 4 min: 1 – ceramic facing; 2 – ceramic glue; 3 – metallic body.

nitrogen or helium, proceeding into the tanks from cylinders where it is stored. The simplicity of such a system is evident, but deficiencies are also evident. Actually, inasmuch as in the tanks raised pressure is created, they should be sufficiently durable and therefore massive. If the engine is powerful the tanks are great in dimensions, and then the pressure feed fuel system becomes simply unfit: it excessively increases the weight of the entire propulsion system.

It is obvious that in the case of a powerful engine the fuel tanks should not have raised pressure inside, but should be, so to speak, unloaded. But then the necessary feed fuel pressure should be created already outside the tanks along the fuel path into the engine. For this purpose there are special pumps, for example, centrifugal, i.e., constituting impeller wheels with blades revolving in the body. Drive in rotation of pumps is carried out, as a rule, by a special turbine operating either on gases tapped from the thrust chamber of the engine or on a gas or gas-vapor mixture forming in a special device – a gas generator. The whole assembly of pumps with the turbine is called turbopump assembly (or TNA).

The majority of the well-known contemporary powerful liquid-propellant rocket engines has turbopump assemblies. These units play so important a role in the operation of the whole engine and, in general, are so complicated in construction that frequently the mentioning encountered in popular science literature about the fact that the liquid-propellant rocket engine is very simple in design and, in particular, does not have one moving part, essentially, loses all meaning.

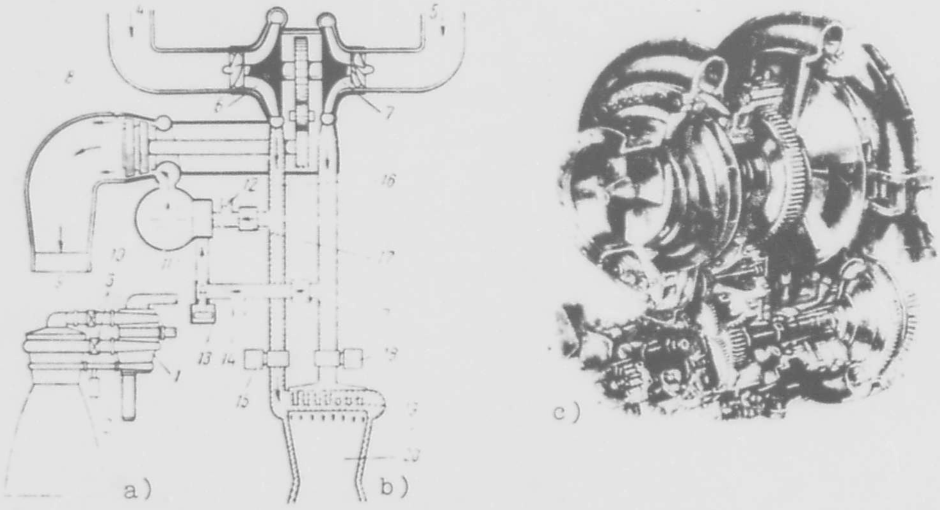


Fig. 43. Turbopump assembly for fuel feed into the combustion chamber of a liquid-propellant rocket engine: a) diagram of turbopump assembly operating on gases tapped from the combustion chamber of the engine (United States); b) diagram of a turbopump assembly with a gas generator of the English engine RZ-2; c) construction of a turbopump assembly of engine (cross section). 1 – turbopump unit; 2 – explosive charge for starting; 3 – fuel flow valves and oxidizer; 4 – fuel supply (kerosene) from tank; 5 – supply of oxidizer (liquid oxygen) from tank; 6 – fuel pump; 7 – oxidizer pump; 8 – turbine of the drive of pumps; 9 – exit of exhaust gases; 10 – gas generator; 11 – inlet valve of fuel into gas generator; 12 – fuel supply from starting tank; 13 – feed adjuster of oxidizer; 14 – supply of oxidizer from starting tank; 15 – main fuel valve into engine; 16 – fuel lines; 17 – check valves (they prevent the entering of priming fuel into the combustion chamber); 18 – main flow valve of the oxidizer; 19 – head of thrust chamber; 20 – thrust chamber.

Incidentally, the considerable complexity of the turbopump assembly, especially for engines of very high thrust installed on space launching rockets, causes the designer to return another time to the thought about maximum simplicity, but a heavier pressurized system. When simplicity, low cost, and, especially, reliability start to play a decisive role, which is characteristic for space rockets, then a certain increase in weight can retreat to the second plan, especially as at high altitudes the necessary pressure in the fuel tanks is low. Another means of simplification of the fuel feed system can be connected with the use of fuel pumps of jet type without revolving impellers and other moving parts. In this case the fuel is sucked from the tank by a stream of liquid of high-speed gas. These are only separate examples of creative searches of designers of rocket engines, especially, superpower ones, which appear now in the armament of space technology.

We will not begin here to touch upon the numerous minute details in the operation of the system of the fuel feed. Let us only mention one problem connected with the control of quantities of both components of fuel fed into the combustion chamber. The fact that such control is absolutely necessary in the case of aircraft engines is obvious, since the thrust of these engines should be regulated in a very wide range. But even with the installation of an engine on a rocket, when the thrust is not changed, the problem of fuel flow control, nevertheless, does not diminish.

It does not diminish if only because the relationship of quantities of the fed components should be strictly defined. It is sufficient to change somewhat the value of this realtionship as compared to the optimum, as now the speed obtained by the rocket and distance of its flight will be sharply changed. This is normal, since only one single mixture ratio (i.e., the ratio of fuel components) corresponds to the most effective operation of the engine — the greatest thrust for every kilogram of burning fuel. But this is not the only situation; this is not the only cause.

Second cause is connected with the starting of the engine.

It is necessary to note that starting is not only very responsible and difficult, but also, perhaps, the most dangerous moment in the operation of an engine. It is easy to understand why. The liquid-propellant rocket engine operates on a fuel which does not simply release a great quantity of heat during combustion but is also characterized by an especially high burning rate. Essentially, this is the current liquid powder. In powerful engines through the combustion chamber every second hundreds of kilograms, tons, of this liquid powder flow. Imagine that in an instant the combustion of fuel in the engine ceases, and unburned fuel is stored in the chamber. What will occur if almost immediately combustion is again renewed? Obviously, the repeated ignition will constitute a simultaneous explosion of a large quantity of the fuel, an explosion having catastrophic consequences.

How many times in the past the starting of an engine was finished in exactly this way! It is sufficient to remember, at least, numerous catastrophes in the launching of "Fau-2" [V-2] rockets at the end of the war or, even quite recently, explosions at Cape Kennedy, from which American rockets are launched.

But the same will occur if with the starting of an engine the fuel will enter the chamber, but the ignition of it will lag very slightly. In order that an explosion will not occur it is very important to provide the supply of components of fuel in a strictly definite sequence (incidentally, it is not the same for various fuels), i.e., at first one, and then the other, and, moreover, in relatively small quantities. This is why when launching a rocket in the beginning the thrust of the engine is considerably less than full – the engine operates, but the rocket stands in place. Only afterwards does the engine emerge, so to speak, into the design point – the rocket at first is slowly detached from the launching pad, but then ever faster lifts upwards. Here is the provision of the needed sequence of supply of fuel components with the starting of the engine and also the needed quantity of fed components, and it is the task of the control system. It has other obligations, for example, those connected with the stopping of the engine (and this is not so simple). It is not surprising that the control system of contemporary liquid-propellant rocket engines, especially powerful ones, appears very complex, with a large number of sensing devices - transducers, control devices, slave mechanisms, different relays, valves and so forth. Elements of radio electronics, telemechanics and cybernetics are widely used in the control systems. All of this is far from concepts about the unusual simplicity of a liquid-propellant rocket engine!

We have talked thus far about the working process of the liquid-propellant rocket engine, its arrangement and the construction of separate component parts. But what are its possibilities, fields of application and place in the family of jet engines?

One characteristic peculiarity of the liquid-propellant rocket engine determining answers to these questions we have already discussed above - it is able to operate at any altitude and outside atmosphere and also at any possible flight speed. This peculiarity is the result of the fact that such an engine does not use for its operation atmospheric air.

But from the same other peculiarities follow. Actually, if in the case of a turbojet or ramjet engine on board an aircraft there should be only one part of fuel, the combustible, and the second part, the oxidizer, this engine draws out from infinite reserves of the atmosphere, then otherwise the matter is in the case of a liquid-propellant rocket engine. Now no longer only the fuel but also the oxidizer should be stored on board the aircraft; this is what is paid for the "autonomy" of an engine, for the fact that it does not depend its operation on the surrounding atmosphere. A natural result of this distinction of the liquid-propellant rocket engine proves to be the considerably greater fuel consumption for every kilogram of developed thrust - now in the expended quantity of fuel the oxidizer is included. With respect to consumption per 1 kgf of thrust (or specific expended) the liquid-propellant rocket engine is 10-15 times worse than that of the turbojet. It is understandable that with the same quantity of fuel on board during the operation of the liquid-propellant rocket engine will be, accordingly, much less.

Thus one more characteristic is clarified and, it is necessary to admit to the very unpleasant peculiarity of liquid-propellant rocket engine – the short duration of its operation. It is true that the thermal balance of the operation of this engine is so strained, which is prolonged, for example, as a turbojet engine, it all the same, probably, could not operate.

However, perhaps, it could be done, but for this it would be necessary specially to adjust and reprocess most radically the design of the engine. However, everytime when it is necessary to increase the reliability and service of the engine (and any other machine), it is necessary, as a rule, to make it more massive and heavy. Weight is the usual pay for reliability. Therefore, for example, an automotive engine weighs much more than a piston aircraft engine (of course, the question is weight per 1 hp of power), and a stationary diesel engine anywhere at an electric power station is considerably heavier than that of an automobile. A liquid-propellant rocket engine, the duration of work of which is inevitably short, can be made very light. And, indeed, it is, probably, unique in this region – it is doubtful whether any other jet engine (except the ramjet in certain conditions) weighs so small per kilogram of thrust developed by it – a total of several tens of grams. In any case, the turbojet engine, for example, although it possesses high perfection in this respect, nevertheless weighs ten times more than the liquid-propellant rocket engine does.

True, it is doubtful whether such a comparison is even legitimate since no turbojet engine can develope so great a thrust. In any case, if the thrust of the most powerful well-known foreign turbojet engine somewhat exceeds at present 10 t, then for a liquid-propellant rocket engine it will attain the level of hundreds of tons, and engines are being developed with a thrust of several thousand tons.

All these and certain other peculiarities of the liquid-propellant rocket engine determined regions of its application in aviation and rocket technology. In aviation these engines were first used, basically, as boosters, i.e., for the facilitation and acceleration of takeoff of aircraft – aviation is fully organized in this case by the short-duration of operation, great thrust and little weight of engine.

Then liquid-propellant rocket engines began to appear on military fighter airplanes in addition to the basic engine, the turbojet. In this case their role consisted in the short-term increase in thrust of the propulsion system of the aircraft and, consequently, its speed when necessary, for example, in aerial combat. This help of the liquid-propellant rocket engine appeared especially valuable at a high altitude; there the thrust of a turbojet engine proves to be many times smaller than that on land, whereas the thrust of a liquid-propellant rocket engine not only does not decrease but even increases by 10-15 percent (this is explained by the decrease in atmospheric pressure, preventing the outflow of gases from the nozzle). Therefore the low-capacity liquid rocket engine in flight at high altitude can appear more powerful than the powerful turbojet engine.

Attempts were made to install a liquid-propellant rocket engine on an aircraft as the basic and only propulsion system; it is clear that in this case the engine should be regulated, i.e., its thrust should be changed on the desire of the pilot in a wide range. The first attempt of this was carried out in our country, at first on a rocket aircraft in 1940 (flights in it were accomplished by pilot V. P. Fedorov), and then on the fighter BI-1. On 15 May 1942 pilot G. Ya. Bakhchivandzhi accomplished the first flight in this first rocket aircraft in the world. At the end of the war at the fronts there appeared German rocket fighters of Me-163. After the war in the United States liquid-fuel rocket engines were installed on a number of experimental research aircraft. These aircraft attained record-breaking heights and flight speeds. The last representative of such aircraft is the now flying aircraft X-15; it reached an altitude of flight of approximately 107 km and speed of 6693 km/h. A jet B-52 carrier aircraft lifts this aircraft to the high altitude.

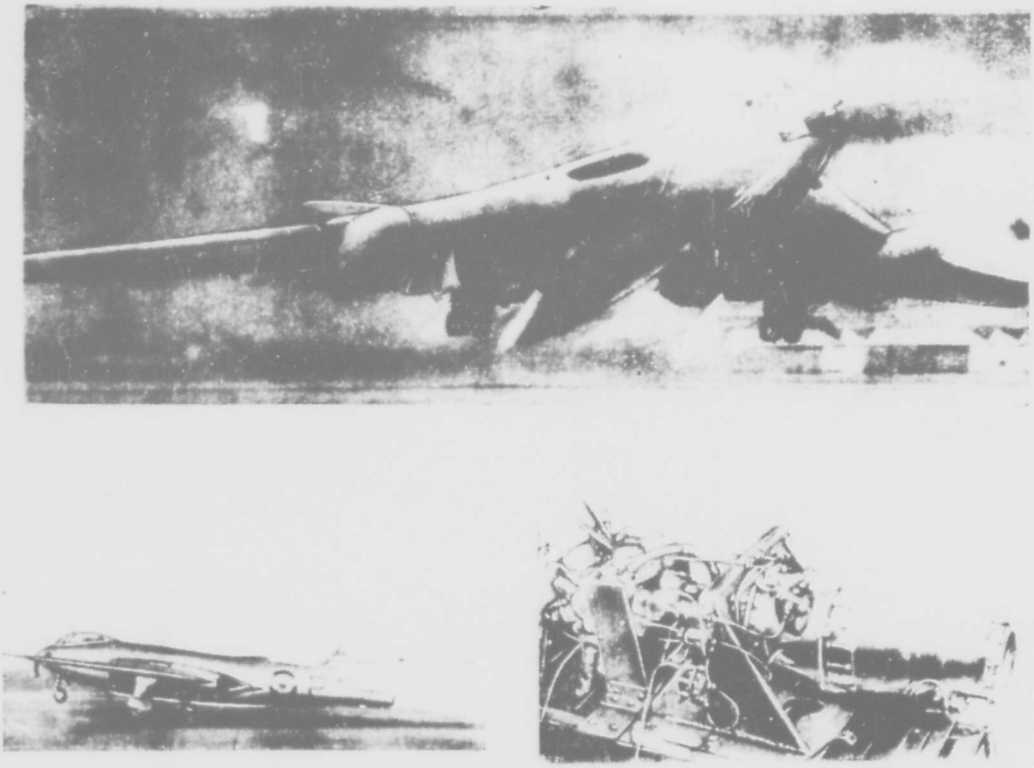
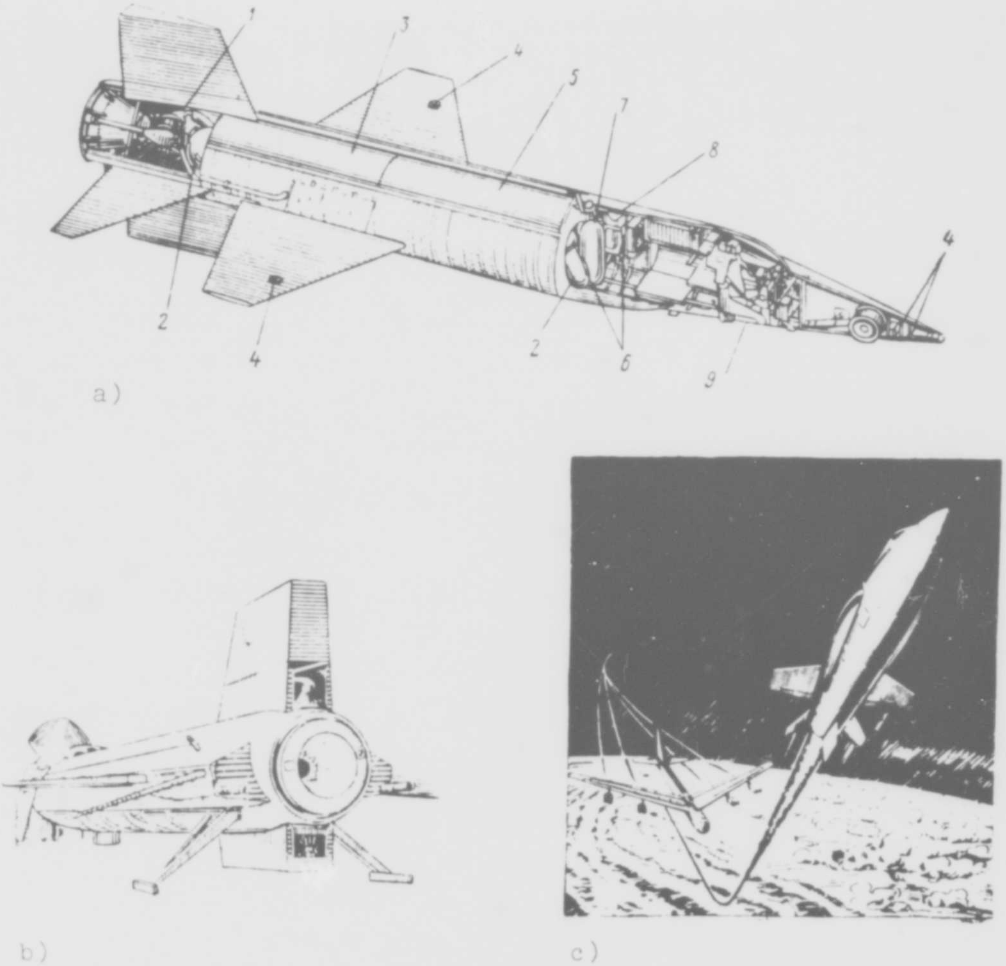


Fig. 44. Liquid-propellant rocket engines in aviation. Above – "Spectre" takeoff boosters on the English jet bomber "Victor" (with four turbojet engines). Both liquid-fuel rocket booster engines with a thrust of 3600 kgf each after takeoff of the aircraft are dropped by parachutes (engines operate on hydrogen peroxide). Bottom – liquid-propellant rocket engine "Snarler" on the English jet fighter "Sea Hawk." The engine has a thrust of 900 kgf and weight of about 100 and operates on liquid oxygen and water-metanilic mixture. It is mounted additionally to the main turbojet engine of the aircraft and from it the drive of fuel pumps of the rocket engine is carried out.



a) b) c)

Fig. 45. Experimental supersonic aircraft X-15 (United States) with a liquid-propellant rocket engine: a) aircraft design; b) outer view of the aircraft (one can see the jet nozzle of the engine with a layer of ceramic coating applied inside; c) figure of the aircraft being separated in flight from the carrier aircraft (jet bomber B-52). 1 – liquid-propellant rocket engine LR-99 with a thrust of 26 t; 2 – tank with hydrogen peroxide; 3 – tank with fuel (waterless ammonia), 4 – nozzle of jet control system of flight of the aircraft; 5 – tank with oxidizer (liquid oxygen); 6 – cylinders with helium; 7 – cylinder with liquid nitrogen; 8 – auxiliary borne propulsion system for driving units and systems; 9 – ejection seat of the pilot.

Peculiarities of the liquid-propellant rocket engine explain why the use in this case of carrier aircraft is necessary and also the fact that rocket aircraft are able to accomplish flight with an engine operating on full thrust for several minutes. And, as this does not seem paradoxical, these aircraft with a liquid-propellant rocket engine, are capable, it would seem, of the most short-term flight, and are able, at the same time, to carry out flight of practically unlimited distance. However, such a flight proves to be so dissimilar to the flight of conventional aircraft, which it is appropriate to discuss after we become acquainted with one and, certainly, the most important field of application of the liquid-propellant rocket engine. The topic of discussion is of rockets, so it is not in vain that the engine itself is called by its name.

Rocket accomplishes, in contrast to an aircraft, a so-called ballistic flight, i.e., flight without the use of force of a lifting surface of a wing along a ballistic curve. There are, indeed, winged rockets, but we do not discuss them now. The ballistic flight obtained its name because it is accomplished not by laws of aerodynamics (as is known, the first aircraft were sometimes called aerodynams...), but by laws of ballistics, as the flight of an artillery shell. Essentially, the flight of a rocket in principle does not differ from the flight of shell, except for the fact that acceleration of the rocket is carried out not by pressure of gas from without (as occurs with a shell in the barrel of an artillery gun) but by recoil force of gases emanating from the rocket itself. Another important distinction is connected with the duration of acceleration: the shell accelerates rapidly, during those considered fractions of a second while it moves in the gun barrel, and the rocket - considerably slower, since the time of operation of its engine is measured already by many seconds and sometimes minutes. Thus, the rocket in this respect occupies as if an intermediate position between the shell and the conventional aircraft, on which tractive force acts during the whole time of flight, i.e., many hours in succession. After the engine of the rocket ceases operating, it flies accurately as a shell flying out of the barrel of a gun, i.e., expending kinetic energy accumulated during acceleration. Thus the cast stone flies.

The first engines of liquid-fuel rockets, for example, which were launched in our country as early as in 1933 (rocket "Grid-X" and others), had a low thrust of several tens of kilograms and were very simple in design. The weight of the rocket was accordingly small (in particular, the weight of the first Soviet rocket, launched on 17 August 1933, equaled a total of 20 kg). The path of development passed during the last few years by liquid-propellant rocket engines is seen from the fact that contemporary powerful rockets weigh hundreds of tons, and their engine develop a thrust exceeding this weight. Thus, for example, in the United States engines are developed with a thrust of approximately 680 t.

The installation of so powerful engines on space carrier rockets is, of course, not accidental. These rockets should necessarily possess enormous weight, since for imparting space speed to a considerable payload, for example, automatic interplanetary station or artificial earth satellite, there is expended a colossal quantity fuel on board the carrier rocket. The superiority of Soviet rocket and space technology with respect to power of carrier rockets is well-known.

It is interesting that along with superpowerful liquid-fuel rocket engines in contemporary rockets technology there are widely used engines of very little thrust, up to the thrust of several kilograms and even grams. Such engines are used for the most diverse purposes: as retrorockets for deceleration during reverse reentry into the atmosphere, vernier engines of heavy rockets (i.e., intended for controlling their flight), engines installed on rotor blades of a helicopter, engines providing manned flight ("rocket belt"), engines of the system of orientation in space of artificial earth satellites and others. Incidentally, these engines usually operate on hypergolic propellant and are not constant, as are their more powerful counterparts but are pulsating – they are switched on ten times per second for a very short time.

The flight of space rockets makes a remarkable peculiarity of any free-flight especially distinct – after the engine finishes its short-term operation the rocket is able to accomplish flight, which

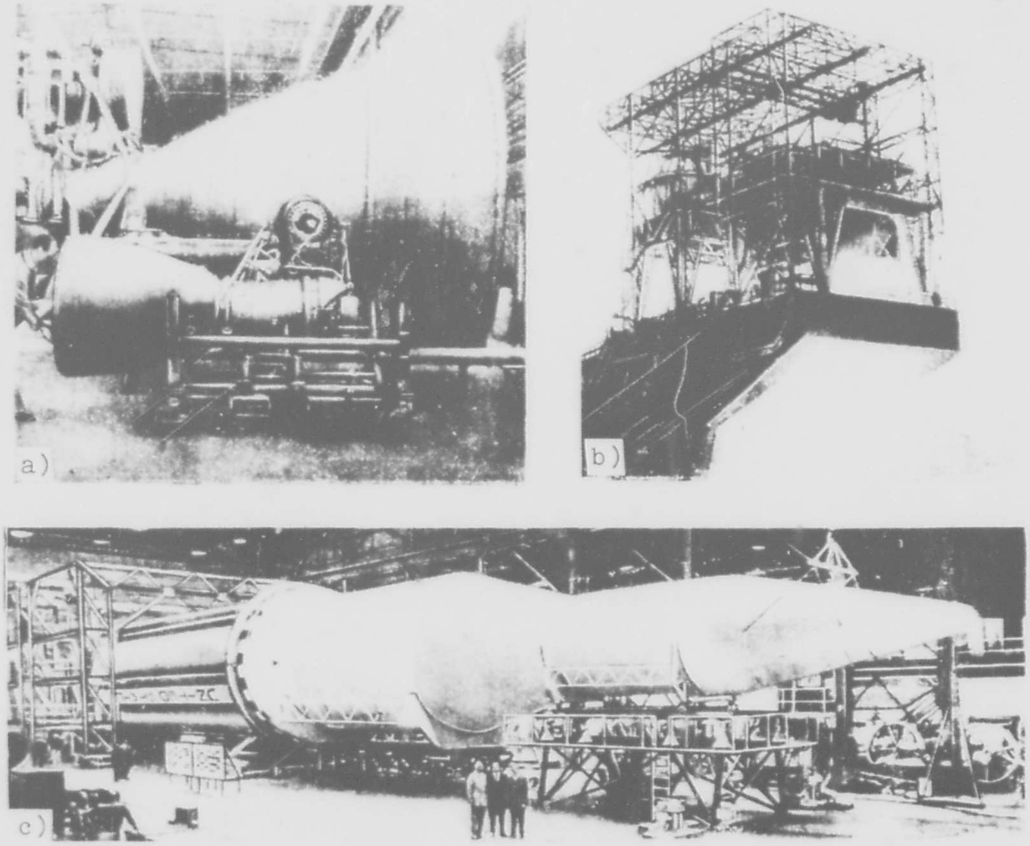


Fig. 46. Superpowerful liquid-propellant rocket engines: a) the two most powerful engines of the United States. Front – engine H-1 for carrier rocket Saturn-1 (its thrust is equal to 85 t, on the first stage of the rocket, there are 8 such engines with a total thrust of 680 t). Behind – mock-up of F-1 engine, it develops a thrust of 680 t (it is assumed such engine is installed on the first stage of the carrier rocket Saturn-5); b) static firings of F-1 engine (maximum attained thrust is equal to 745 t for 13 s). This engine weighs 68 t, its diameter is equal 2895 mm, length 3360 mm, power of turbopump assemby with a weight of 1135 kg is equal to 60,000 hp, fuel consumption 3 t/s; c) assembly of carrier rocket Saturn-1.

is practically unlimited in duration and distance, Such an eternal flight was accomplished, for example, by the Soviet space rocket "Mechta" (or the first "Lunnik"), which for the first time in the world on 2 January 1959 exceeded the so-called escape velocity equal to 11.2 km/s and necessary for any body to break forever the chain of terrestrial gravitation.

However, the satellite spaceship "Vostok-5" with pilot-astronaut Valeriy Fedorovich Bykovskiy on board accomplished during 14-19 June of 1963 the record-breaking flight of 3,326,000 km and duration of more than 119 hours after engines of the carrier rocket operated for the calculated time during the launch of the rocket. This is what ballistic flight means! Is it not true that it opens up absolutely fantastic possibilities of high-speed service for any distances on earth?

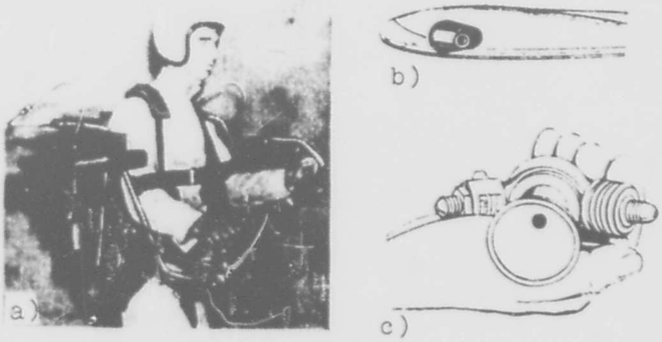


Fig. 47. In the family of liquid-propellant rocket engines there are also these "babies": a) two engines with a thrust of 135 kgf each lift a person into air; b) engine on the blade tip of a rotor of a jet helicopter; c) pulsejet engine of the system of orientation of an artificial satellite (its weight is 0.5 kg and thrust from 0.2 to 4.5 kgf).

We considered exactly this when we talked above about the paradoxical possibility connected with the application of the liquid-propellant rocket engine in aviation. In fact, the engine, which is able to operate in much less time than any other known aircraft

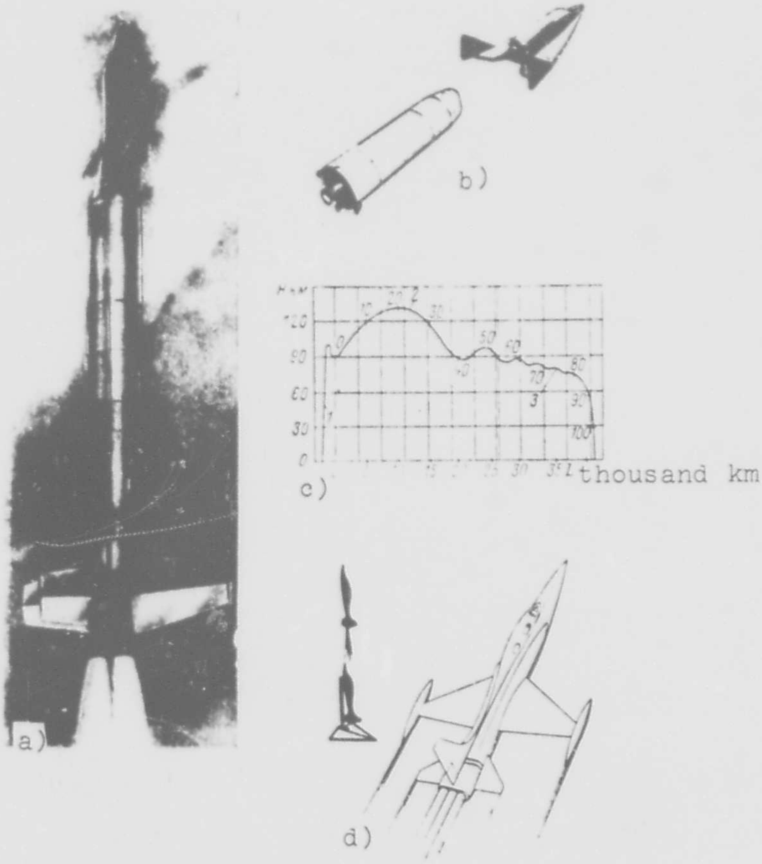


Fig. 48. Aerospace rocket aircraft: a) takeoff of carrier rocket with the aircraft "Dyna Soar" (project of the United States); b) separation of this aircraft from the carrier (figure); c) calculated trajectory of the flight; d) training rocket aerospace aircraft N-205 (project of the United States). 1 -- takeoff of carrier rocket; 2 — orbital flight; 3 — suborbital flight — reverse reentry into the atmospheres (figures on the curve show time in minutes); H — altitude of flight; L — flying range.

engine, is able, at the same time, to provide the most distant and, simultaneously, most high-speed flight! An especially effective result can be obtained with the organic combination of miraculous properties of the rocket engine and aircraft wing. The winged rocket is an indisputable favorite in high-speed and super-range passenger service of the future.

The evident advantage of the winged rocket over the conventional wingless, i.e., ballistic, is that it is able to combine ballistic flight with aerodynamic gliding in the terrestrial atmosphere. This permits not only considerably increasing the flying range or payload with that same power of the engine and fuel consumption, but also to carry out a smooth "aircraft" landing at the point of assignment. Besides such simple gliding descent from that high altitude where the rocket is taken by its engine, it can accomplish a more complex flight, which sometimes can be more effective. This flight is sometimes called semiballistic and sometimes ricochetting; the winged rocket in this case as if it ricochets from dense layers of the atmosphere where it penetrates at high speed. As a result of this gigantic "ricochet" the rocket again soars upwards, again ricochets and so forth, up to the concluding sloping glide path of descent to earth.

There is one more indisputable long-term field of application of the liquid-propellant rocket engine on joint of aviation and astronautics – this engine is as if it stresses the organic connection of both indicated branches of science and technology. The topic of discussion is the so-called aerospace aircraft, i.e., piloted aircraft able to accomplish flight both in terrestrial atmosphere and outside it. Besides the possible military use of similar aircraft (in the United States there is developed for this purpose, for example, the aircraft "Dyna Soar"), they can appear irreplaceable for the organization of transport (passenger and cargo) service between earth and numerous orbital scientific stations and artificial satellites of applied assignment – communication, meteorological, navigational and other (both in the course of their construction and in the process of operation).

So the liquid-propellant rocket engine builds one more bridge between aviation and astronautics. However, this engine is not the only one playing such a role, but it is the main one. Another engine of this kind will be discussed in the following chapter.

CHAPTER VII

ANCESTORS AND DESCENDANTS OF "KATYUSHA ROCKET LAUNCHERS"

In the preceding chapter we learned about how stormy the short history of development of the liquid-propellant rocket engine was. The fate of the solid-propellant rocket engine (RDTT), or, as it has frequently been called up to now, the solid-propellant engine appearing earlier but playing a smaller role, formed otherwise.

The first rocket weapons created with the help of a solid-propellant rocket engine were "fire arrows" of the ancient Chinese and Hindus. It is possible to think that just such a weapon is connected with the first invention (first because then it was repeated in Europe) of powder. This was very long ago, more than a thousand years ago.

In the Dark Ages solid-propellant rockets were not mentioned; apparently, they had been forgotten or were used very rarely. Rocket weapons appeared again much later, 150-200 years ago. It is known, in particular, what a startling impression was made on English troops by regiments of missilemen of India. The Englishmen did not fail to borrow this idea from the Hindus and with the help of new achievements of science and technology considerably improved this weapon. It appeared in the armament of a number of other countries and was used with success in many military campaigns.

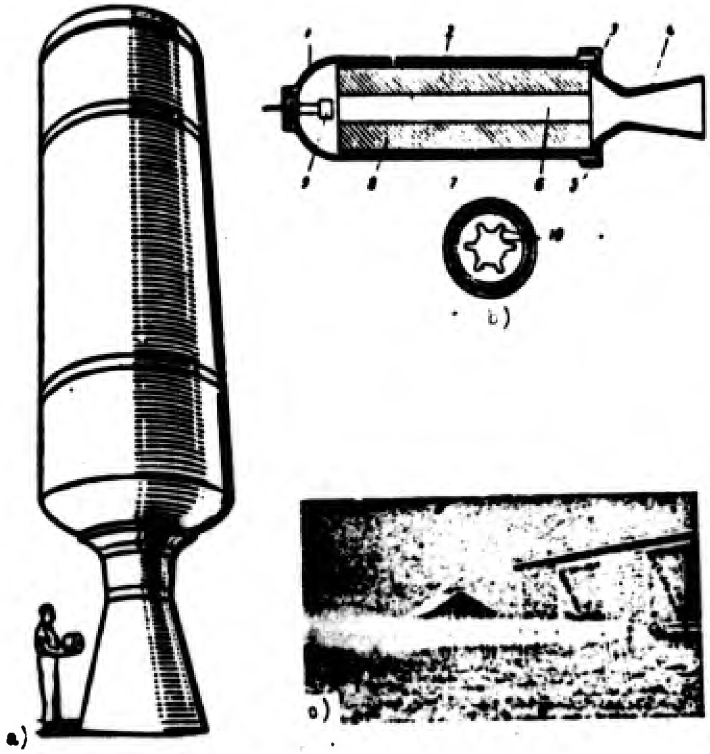
The history of our domestic solid-propellant rockets covers approximately a millenium. As far back as the reign of Peter I the powder business obtained considerable span, but, basically, for "sweated fires." Improvement and wide application of combat solid-propellant rockets pertains only to the beginning and middle of the past century. Great fame was then obtained, in particular, by the works of the Russian specialists A. D. Zasyadko and especially N. I. Konstantinov, working in the forties through sixties of the XIX Century.

From the end of the past century combat solid-propellant rockets were again practically forgotten, and displaced by quickly progressing barrel artillery, obtaining on armament cut implements.

The new history of the rocket weapon is durably connected with guard rocket mortars "Katyusha rocket launchers" which hit the enemy during the war years. The rocket missiles which conducted the fire of the "Katyusha rocket launcher" flew toward the target at high speed, leaving behind a fire tail of incandescent stream of gases. These gases are products of combustion of powder — solid rocket propellant which ran the engines of the missiles.

Before telling about the "descendants of the Katyusha rocket launchers," and the new solid propellant rockets, used more and more in a number of countries, there is called for at least a short description of the arrangement of the contemporary solid-propellant rocket engine. This engine, very simple in schematic diagram and, incidentally, much simpler in construction than a liquid-fuel rocket, in contrast to it has, essentially, only one main part — a traction chamber — consisting, in turn, of a combustion chamber and a jet nozzle.

It is easy to see why in this case there are no such parts peculiar to any liquid-fuel rocket as fuel tanks, a system of fuel feed or head of traction chamber, through which fuel is injected into it. All this is not simple because in the solid-propellant motor the fuel tank is the traction chamber itself. Supplying solid fuel to the working engine is nothing like feeding liquid fuel. Such attempts have been made more than once, but all of them up till now have ended in failure — this problem is too complicated. This is why it is necessary to place all fuel inside the combustion chamber. It is doubtful whether it is worth proving that this is never a merit of the engine.



GRAPHIC NOT REPRODUCIBLE

Fig. 49. Solid-propellant rocket engine: a) solid-propellant motors can be various sizes (large engine — 3 m diameter, small — 250 mm diameter); b) diagram of engine; c) static firings of engine. 1 — front section of engine (head); 2 — cylindrical combustion chamber; 3 — lining; 4 — jet nozzle; 5 — thread connection; 6 — internal channel in charge; 7 — protective covering of surface of charge; 8 — fuel charge; 9 — igniter; 10 — surface of burning.

It is true that at first glance it can appear that this is not such a bad thing. Indeed, is it not an advantage that there is absent a complex fuel system the creation and work of which is connected with so many difficulties in the case of a liquid-propellant rocket engine? But it immediately becomes clear that this is not so. The need to dispose the whole reserve of fuel in the combustion chamber itself strongly limits this reserve. It is clear also that it is much more profitable to store fuel in light tanks than in a combustion chamber, the walls of which inevitably have to be massive – after all, during combustion of fuel there are developed very high pressures – tens and hundreds of atmospheres. It is necessary to think that the combustion chamber is necessarily large and, this means that the whole engine is heavier. But that is not the worst of it.

Is it possible to imagine a case in which a shot which has already been fired from artillery is suddenly interrupted in the middle? It is certainly doubtful. The powder charge, once it has started to burn, very quickly burns wholly, and to stop this combustion, even if it is not impossible, is nevertheless extremely difficult. Therefore, in practice it is extraordinarily difficult to stop combustion of solid fuel which has already started in an engine: after all the whole work of such an engine is essentially only a somewhat tightened shot from a gun. In exactly the same way it is difficult to change at will the character of combustion once started – to accelerate or to delay it.

Meanwhile, after all, all of this can be not only useful but frequently simply necessary in the operation of the engine of any aircraft. In flight frequently it is necessary to change both the magnitude and direction of thrust and sometimes also completely stop and then again start the engine. According to published data with a solid-propellant rocket engine this up to now either has not been managed at all or success has been with great labor and has been by far not as complete as could be wished. It would have been possible to relate such attempts in greater detail, but now we will limit ourselves only to constatation of this deficiency of the solid-propellant rocket engine.

The traction chamber of the engine, which in this case is actually the whole engine, is prepared in the form of a vessel of approximately cylindrical form with jet nozzle. It is understandable that with development of solid-propellant motors traction chamber construction changed. In the beginning this was an ordinary tube of dense paper or cardboard with a simple hole instead of a nozzle, then the tube became iron and steel, and recently frequently titanium, and the hole was replaced by a Laval nozzle. In recent years plastic chambers of various construction are being used more and more. In particular, for example, there is used the technological method, by which the chamber is formed by winding tapes or filaments of fiber glass on a special ingot, reproducing the form of the chamber. After impregnation of this winding with various plastics there is formed a very light and durable shell, and the ingot is taken away. In this case combustion chamber and nozzle are prepared usually simultaneously, in metallic chambers, i.e., up to now in most cases they are individual centers then connected with the help of bolts or on thread.

It is understandable that such a thin plastic engine body is very profitable in weight ratio; namely, if in usual metallic chambers propellant weight attains at best 90% of the total weight of the engine, whereas in "plastic" engines this fraction can be brought up to 97%. Thus, almost the whole engine consists of only one fuel! However, to reach such a remarkable result, such engines must have, as it were, a second "body" invisible from the outside, which consists of fuel and is completely expended, i.e., burns during operation of the engine. For formation of such a "burning body" the fuel charge should have a sufficiently durable external layer and burn in such a manner that the pressure of combustion gradually decreases. It is natural also that the charge should in this case densely adjoin the wall of the chamber, which is mentioned in greater detail below. In other constructions of engines with "burning body" there are used nevertheless special tie pins connecting the nozzle with the head of the engine, not relying on the strength of the fuel itself.

In contrast to liquid-propellant rocket engines in solid-propellant motors the walls of the chamber are not cooled, which of course, considerably simplifies construction of an engine characterized by short duration of work. Usually the engine walls are protected from heat, liberated during combustion of fuel by a layer of thermal insulation covering, and recently the same fuel has been used for this with great success. There is nothing strange in this – after all the fuel in this case is solid and, incidentally, conducts heat rather badly. Therefore, it is worthwhile to line with fuel from within the wall of the chamber and this "lining" will protect the wall from direct influence of hot products of fuel combustion. It is true that it is necessary to ensure combustion of portions of fuel adjacent to the walls in the last turn, i.e., combustion of charge of fuel from center to periphery, but this, as we will see below, succeeds. Furthermore, it is certainly necessary to be concerned about the fact that the fuel "lining" did not lag behind the walls since then incandescent gases will penetrate this clearance and not flavor the walls. As was noted above, such "construction" of charge permits creating an especially easily "burning" engine body.

It is obvious that it is much worse with the walls of the nozzle. After all they directly touch gases emanating from the engine. Here it is already necessary to calculate on short-term work of the engine, make the walls of the nozzle massive enough so that they could accumulate heat, and use various artificial methods of decreasing transmission of heat from gases to walls. In their number with success there are used, for example, heat-resistant ceramic coatings, deposited by atomization or any other method on the internal surface of the walls of the nozzle and also ablative, expended coverings discussed in the preceding chapter in reference to the liquid engine. Sometimes there are obtained uncooled nozzles rather complex in construction with several layers of various materials.

When we talk about the construction of a solid-propellant rocket engine, then, in contrast to the liquid engine, we have to consider the construction of the fuel itself. No, here it is not a question of chemical structure, but of the construction, if desired, even of the architecture of the fuel charge.

Fig. 50. Uncooled nozzle of solid-propellant rocket engine can have complex laminar construction: 1 – tungsten inner shell, flowed around by gases with a temperature of the order of 3000°C; 2 – intermediate layer of heat-resistant material, for example, carbide, preventing direct contact of tungsten shell with following layer – graphite (otherwise graphite will diffuse in tungsten, lowering its mechanical qualities); 3 – graphite absorber of heat, transmitted by gases to nozzle; 4 – layer of ceramic insulation protecting the following layer of insulation from high temperature; 5 – plastic insulation preventing overheating of outer shell and increasing rigidity of nozzle; 6 – supporting members of nozzle – flange with strips of highly durable alloy; 7 – external shell – winding of light and durable fiber glass.

In relatively old solid-propellant rocket engines the charge represented one or more powder charges, usually of simple cylindrical form. Such grains burned both from the end and from the lateral surface so that nothing was said about shielding the walls with fuel. Inasmuch as with the combustion of charges the surface of burning gradually decreased, there decreased, consequently, the quantity of burning fuel and, accordingly, engine thrust. Meanwhile, this is by far not always acceptable; usually preservation of at least approximately constant thrust is required.

Radical improvement of construction of charge, allowing ensuring satisfaction of this requirement, was made by N. I. Konstantinov. He proposed making charges hollow in such a manner that combustion of fuel occurs both on the outside and from within. Then decrease of external surface of combustion is compensated by increase of internal surface, and thrust remains approximately constant.

Fig. 51. Section of charges of solid fuel burning from lateral surface can be the most diverse.

This idea turned out to be very fruitful. There were created numerous types of charges with internal cavities of various form, including a rather whimsical one. Combining different geometric outlines of external and internal surfaces of combustion of charge, it is possible to secure at least a certain change of value of thrust in time, i.e., a known adjustment of engine, although, of course, also prescribed, i.e., programmed. For this purpose certain surfaces of charge, on which there should not occur combustion, are frequently "armored," i.e., covered with a special substance – an inhibitor – preventing burning of fuel.

However, in recent years the glory of similar "figure" charges is dimmed since other types and constructions of charges have presented themselves brilliantly. This was connected with development of new solid rocket propellants with other chemical composition and qualitatively other physical properties. But more will be said about chemistry of fuels in this chapter, and mainly in Chapter IX; now only charge "construction" interests us.

The new fuels permitted completely getting away from charges and reaching, finally, the desired goal – such dense adjoining to the wall of the chamber, in order to ensure their "lining," which was discussed above, i.e., protection from direct influence of hot gases. Understandably this is profitable at least from the point of view of engine weight. After all if the walls of the chamber during work are heated to high temperature, then they have to be made from more durable metal and, furthermore, more massive, in order to stand the stress from forces of pressure of gases during combustion. With temperature rise the strength of all known steel alloys sharply descends; if, however, the walls remain cold, then there can be used "cold," i.e., full strength of metal. It is clear that the engine is facilitated.

In order to reach dense adjoining of fuel charge to walls of chamber, new fuels are simply poured into the chamber, in the melted state as into a large bottle. After cooling and intermediate operations of heat treatment the fuel charge durably communicates with the walls. So that no temperature and other deformations of the chamber lead to exfoliation of charge from the walls (this would threaten catastrophe), fuel should be, obviously, sufficiently elastic, rubber-like. Such properties are possessed by new fuels on the basis of plastics.

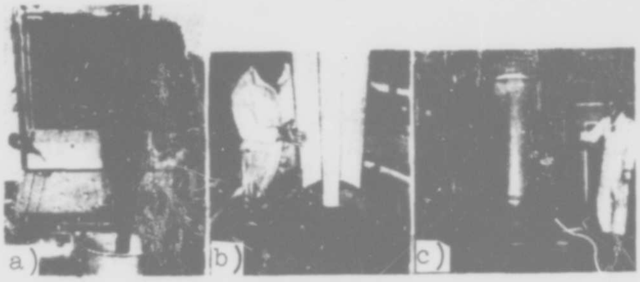


Fig. 52. Engine with monolithic solid fuel charge flooded into body (the United States): a) fuel is poured like sour cream; b) from charge flooded into body of engine (its weight is equal to approximately 1600 kg) there is extracted a core, serving for formation of profiled internal channel; c) engine with flooded charge is extracted from furnace well, in which was carried out flooding (engine thrust is equal to approximately 8200 kgf, and its diameter is 965 mm).

Incidentally, during filling of charges of fuel (instead of their pressing and extruding, i.e., drawing on special machines, as this was earlier and frequently is still now used) inside them there will also be formed cavities of various form. This ensures combustion of charge from within to periphery and, at the same time, certain possibility of safeguard of assigned law of change of thrust in time of work of engine. For this sometimes the charge is made nonuniform, for example, its internal part consisting of fuel burning faster, and its external part of fuel burning slowly.

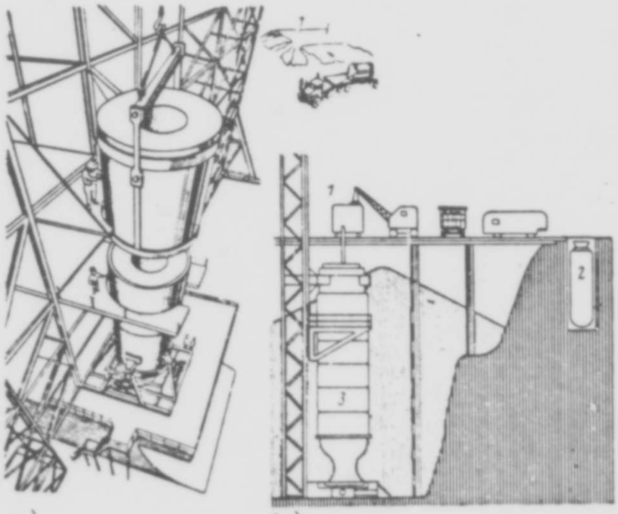
Very recently abroad there have been conducted works on powder charges of new "construction." And these charges are also usually poured directly into the chamber, but their peculiarity is the fact that they consist of several parts, so-called sections or segments, from which the charges themselves (and engine with them) were called sectionalized or segmented. With what is there connected such indubitable complication of engine, which is accomplished, obviously, by a certain decrease of their reliability, which is hardly the main merit of solid-propellant engines in their argument with liquid-propellant engines?

The answer to such a question will become clear if one considers that sectionalized engines usually have very large, probably, even record-breaking large thrust. Actually, transition to such construction is in large measure forced in those cases when it is necessary to create an engine of very large thrust, and this is one of the tendencies in the development of contemporary solid-propellant motors, especially in connection with problems of cosmonautics.

In fact, increase of power of engine (it usually is characterized by so-called total impulse, i.e., product of thrust and time of its action) requires increase in value of charge. But is it possible infinitely to increase the weight and diameter of the engine? Here special limitations are lacking if the possibilities of railroads are not taken into consideration. Really is it not clear whether they are here? After all the engine built at the plant must be delivered to the launching site. How can this be done if it is too heavy for railroad (several hundreds of tons!) and an "awkward" load? It is possible, of course, to try to use water or air transportation, but it is easy to see the difficulties of such a decision also (it touches on, of course, powerful liquid-fuel rocket).

There are used two means of technically acceptable solution of the problem. One of them is equipment of the engine directly on the launching site, and the other is separation of one large engine into several smaller ones easily transported and also collected at launching site. In the first case it is necessary to create directly at the launching site a plant for equipment of the engine, i.e., filling it with fuel, its heat treatment, etc., where, obviously, such a plant should be mobile. In the second case the problem is solved by a sectionalized engine. Certainly, both methods possess their merits and deficiencies, but till now there has still not been established the advantage of one of them – various firms abroad use various ways.

Recently certain attention abroad has been attracted by sectionalized engines having the form of a frustum of a cone expanded to nozzle. The internal channel of fuel charge of such engines has the same conical form. What is the sense in this? It is connected with one of the peculiarities of burning of fuel in an engine. When burning starts, then along the internal channel of the charge to nozzle there rushes with considerable speed the flow of incandescent gases — products of combustion. It is not surprising that such flow erodes the burning surface of the charge similarly to the way hot winds of the desert corrode the soil and cause its erosion. This is why such combustion is also called erosion combustion. But as a result the fuel charge burns nonuniformly and engine thrust is changed so that it cannot be calculated beforehand. In the conical engine speed of gases in internal channel turns out to be much smaller, which essentially lowers troubles connected with erosion burning.



a) b)

Fig. 53. Powerful solid-fuel rocket engines can be prepared by two methods: a) assembly of sectionalized engine at starting position: in background — transport of section; b) equipment of rockets in starting position. 1 — installation for continuous preparation of fuel (mixing); 2 — second stage of rocket; 3 — first stage of rocket (booster).

What solid rocket propellant is with respect to its chemical composition will be related in detail in Chapter IX, dedicated to the problem of rocket fuels. Here we will indicate only a few characteristic peculiarities of solid fuel and requirements for it.

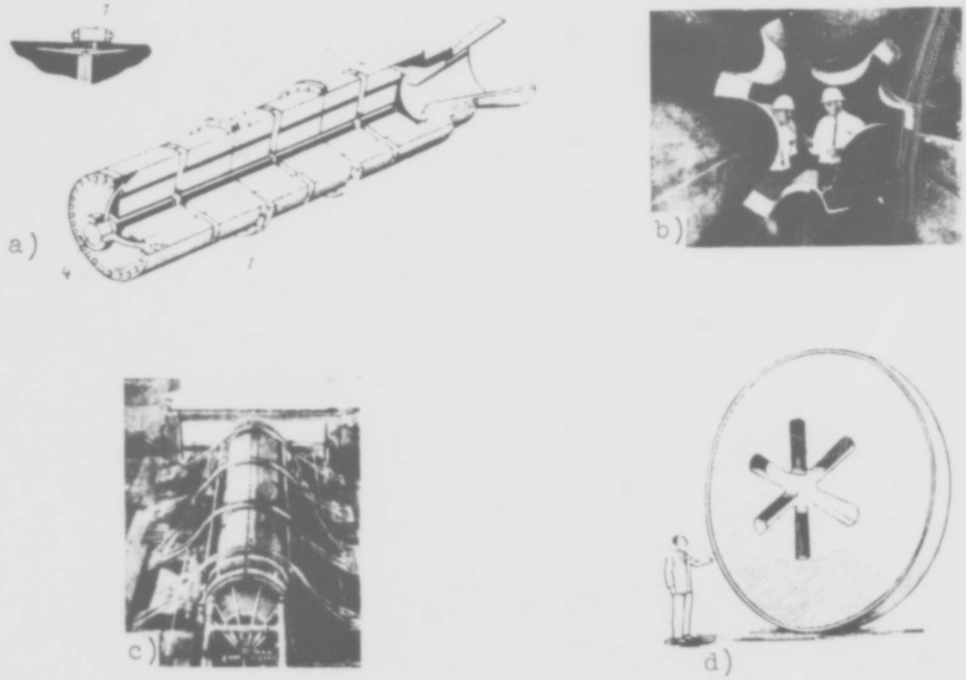


Fig. 54. Sectionalized solid-propellant motor: a) sectionalized motor consisting of three sections (thrust of engine 17 T, duration of work 9.7 s, weight of charge 8.2 t, pressure of combustion 53 at, temperature of of burning 3000°C, engine was tested in USA); b) form from inside one of sections of engine with thrust 227 t (made by Arrowjet, USA); c) test of sectionalized engine of the same firm with thrust 272 T, made 7 February 1962 (engine worked 98 s). This engine consists of 5 sections 2.5 m in diameter, its length is more than 16 m, and its weight is equal to 119 t, of which 107 T is fuel; d) cross section of mockup of sections of gigantic engine with thrust of the order of 1100 T during 82 s; proposed by Thiocol, the United States. Engine should be more than 19 m long. 1 — connection of sections; 2 — fuel charge; 3 — combustion chamber; 4 — igniter.

The most important requirement for any rocket fuel is connected with its energy productivity or calorific value, i.e., with the

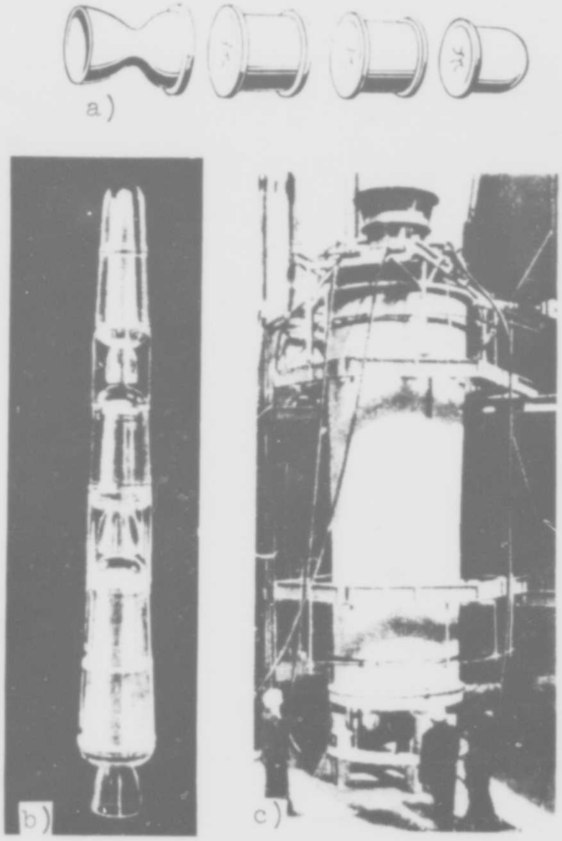


Fig. 55. Conical sectionalized solid-propellant motor: a) diagram of conical sectionalized engine; b) transparent plastic model of sectionalized rocket; c) conical sectionalized engine (with 3 sections) with thrust 113 T for 80 s. Maximum diameter of engine 2.3 m, its length 8.1 m, weight of engine 70 T, weight of fuel charge 40 T. Engine on stand for testing nozzle upwards (USA).

value of thermal energy liberated during combustion. This requirement is most important because energy productivity of fuel directly determines the value thrust developed by the engine for every kilogram of fuel burning in it (i.e., so-called specific thrust). In this respect solid fuels still essentially lag behind the best liquid ones, although recently this lag has been somewhat reduced. Nevertheless, the lag will probably always be there which must be taken into consideration when considering fields of application and prospects of solid-propellant motors.

Solid rocket propellant has one very important difference from powders used in barrel artillery. The main problem of the latter is to create high pressure in the gun barrel in order to impart high speed to the shell. For this, artillery launching powders, as they are called, have to possess a very high burning rate: they have to be through burning in the short time the shell is moving along the gun barrel. If the fuel in the rocket engine burned as fast, then the pressure in it would increase to a thousand atmospheres and the engine would be destroyed, not having such massive walls as the artillery barrel. Here, as one may see, this is only harmful and, therefore, rocket "powders" burn slowly.

It is very important that this burning rate be essentially constant and not subject to sharp changes under the influence of changes of pressure of combustion, temperature, humidity of charge, etc. Especially unpleasant in this respect is cracking and stratification of charge. Via forming cracks combustion can be moved inside the charge, embracing so much surface that pressure inside the engine increases to dangerous limits. At the same time, solid-propellant motors should if necessary be kept in constant readiness for action, where this storage can last years. Clearly, it is not simple to ensure stability of physicochemical properties of charge in the most, difficult conditions of storage. However, this problem is successfully solved by contemporary rocket technology.

Remember what was said in the preceding chapter about pulsations appearing during combustion of fuel in liquid-propellant rocket engines? It turns out that solid-propellant motors are not free from this trouble either, although in this case there are usually other reasons. Vibration combustion in the same way prevents creation of powerful solid-propellant motors, as was noted for liquid-propellant engines. Appearance of vibration combustion is connected, in particular, with oscillations of pressure of acoustic type, appearing in a charge of solid fuel. Every time a pressure wave reaches a surface of burning, the burning rate increases (it is interesting that the same growth is fixed in experiment also under the impact of acoustic waves from an ordinary siren at certain fully defined frequencies). These pulsations of burning rate, in turn, strengthen the intensity of pressure waves. Finally, there appear impermissibly large oscillations of pressure, which can lead to blowout or to destruction of charge and its explosive combustion. For suppression of pulsations the designer can use various methods: increase viscosity of fuel, which will lead to weakening of pressure waves, introduce into the fuel various additives extinguishing pulsations during combustion, change geometry of charge in order to remove coincidence of frequency of pulsations of pressure with frequency of its natural oscillations (otherwise there will appear resonance burning with very high amplitude of pressure oscillations) and others.

In order to complete our story about combustion in the solid-propellant motor it is worth mentioning how such an engine is started, i.e., how fuel is ignited during starting. For this there exist various igniters, the basis of which is, as a rule, an electric fuse. An electric discharge through a thin wire in this fuse leads to separation of a large quantity of heat and explosive evaporation of the metal of the wire. Usually this causes ignition of surrounding wire of a small powder charge with rapidly burning powder, which already initiates combustion of the basic fuel charge of the engine.

Recently abroad there is starting the wider use of methods of starting an engine, i.e., ignition of its charge by way of injection into the combustion chamber of a small quantity of spontaneously inflammable liquid fuel. Such "chemical" ignition constitutes already a certain "collaboration" of both forms of fuel — liquid and solid. This will be discussed in greater detail in the following chapter.

But let us return to solid-propellant rocket engines. Where and how are these engines used at present?

It is necessary to note that solid-propellant rocket engines must assert their right to be used in a rather violent struggle with their competitors — liquid-fuel rocket engines. And such is the logic of this struggle that not one of the sides is in a state to gain decisive victory — each has both strong and weak places, and each has conquered certain fields of application. However, this does not mean that everything is already once and for all formed — sometimes one of the sides goes on rather decisive offensive and presses the "enemy." Probably recently the advancing side has been solid-propellant motors. This is explained by many indubitable merits of such engines.

Actually, is there not thrown in the eyes indubitable relative simplicity of solid-propellant motors as compared to liquid? For one thing absence of a system of fuel feed or cooling of walls makes the engines relatively cheaper. Certainly, the merits carry with them certain deficiencies — limitedness of time of work, impossibility of thrust control and others, which should be considered in determining field of application. But for a number of very important regions such deficiencies do not have practical value.

An important merit of solid-propellant motors is their constant readiness for action. An engine of this kind or rocket with it can be kept at the storehouse for years, and then, at any minute, it can be put to use. It is doubtful whether it is necessary to prove how important this possibility is in a number of fields of application, especially in military technology. For the sake of justice it is necessary to note that in recent years there have already appeared the first liquid-propellant rocket engines and rockets with them "preserved" or "beforehand equipped," as they are called. It is easy to see what methods can create similar liquid engines. First of all, the reserve of fuel on the rocket in this case should not decrease in time, i.e., fuel does not have to evaporate, as it should not, however, freeze. It is obvious, for example, that engines working on so-called cryogenic fuels, i.e., liquidfied constant gases — liquid oxygen, hydrogen, and others — do not fit here at all; after all, in the completely filled tanks of the rocket after even relatively brief storage there will simply not remain fuel; it will all wholly evaporate. Unfortunately, cryogenic fuels possess especially great potential possibilities and prospects of application in rocket technology of the present and future (we will learn about this in Chapter IX). Preserved liquid fuels, i.e., those useful for prolonged storage, for example, nitric acid, kerosene, and others, are qualitatively inferior to cryogenic fuels with respect to characteristics of aircraft which they can ensure. And yet the need for prolonged storage frequently turns out to be stronger, for which reason there are developed "preserved" liquid engines. Solid-propellant motors in an absolute majority of cases possess good characteristics in this respect.

If, however, we talk about deficiencies of solid-propellant motors, then, besides those already known to us, namely, difficulty of thrust control and short duration of work, a very important deficiency is relatively smaller specific thrust as compared to liquid engines. Small specific thrust signifies greater fuel consumption with the same thrust and, consequently, the need for greater reserve of fuel on the rocket. In many cases, in particular, in cosmonautics, specific thrust is a decisive factor — only with sufficiently high specific thrust in general is it possible to accomplish one space flight or another. In general, decrease of specific thrust signifies natural decrease of payload on rocket. It is true that some decrease of specific thrust can be more than compensated for by decrease of weight of the engine itself — after all, this permits accordingly increasing reserve of fuel on rocket, which requires thorough appraisal in every concrete case. But here as well solid-propellant motors are clearly inferior to liquid ones, or it is more correct to say that solid fuels are inferior to liquid ones.

Another serious deficiency of the solid-propellant engine concerns the possibilities of change in both directions and magnitude of tractive force, created by the engine. It is easy to see why it is necessary to change direction of action of tractive force, or, so to speak, direction of thrust vector: we are talking about flight control of the rocket when the engine is working, i.e., on the so-called active part of flight trajectory.

General principles of such control were developed by K. E. Tsiolkovskiy, and certain methods proposed by him are widely used even at present. In particular, for example, there are used so-called gas rudders, i.e., steering planes located in a stream of gases emanating from the engine. However, such planes are in too difficult conditions of work since they are washed by a high-velocity flow of heated gases; therefore, they are made of heat-resistant materials, for example, graphite. It is understandable that such a relatively complex and expressive system of controlling thrust vector is not very good for a solid propellant engine.

Another method is turn of traction chamber of the engine, for which it is set on a special hinged suspension, a so-called Cardan ring. But this is convenient in the case of a liquid engine when the traction chamber is relatively small, and to turn such a bulky (after all it has the whole reserve of fuel!) traction chamber of a solid-propellant motor is by far not so simple. Therefore, such a method is practically not used for solid-propellant engines.

But how can this be? After all, it is necessary to change direction of thrust vector nevertheless, otherwise, flight of rocket on active section cannot be controlled. It is possible, of course, to use aerodynamic rudders like those of aircraft, but they usually turn out to be too large and are useful only in dense atmosphere.

This is why until recently solid-propellant engines were used only in unguided rockets. In this case fixed aerodynamic surfaces, so-called stabilizers serve only (together with certain other methods) to ensure stable rocket flight as this is done, for example, in shells of "Katyusha rocket launchers." Only liquid engines were used in all guided rockets. However, recently the situation has changed – there are already a large number of controlled solid-propellant rockets. One of the methods used of controlling direction of thrust vector on these rockets is the use of swivel engine nozzles.

It is obvious that to change the direction of the stream of gases emanating from the engine there is no need to turn the whole traction chamber of the engine to the corresponding position as is done in the case of the liquid engine. It is sufficient only to note, here there is opened an extensive and thankful field for inventor activity. It is not possible to doubt that there will be worked out successful, reliable, and simple constructions of engines with swivel nozzle, which will find wide application in guided rockets of many types. It will be sufficient to connect the nozzle with a system of control of rocket flight so that this flight is really automatically controlled.

But it is possible to change the direction of the jet stream emanating from the nozzle otherwise. In order to understand what we are talking about it is enough to remember what was mentioned above about so-called "aerodynamic" nozzles, i.e., those in which a stream is formed with the help of auxiliary streams of another gas or liquid. Actually, it is sufficient to introduce into the nozzle near its outlet section a stream of gas (for example, to lead for this purpose gas through a tube from the combustion chamber of the engine) or liquid, so that the flow of gases in the nozzle changes its structure and is deflected in the opposite direction. Probably, such a system can turn out better than all the others.

Regarding change of value of thrust, matters are much worse Essentially, as was noted above, it is possible only to carry out certain preassigned, i.e., programmed change of value of thrust with respect to time by means of selection of corresponding geometry and structure of charge. Separate attempts of more radical solution are almost not counted. Practically the only thing the designer tries to reach is exact cutoff of engine in assigned moment of flight, without which it is impossible to provide the right trajectory of the rocket. Usually for this purpose the interior of the combustion chamber communicates with the atmosphere through a special hole, as a result of which pressure in the chamber falls, and this stops fuel combustion.

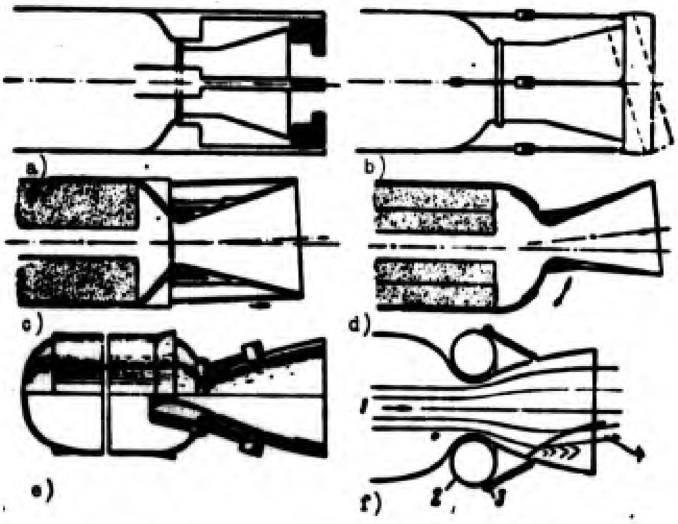


Fig. 56. Thus it is possible to control direction of thrust vector of a solid-propellant motor (i.e., direction of jet stream): a) swivel rudders placed in jet stream; b) swivel ring at outlet of nozzle; c) swivel nozzle with elastic connection (metallic "bellows"); d) swivel nozzle on spherical (Cardan) suspension. But it is possible also thus: e) bypass of gases from combustion chamber into nozzle deflecting jet stream; f) injection of liquid into jet nozzle for deflection of stream. 1 – direction of flow of gases; 2 – tank with liquid; 3 – cock; 4 – deflected gas flow.

After all what has been said becomes clear, where and why are solid-propellant motors used at present. In aviation these engines

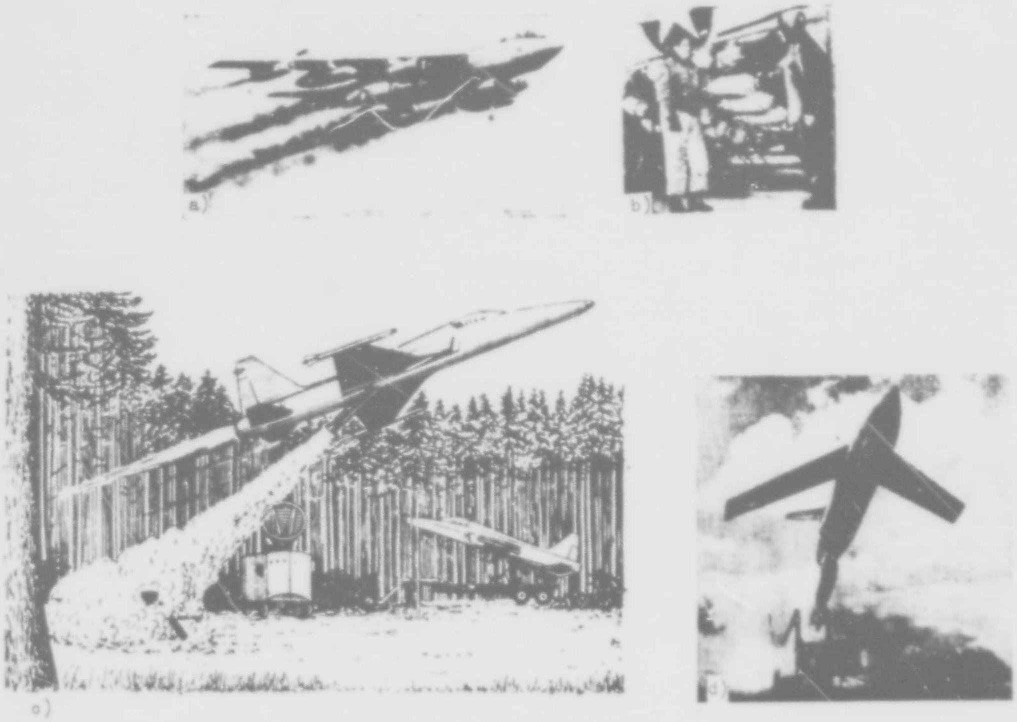


Fig. 57. Booster rocket solid-propellant motors in aviation: a) takeoff of jet bomber with help of booster rocket engines; b) 33 such engines with 450 kgf thrust are dropped after takeoff; c) catapulted takeoff of fighter with help of solid-propellant booster rockets; d) takeoff of pilotless winged missile "Matador" with help of booster rocket engine with approximately 23 T thrust (the United States).

fire on targets tens, hundreds, and thousands of kilometers away. It is clear that in this case shells have to be controlled (otherwise it is difficult to strike the target), and also have to possess impressive dimensions. Actually, some of such foreign long-range ballistic solid-propellant rockets are sometimes over 10 m long and weigh (mainly, of course, this is the weight of the fuel charge) several tons. The engines of these rockets sometimes develop thrust of more than ten tons and are able to work for several minutes.

In this region of long-range rocket artillery, solid-propellant engines successfully compete with liquid-propellant engines, but

Fig. 58. Close combat rocket artillery: a) individual "Bazooka" type; b) battery of "Katyusha rocket launchers" (combat installations M-13) is prepared for next volley.

only until the flying range of rockets becomes very great, for example, intercontinental. In this case the role of specific thrust already becomes very significant. And in this respect the solid-propellant engine lags behind liquid-propellant rocket engines. Therefore, until very recently all foreign intercontinental ballistic missiles, for example, "Atlas" and "Titan" missiles in the United States, had liquid-propellant rocket engines.

found, in general, rather limited application as boosters. In this role they successfully compete with liquid engines. Light, simple, reliable and, at the same time, sufficiently powerful, they are able considerably to accelerate and facilitate takeoff of aircraft, to shorten takeoff run (or else accomplish the so-called catapulted takeoff without run) or allow increasing takeoff weight of aircraft, i.e., its payload. After the solid-propellant rocket works for fractions of a minute during takeoff (in these cases usually the engine works no more than that), they are most frequently simply dropped from the aircraft. Usually for this purpose the aircraft has not one but a whole battery of rockets — they are suspended under the wing or are disposed in special cassetes — holders on the fuselage. Thrust of such an engine is from several hundred kilograms to tens of tons (usually for pilotless aircraft — missiles).

But then in rocket technology and, first of all, in rocket artillery solid propellant engines found wide application. This probably first of all concerns jet mortars of the famous "Katyusha rocket launchers" type, able to conduct mass volley fire by shell-mines with solid fuel rocket engines. Easily launched from light truss or tubular guides on motor vehicle, cutter, aircraft, or tank, these shells acquire high speed. As was already noted above, such shells are, as a rule, uncontrolled.

The distance of their flight is relatively small; usually it is a few kilometers; weight of shell oscillates from several kilometers to tens and even hundreds of kilograms.

Similar shells are used against tanks, where in this case they usually become controlled. Sometimes for control of flight of such rocket missiles there is used wire communication — a flying shell unrolls from the drum a telephone wire on which commands are fed from the point of firing to shell controls, usually, aerodynamic rudders.

But solid propellant rocket shells are not used only in close combat artillery. Many of such ballistic missiles are able to train

But in recent years solid-propellant motors, as rockets with them, have been improved so much that they are becoming more and more dangerous competitors to liquid engines even in the region of intercontinental rockets. First of all, of course, this is explained by the development of improved solid fuels and also by the merits of solid-fuel rockets. In the United States, for example, there is the "Minuteman" intercontinental ballistic missile with solid-propellant motor. The initial weight of this missile is equal to approximately 29 t, and it constitutes a three-stage rocket with solid-propellant motors on every stage, where the engine thrust of the first stage is equal to approximately 72 t. The total length of the missile is equal to 17 m, and its diameter is approximately 1.9 m.

Along with use in military technology, solid-propellant rocket engines obtained large peaceful application. First of all, they kept their old and widely known role of fireworks, signal, rescue, and other rockets. In the postwar years great value was obtained by scientific research solid-propellant rockets of various assignment. Such rockets serve for aerodynamic, meteorological, geophysical, biological and other investigations; where, sometimes they have not one but two, three and even four and five stages. Frequently solid-propellant motors are used as so-called boosters, i.e., boosters of liquid-fuel rockets, and are very powerful.

And the conquest of space? What is the role of solid-propellant motors here?

And in this respect views on the possibility of solid-propellant rockets abroad in recent years were subjected to rather thorough processing, as this took place with respect to distant combat rockets. The first time in the United States, for example, solid-propellant engines were used only in upper, small stages of space rocket carriers and also as boosters. But then such engines began to be used also in other stages, and recently there have already been carried out launchings of satellites with the help of a multistage rocket with only a few solid-propellant motors (for

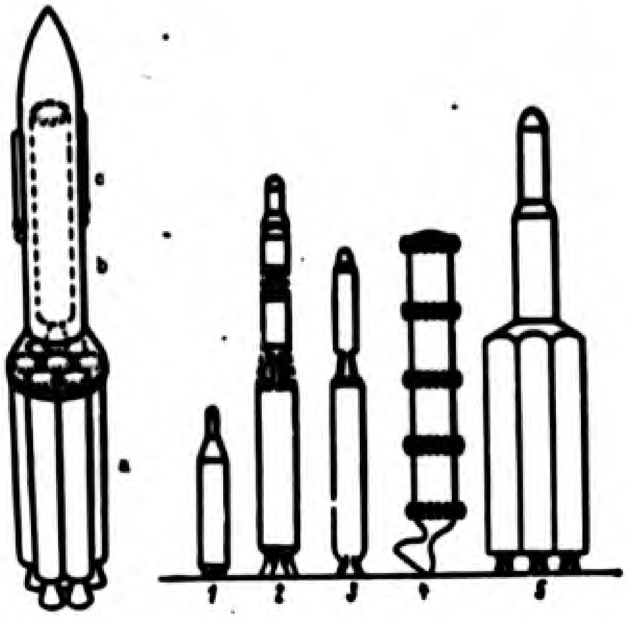


Fig. 59. Powerful solid fuel rockets. On the left – diagram of two-stage solid fuel rocket: a) cluster of seven engines of the first stage; b) one second-stage engine; c) engine of the rocket flight control system. On the right: 1 – "Polaris" intermediate range ballistic missile (the United States); 2 – "Minuteman" intercontinental three-stage ballistic missile (the United States); 3 – project of two-stage intercontinental ballistic missile; 4 – space carrier rocket with sectionalized engine; 5 – project of three-stage rocket for flight to moon with payload of 900 kg (on first stage – engine cluster).

example, the "Explorer XVI" satellite launched 16 December 1962 in the United States with the help of the "Scout" 4-stage rocket). These engines will be used for such purposes henceforth since in those cases in which they are able to cope with the problem they are simpler and cheaper than liquid-propellant engines. But, of course, far from all the problems within the powers of liquid-space rockets can be handled by solid-propellant rockets. It is possible to think that for solid-propellant rockets there will remain a region of space flights with comparatively small values of so-called ideal speed (this term characterizes total expenditure of energy on accomplishment of flight, inasmuch as the more the energy, the greater the possible or ideal speed of the rocket). In particular, this touches on a majority of circumterrestrial flights if payload is not too great. It is known that for these purposes abroad there are being developed powerful sectionalized solid-propellant motors with a thrust of several hundreds and even thousands of tons. Liquid-fuel rockets will be used for more complex flights – on large distances and with large payload, for example, to the moon and planets. However, for still more complex space flights these rockets should give way to improved rockets – they are the subject of the last two chapters of the book.

CHAPTER VIII

"SYMBIOSIS" IN THE WORLD OF JET ENGINES

The name of this chapter can lead one into a quandary: after all symbiosis is specifically a biological concept. Let us recall: this term is usually used for a form of cohabitation of different biological organisms – plants and animals, in which both "sides" obtain mutual benefit. Indeed, the best known forms of symbiosis return to one's memory: bacteria and the roots of plants, the hermit crab and the sea anemone, the pilot fish which feeds from the shark's table and, at the same time "guides" it to its prey.

But how does all of this relate to jet engines? It turns out that here also there are examples of such interbeneficial "cohabitation". And there's nothing surprising in this, since we know that each type of jet engine has its own deficiencies and weaknesses, sometimes lacking in an engine of another type. Why not "cooperate" in this case, borrowing experience from living nature? After all this method is already used by many sciences; a special science of such borrowing has already been developed – bionics.

In jet engineering there already exist several examples of the "symbiosis" of different jet engines. Sometimes similar "symbiosis" simply leads to the simultaneous arrangement on aircraft of engines of various types (for example, the installation of a liquid-propellant rocket engine on aircraft in addition to a turbojet engine). And sometimes it goes much further so that both types of engines are organically united; they merge into one qualitatively

new engine. Here there is obtained something similar to a certain interspecific crossbreeding, a unique hybridization, if one were to use biological analogies as previously. The engine "hybrids" obtained as a result frequently possess very valuable qualities, as also occurs in living nature.

For acquaintance with examples of "symbiosis" in the world of jet engines and diverse engines - "hybrids" we will start with the engine, about which we have already spoken in Chapter IV. Remember, there was discussion about a turbojet engine with an afterburner? There was also noted the circumstance that the afterburner in its operating process and construction is, essentially, the same as a ramjet engine. Here it is as if two engines operate in harmony as one. We already know, how fruitful this "cohabitation" has been - a huge number of such engines is at the present time part of the equipment of contemporary aviation, primarily, military. With their help aviation has attained many successes, yes and in future, as many foreign specialists consider, precisely the turbojet engine with an afterburner can become the basic engine of supersonic aviation with flight speeds exceeding sound by 2-3 times.

But it is well-known that with the increase of flight speed the ramjet engine becomes more efficient than the turbojet engine, and it is as if this latter one "degenerates" - loses its need for its compressor and turbine. Therefore, the circumstance that the air on the way to the ramjet engine (the afterburner) must necessarily in all cases pass through a turbojet engine, becomes a shortcoming during such high speeds. Is it impossible to get rid of this shortcoming?

There is a way for such improvement of the "symbiosis" of the turbojet and ramjet engines. It consists in creating an engine, receiving the name turboramjet and constituting another variant of the same "hybrid" of these two engines. It is obvious that if there is the necessity for temporary "cutoff" of the turbojet engine, then it is necessary to anticipate the possibility of changing the airflow going into the engine, in such a manner that it is directed directly into the ramjet past the turbojet. This is the essence of the idea of the new "hybrid," which it is possible to call the turboramjet engine.

However, more frequently this term pertains to an engine arranged otherwise. If in the first example of "symbiosis" both components of the engine - the turbojet and ramjet - are located in sequence, one after the other, then it is also possible to arrange them in parallel. For this, indeed, there is no necessity to arrange both engines in a row, side by side; it is much more advantageous to place the turbojet engine... inside the ramjet in the form of a unique central body. After all, as we already know, a supersonic ramjet engine practically always has such a central body.

Then the turboramjet engine works like a turbojet at relatively low flight speeds, where under these conditions the entrance into the annular passage of the ramjet engine (around the turbojet) can be closed by a special flap. Then both engines are working, now, finally, attaining such high flight speeds, when the turbojet engine will be turned off (its inlet can be covered) so that only the ramjet works. An engine of a similar type is installed, for example, in the French fighter airplane "Griffon" II. The housing of the ramjet engine is formed by the fuselage of the aircraft; inside the ramjet is placed the turbojet engine.

On another, also a French project, a vertical takeoff fighter with an annular wing must be equipped with a turboramjet engine. A similar aircraft, receiving the name "coléoptere," is already being tested, but only with one turbojet engine. It takes off and lands vertically, i.e., it does not require the long runways of ordinary airfields (below we will return to aircraft of another type, possessing the remarkable quality), and then it swings onto its belly and flies in horizontal flight like an ordinary jet aircraft. This is the "coléoptere" which it is proposed to equip with a turboramjet engine instead of with a turbojet. For this the annulas or ring channel between the fuselage and wing should be used, at least partially, as the ramjet duct - the "conveyer" of the ramjet engine. As a result the aircraft would be able to fly with great supersonic speed.

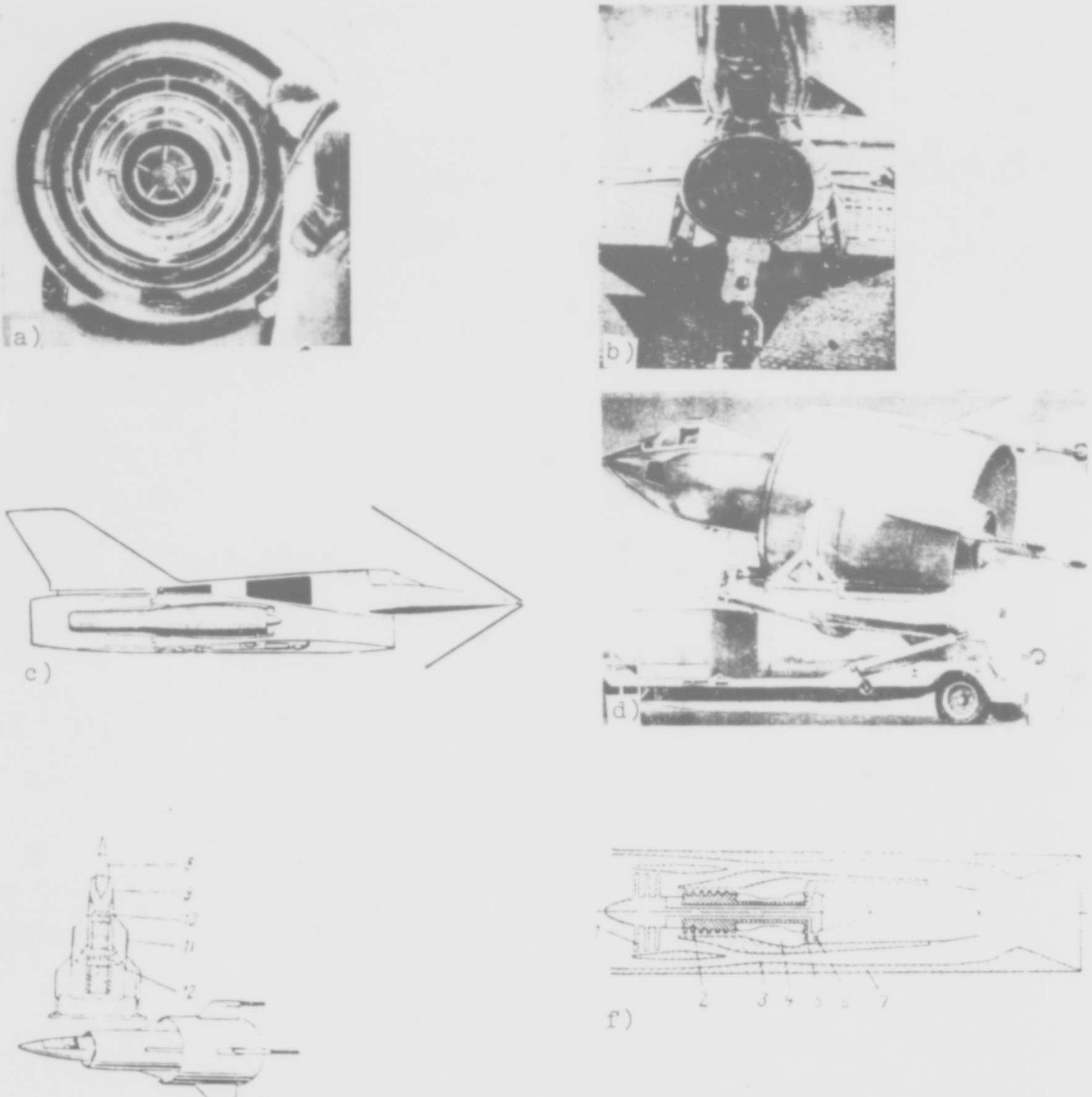


Fig. 60. Turboramjet "hybrid." The French fighter "Griffon" II with a turboramjet engine: a) view of the jet nozzle of the engine; b) view of the air inlet; c) diagram of the aircraft; d) testing of the "coléoptere" with turbojet engine in France; e) designing of the "coléoptere" with turboramjet engine; f) diagram of a "turbofan-ramjet" engine. 1 – fan; 2 – compressor; 3 – fan contour; 4 – combustion chamber; 5 – high-pressure turbine; 6 – low-pressure turbine; 7 – engine housing; 8 – cockpit; 9 – air inlet; 10 – engine; 11 – annular wing; 12 – fuel injectors of the ramjet engine.

A turboramjet "hybrid" can also be created on the basis of a bypass turbojet engine; this will even improve its characteristic during subsonic flight. It is not surprising that a similar engine (it can be called a "turbofan-ramjet") is being proposed abroad for use on supersonic passenger liners of the future.

However, a turbojet engine never necessarily enters into "symbiosis" only with a ramjet (as, however, a ramjet also does not with a turbojet). In order to give one more example of such "symbiosis" of a turbojet engine, we must touch upon an absolutely new (for our book), but very important subject for contemporary aviation. There will be talk about vertical takeoff and landing aircraft, among which belongs, however, the "coléoptere" already mentioned above.

The creation of aircraft, possessing the ability to accomplish vertical takeoff and the same kind of landing, is acquiring especially great significance precisely in connection with the rapid increase of flight speed of aircraft. After all the greater the flight speed, usually, the greater also is the length of the takeoff and landing distance, since the increase of speed is accompanied by the decrease of the lifting surfaces of aircraft, i.e., its wing. Contemporary high-speed jet aircraft, both military, and also civilian, for example, the TU-104, cover during takeoff and landing along a concrete strip of an airfield more than two, and sometimes three kilometers.

Absolutely understandable is the tendency of designers to create aircrafts, free from this deficiency – the matter is not only and not even so much in the fact that contemporary airfields are very expensive and require great areas, as in the fact that the forced landing of aircraft anywhere but at such an airfield usually turns out to be equivalent to a catastrophe.

Well-known and widely used are the aircrafts-helicopters, which do not require large airfields, inasmuch as they are able to accomplish vertical takeoff and landing. However, the characteristics of helicopters force it to pay dearly for this remarkable capability, first of all, with its relatively low flight speed, which is not comparable, of course, with the speed of contemporary jet aircraft. Somewhat better in this respect are the characteristics of unusual aircraft, combining the features of an aircraft and a helicopter, i.e., a wing and rotor – such craft obtained the name rotorcraft. One of them, designed by N. I. Kamov, was first shown in flight during the traditional aviation holiday in Tushino in 1961. However, even the rotorcraft does not in any way compare with the aircraft in flight speed.

How is it possible to visualize an aircraft, in which preserving the contemporary high flight speeds of aircraft there would appear the remarkable feature of vertical takeoff and landing?

Designs and even accomplished constructions of such aircraft are already numerous. Some of them are based on the turning of the engines, creating vertical thrust during takeoff and landing and normal horizontal thrust – in flight; in others deflection of the jet stream of the engines is used; in a third the turning of the whole wing with the engines mounted on it is employed; in a fourth they turn themselves in flight similar to the above-mentioned "coléopter," finally, in a fifth special light and powerful so-called lifting engines are installed, working only during takeoff and landing, etc.[1]

But whatever was the configuration of such aircraft, their designer must encounter one, general problem, connected with the propulsion system of the craft. The essence of this problem consists in sharply different operating conditions of the engine of the aircraft, creating thrust for horizontal flight or lift for takeoff, since for the accomplishment of horizontal flight of an aircraft the engine must create the thrust, necessary for surmounting drag, which

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[1] For greater detail about these aircraft see, for example, the author's book "In the Sky of Tomorrow", Detgiz, 1964.

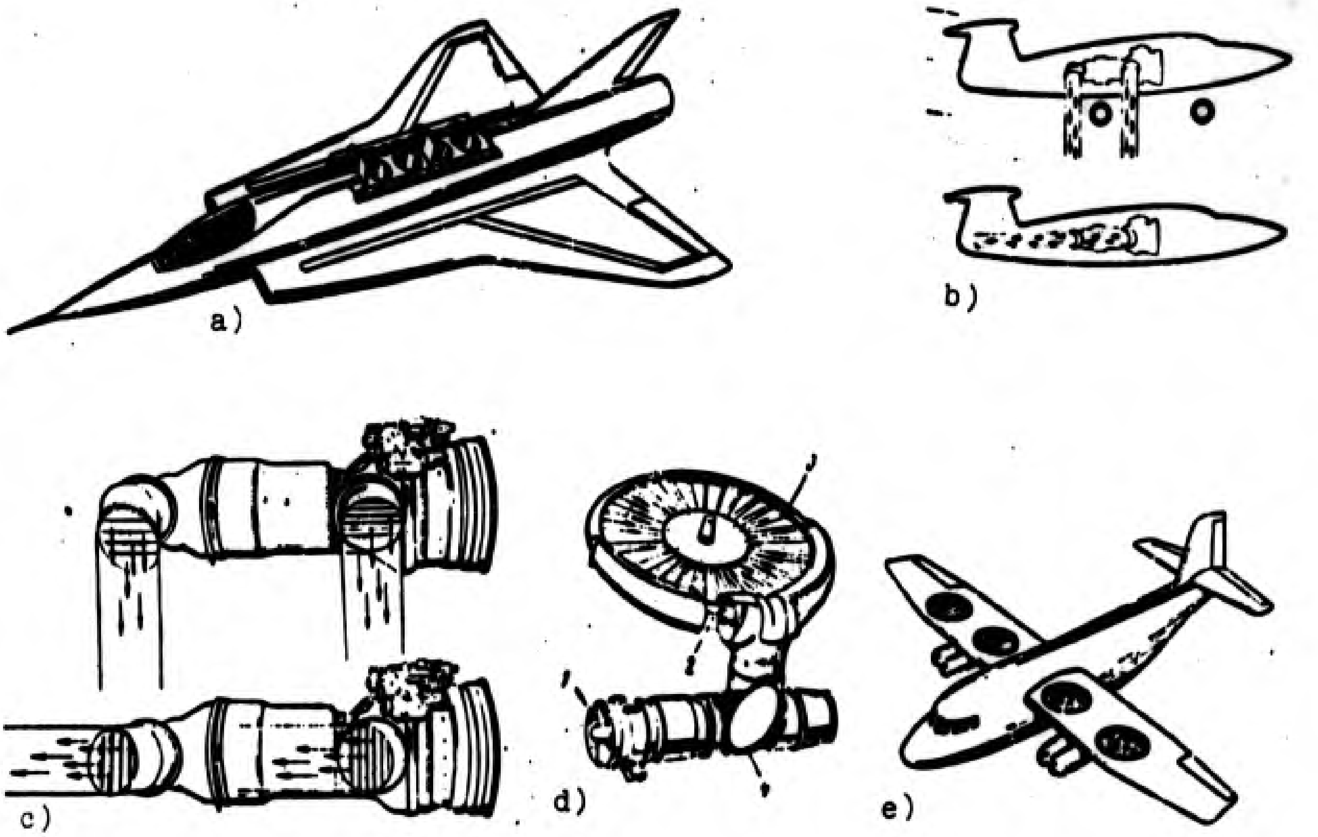


Fig. 61. Vertical takeoff jet aircraft: a) the principle of separate engines: model of a fighter with one thrust and four lifting turbojet engines (England). The principle of jet deflection, a BS53 turbofan engine (England) with turning jet nozzles; b) direction of jet streams during takeoff-landing and in horizontal flight; c) corresponding positions of the jet nozzles, equipped with rows of deflecting blades. The principle of "symbiosis," a turbojet engine is combined with lifting fans; d) the "symbiosis" of a turbojet engine with a lifting fan; e) design of an aircraft with four turbojet engines and rotors in the wing (the United States). 1 – turbojet engine; 2 – blades of the turbine on the rim of the fan; 3 – fan; 4 – changeover valve.

for an ordinary aircraft is at least a few times less than lift, i.e., the weight of the aircraft. Therefore for vertical takeoff there is needed accordingly, a several times more powerful engine than for normal flight. How is this problem coped with?

One possibility of its solution is connected with that physical process, which lies at the basis of the creation of propulsive force on an aircraft, precisely, with the thrust of air (or gases). We already know (it was covered in Chapter I) that the propulsive force, constituting the reaction to the ejected stream, is numerically equal to the momentum of this stream, i.e., to the product of its mass times speed. Consequently, the same propulsive force can be obtained with various combinations of values of thrust mass and speed and, accordingly, of various values of engine power (this latter is proportional to the kinetic energy of the stream, i.e., to the product of the mass times the square of the speed). We have already encountered cases, when the designer successfully used such a possibility for increasing the propulsive work of the engine. Remember, in Chapter III there was recounted the various "close relatives" of the turbojet engine? Some of these are distinguished precisely by this mass-speed ratio. Thus, for example, in the turboprop engine much air is ejected with relatively low speed, and in the turbofan engine two streams are combined – hot air (gases) with high speed and cold air-with low speed. This makes it possible to select during one and the same power the most efficient stream speed – with the decrease of flight speed this most efficient speed decreases.

But what is there to do in the case of a vertical takeoff craft? After all in the takeoff process it would be expedient to have the highest possible mass with the minimum speed of ejection, but in horizontal high-speed flight it is advantageous to greatly decrease the mass with the corresponding increase of the speed of ejection. And although similar "reconstruction" of the engine in the process of flight is a very involved matter, the designers go for it, since other ways of solving the problem frequently turn out to be even more complex. Furthermore, it is also necessary, usually, to use methods of "symbiosis." Perhaps the turbofan jet engine already to some extent is an example of such "symbiosis," since in it are combined the turbojet and the turboprop engine. In a number of proposed and, partially, carried out vertical takeoff aircraft designs there are being applied, for example, special rotors with rather large diameter, mounted in the fuselage or on the wing – they create lift. Besides ordinary turbojet engines of an aircraft, creating thrust in flight, on takeoff do not eject the jet stream backwards, as usual, but direct it into the turbine, the rotating rotors. Thus there is provided an increase of ejected mass at the expense deceleration which makes it possible with same engine power to create both effective propulsive thrust for flight and a much greater value of lift for takeoff. Such "symbiosis" of the turbojet engine and the turboprop is clearly advantageous for the aircraft: after all the prop with large diameter develops thrust several times larger than the jet stream of the engine with the same power.

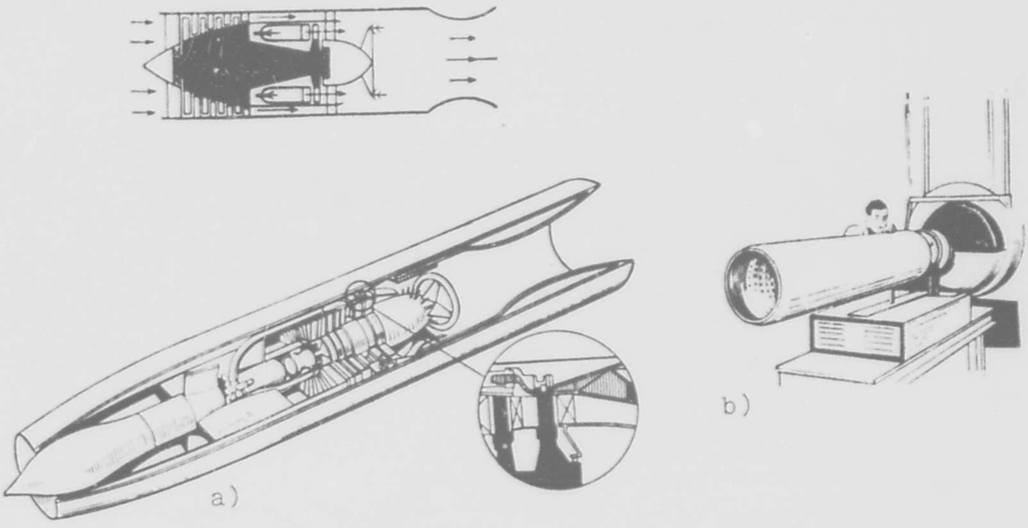
Everything that has been said about the "symbiosis" of the turbojet engine can lead to the incorrect idea that "symbiosis" is possible only with other jet engines. In reality this is not so. There are also proposed aircraft "symbiotic" propulsive systems, in which a turbojet engine is combined with liquid-fuel rocket engine. Such engines are usually called turborocket engines. What is their purpose?

It is connected with the turbine, this Achilles' heel of the turbojet engine. After all we know that the turbine, more exactly, its blades greatly dilute with air the gases, coming out of the combustion chamber, and cool them. But this sharply decreases the possible thrust of the engine, which is so necessary for accomplishing supersonic flight. The thought involuntarily comes to mind, of whether it is impossible to somehow do without the turbine blades? One of the possible solutions is the "symbiosis" of turbojet and rocket engines. Actually, if one were to remove the turbine from the gas stream, going from the combustion chamber to the jet nozzle, to simply eliminate this post on the "conveyer," the necessity of cooling the gases will be done away with. But then how can the turbine be made to turn; where is the tremendous force of tens of thousands of horsepower necessary for this to be found? This is where the second member of the "Association" enters into the picture – the rocket engine. The gases, expanded at the turbine blades, will in this case be formed as a result of the combustion of rocket fuel in a special liquid-propellant rocket engine. It is especially advantageous to use certain monopropellants in such an engine, in particular, acetylene. The "Combustion" of acetylene in the engine constitutes its dissociation, i.e., its decomposition into molecules of the chemical elements comprising acetylene – hydrogen and carbon.

Furthermore a rather large quantity of heat would be released, and the temperature of the dissociative products would reach approximately 1500°C. At such a temperature they can be directed into the turbine, the blade resistance of which in this case will be much greater in connection with the reducing (i.e., nonoxidizing) character of the gases. Moreover, beyond the turbine, in a device, similar to an afterburner, the products of dissociation can be burned in the air, which the compressor supplies, which also removes the necessity for any other combustion chamber, and any fuel, except the rocket fuel. Such a turborocket engine could be designed for successful application on supersonic, high-altitude aircraft, having less fuel consumption than a rocket engine, and greater altitude capability than a turbojet engine. There are prospects for its application and on the first stages of carrier rockets. It is true, these are still only ideas, designs, experiments. Information about the application of such an engine has not been published abroad although there are data about the carrying out of tests.

But if the "symbiosis" of a rocket engine with a turbojet engine can be successful then it is possible to anticipate still more from the "symbiosis" of the rocket engine with another representative of the family of airbreathing-jet engines – the ramjet. It is necessary to acknowledge that the idea of realizing such a "symbiosis" seems completely logical, as long as the ramjet engine is not in a position to provide independent takeoff of the aircraft because for this the assistance of another engine is required, for example, a rocket engine. Flying pilotless craft are already well-known abroad, on which are mounted both these engines. In these cases the rocket engine accelerates the craft to a speed, where the ramjet engine can be in to develop the thrust necessary for flight.

But such a simple setup on one aircraft in the form of a so-called combined propulsion system can be replaced by a much more efficient organic "symbiosis." In such cases, for example, the liquid-propellant rocket engine is placed in the central body of a supersonic ramjet engine similar to the way the turbojet engine is placed in it (recall the turboramjet "hybrid"). The engine,



a)

b)

Fig. 62. Turborocket "hybrid" engine: a) diagram of the engine; b) external appearance of one of these experimental engines (USA).

which is obtained this way, is usually called a rocketramjet. It is possible to assume that it will find application in the future; experimental models of such an engine are being investigated abroad.

In one of the patents issued in the United States there was proposed a "hybrid" rocketramjet engine, which can work either as a rocket, or as a ramjet. Such a reorganization is carried out with the help of a sliding flap, regulating the admission of air into the combustion chamber of the engine. If the air enters the chamber, then the engine works like a ramjet engine, if not, then like a rocket engine. Not excluded is the application of such a variant of the very same "hybrid."

The latter example of "symbiosis" in the world of jet engines, which will be discussed here, pertains to only some rocket engines and has a somewhat different character than those, which have already been covered. We know that all rocket engines are divided into two branches depending upon what kind fuel they use, liquid or solid. Both these types of rocket engines have their own merits and deficiencies. It is possible here to use the method of "symbiosis," to develop some unprecedented hybrid?

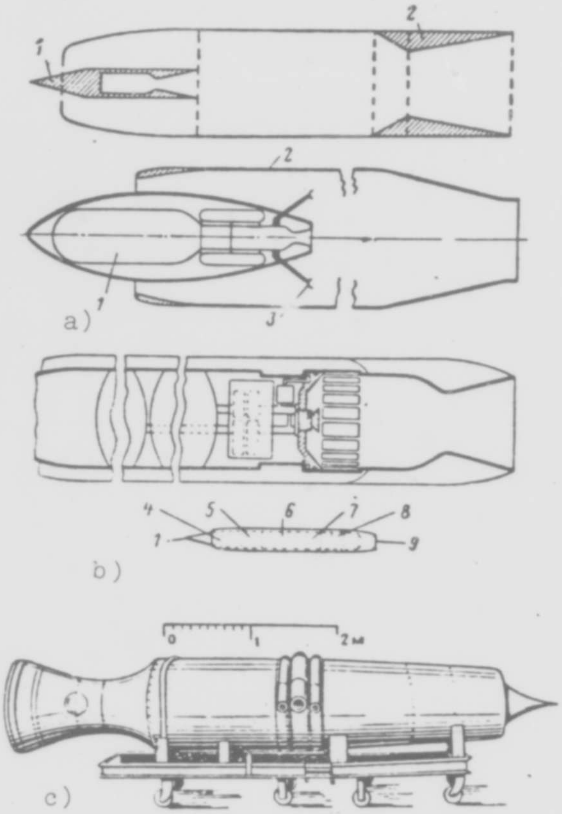


Fig. 63. This is how the "rocketramjet" hybrid can look: a) diagram of the engine; b) patent (United States) for an engine, working both as a rocket, and as a ramjet; c) external appearance of the engine; 1 – central body; 2 – engine housing; 3 – fuel injectors; 4 – payload; 5 – regulators; 6 – fuel supply; 7 – oxidizer supply; 8 – pumps; 9 – gas discharge.

Such a possibility exists: it is connected with the simultaneous use and liquid, and solid rocket propellant in one engine, which makes it possible to select the best fuel combinations. Especially efficient is the application of liquid oxidizer and solid fuel, especially, the spontaneously inflammable combination. Such a rocket engine with mixed fuel is more simply obtained that the ordinary liquid-propellant engine, provides higher specific thrust than ordinary solid propellant, and, at the same time, its thrust is easily regulated (by varying the supply of liquid oxidizer into the chamber with the solid fuel), and it is possible just a simply to completely shut off the engine and to turn it back on again. The preservation of this "hybrid" engine in a state of constant readiness for action has also been simplified. All this makes explicable the persistent attempts of designers to create such an engine and to put it into operation.

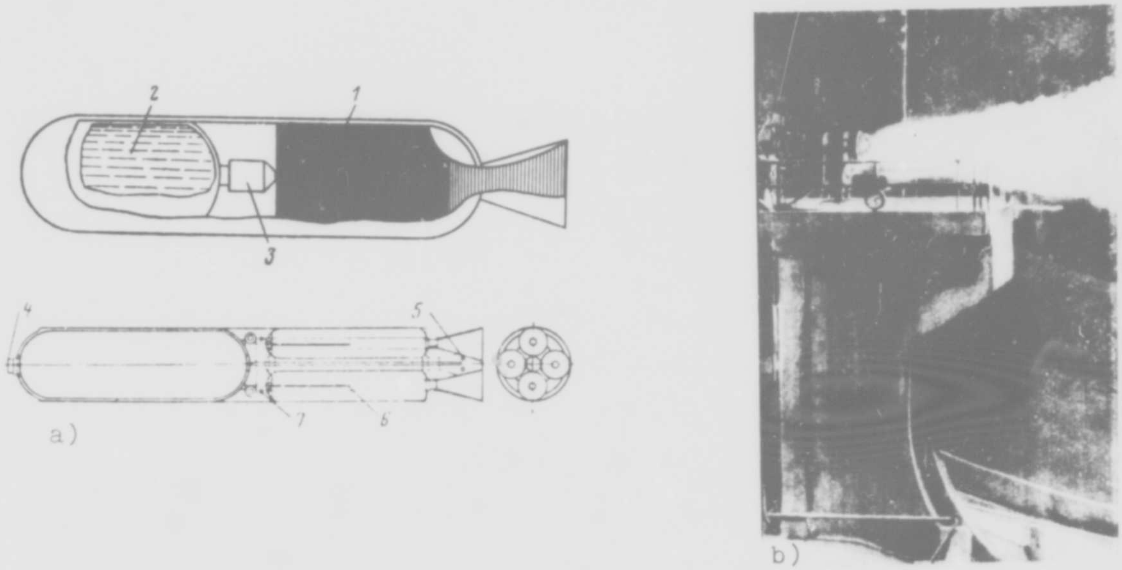


Fig. 64. Rocket engine for mixed (solid-liquid) fuel: a) diagram of an engine with a thrust of 90 t, designed in the United States; b) testing an engine with a thrust of 4500 kgf (United States). 1 – solid fuel; 2 – liquid oxidizer; 3 – valve; 4 – gas generator for solid fuel; 5 – regulation of the thrust vector by the injection of the liquid oxidizer; 6 – injectors; 7 – ignition by the injection of hypergolic fuel.

Such an engine has great possibilities for application in cosmonautics, in particular, in the control systems of space rockets and others.

The list of possible jet engines, embodying the idea of "symbiosis," could have been continued, proposals of a similar kind, and also information about their development, the testings of engines, etc., are constantly being published in special foreign journals. Judging from all the facts, this is one of the promising directions of the development of jet engineering.

CHAPTER IX

JET ENGINES AND CHEMISTRY

It is not accidental that we dedicate to chemistry and its collaboration with jet engineering a whole chapter in this book.

In our time it is impossible to name one branch of technology, in the formation and development of which chemistry did not play a large role. This is also understandable, after all chemistry – includes all metallurgy, different plastics and polymers, the use of which in many branches of technology is being continually expanded, and lubricating substances without which not one machine nor one mechanism could operate, and the numerous chemical reagents used in various industries, and the various technological methods of the chemical processing of metals and other materials, and many, many others.

But there is one branch of technology, which without chemistry is simply inconceivable, since chemistry – the foundation, on which this branch rests. We are discussing the whole armada of thermal engines, i.e., engines using thermal energy, into which the chemical energy of the fuel will be converted. Without the fuels, which chemistry gives us – millions of motor vehicles, tractors, aircraft, and ships would come to a standstill and stop, electric power stations and central heating plants would cease their operations; departments of plants and factories would stop dead. Certainly, this concerns such engines, which operate on liquid fuel obtained from oil, or on gaseous fuel obtained as a result of the chemical conversions at the plants. But after all, there are still solid, gaseous and liquid fuels, which nature gives ready-made - these are wood, coal, shales, natural gas, crude oil. However, more and more frequently these fuels also before their being used are subjected to preliminary chemical processing or combine such processing with the burning of fuel itself by the use of so-called energy-technological methods and the creation of whole electrochemical combines.

If chemistry - the basis of the absolute majority of thermal engines, then still greater basis it pertains to that group of thermal engines, to which this book is dedicated, i.e., to jet engines. Since without exception all jet engines operate on fuels, which are not natural substances, but products of complex chemical manufacture. Moreover, the degree of perfection of jet engines and the prospects for their further development to a very great extent are connected with chemistry, with how successful are the results of its work in the field of creating the fuels for these engines.

It is precisely for this reason that in the present chapter telling about the collaboration of jet engineering and chemistry, we will discuss fuels for jet engines.

Numerous demands are being made for fuels for jet engines. Actually such demands depend on what engine is being discussed, and, everything being equal, their composition is unique each time, and the demands being made for fuel are so unusual and frequently contradictory. It is obvious that this is not arbitrariness or chance - jet engines with unusual and high characteristics also require unusual and exceptionally high-quality fuels.

At least, two very important, basic requirements are general for all fuels without exception. One of them is absolutely obvious - this is the requirement for the greatest energy productivity or calorific value (sometimes they still say - caloricity) fuel. This means, that the fuel should liberate during combustion the greatest possible heat. And it is clear, why such a requirement is necessary - after all the whole operating process of the engine is only a chain of transformations of the potential chemical energy of the fuel into effective work, and the greater the energy productivity of the fuel, the greater the effective work. But this means that with the same useful output (power or thrust) of the engine the expenditure or consumption of fuel will be the lesser the more energy productive it is. Moreover, the decrease of fuel consumption, which is very important, also makes the engine and the aircraft more economical, i.e., cheap to operate. After all, all the fuel, expended by the engine in flight, should be stored onboard the aircraft. And carrying the fuel in flight also requires expenditure of the fuel itself, i.e., also increases fuel consumption. It is also clear that the possible fuel reserve onboard also determines possibility of accomplishing one or another flight. Therefore, there is always the tendency to make fuel consumption minimal, and for this the fuel should possess maximum energy productivity.

But how should we determine the energy productivity of the fuel, per kilogram or liter of it? At first glance the answer seems evident – certainly, per kilogram, since only in this case can the total number of kilograms of fuel stored on the aircraft be made minimal. But then doubts appear: and what, if some other fuel possesses somewhat lesser energy productivity per kg, but instead a considerably greater specific weight so that the energy productivity per ℓ of fuel is considerably greater. Will this fuel be better or worse than the first?

Certainly, for this second fuel the total required reserve onboard will be greater, but then the volume of the fuel tanks for carrying this somewhat larger quantity of fuel will be essentially smaller. It very frequently happens thus, that the quantity of fuel, which can be taken onboard the aircraft, is determined precisely by the volume of the fuel tanks, and not by the allowable weight of the fuel. It is obvious that in this case the second fuel will undoubtedly be better. But even in those cases, when the situation is not so, the volume of fuel in the tanks nevertheless plays a large role, after all the lighter the fuel, the larger and, this means, the heavier the tanks. Excessive weight of the tanks, it is obvious, is always a deficiency, and frequently it simply and proportionately decreases the maximum possible reserve of fuel onboard. Thus, as we see, it is not always possible to decide, which fuel is better, if for one the energy productivity is more per kg, and for the other – per ℓ. In each actual case it is necessary to carry out an exact calculation taking into account both the energy productivity, and also the specific weight of the fuel. In any event, the specific weight of the fuel is always an important factor and should be as great as possible.

However, let us return to the second, basic, and most important requirement, common for all fuels without exception, although it is not so obvious as first. This second requirement consists in the fact that any fuel should form during combustion a large quantity of gases. At first glance it seems that the volume of the gaseous products of combustion is not so important, inasmuch as the energy of the fuel during combustion has one way or another already been released. However this is not so.

That the products of combustion of any propellant must be gaseous, is easy to understand. In fact, if these products were, for example, solid (and this is completely possible), then what force would cause them to emanate at high speed from the engine for the formation of jet thrust? The usual force of the gas pressure in this case would be absent (after all the gases themselves would be absent), and to replace it with some other would not be very simple, and sometimes it would even be impossible. Such an engine simply would not operate, since it would very quickly be clogged by the solid products of combustion. Even if it were possible to somehow remove these products from the engine, then, just the same, it still would not create jet thrust.

But if the gases form, would it still not matter what their volume would be? It turns out that this is not unimportant for the engine. After all the jet thrust, created by it, will be the greater the greater the exhaust velocity, since thrust is the momentum of the emanating gases, equal to the product of their mass times the exhaust velocity. And this speed, it turns out, depends directly on the volume of gases – it is the greater, the greater the volume. Why is this so? This can be seen from the following arguments. When in the combustion of fuel in the engine its chemical energy is liberated then it converts into thermal energy the products of combustion, which are in a gaseous state. But the thermal energy of gas is none other, than the kinetic energy of the thermal motion of its molecules. As a measure of this energy there serves the absolute temperature of gas. With the same kinetic energy of the molecules the speed of their motion will be the greater the less is the mass of the molecules, i.e., the molecular weight of the gaseous products of combustion. After all kinetic energy is also the semiproduct of mass times the square of the speed. Therefore, the less the molecular weight, with the same gas temperature the greater the speed of the thermal motion of the molecules. But the molecular weight, in turn, is the less the greater the volume of gases forming during combustion, since the volume of gas is proportional (at a given pressure and temperature) to the number of molecules, and this latter is the greater the less the weight of each molecule, since the total mass of all the molecules is the same. Finally, in order to complete this line of reasoning, it is necessary to consider that the exhaust velocity is directly connected with the speed of the thermal motion of the molecules. After all exhaust is simply the organization of the earlier disorderly, chaotic motion of molecules in such a manner, that they all moved not in all directions, but in one direction. Thus it is also obtained that the greater the volume of gases, the greater the exhaust velocity and, consequently, the thrust of the engine. This is why the dissociation of the products of combustion in a liquid-propellant rocket engine does not have such a great infuence on the exhaust velocity, as was mentioned in Chapter VI.

Besides the indicated, basic requirements, fuel for jet engines should also answer many others. It should not be very poisonous and this also pertains to the products its combustion; it should not be rare or expensive; it should be chemically stable and capable of prolonged storage; it should not cause corrosion of metallic surfaces with which it comes into contact; it should neither evaporate excessively nor evaporate too poorly, it should not freeze, if it is a liquid fuel, or crack, if it is a solid fuel... The list of requirements could be made very long. But first of all the fuel should answer the two main requirements, which were discussed above. Chemistry attempts to satisfy all or at least many of the contradictory requirements, made on the propellants, but in the first position there always stand precisely these requirements.

For various airbreathing-jet engines, i.e., turbojets and ramjets, and also turboprops, at the present time there are used almost exclusively fuels of petroleum origin. Oil, which for already a century has run motor vehicles and tractors, railroad locomotives and maritime vessels (since on it distillates operate all internal-combustion engines), and now the same is also true for jet aviation. Usually as fuel for this aviation there are used various kerosenes and gasolines. They possess a sufficiently great energy-productivity (during the combustion of 1 kg there is liberated more than 10,000 kilo-calories of heat), good operational properties, and are inexpensive.

But natural fuels in recent times are already becoming unsatisfactory for jet engineering and, in the first place, cannot provide prolonged flight at supersonic speed; in carrying out such flights it is necessary to use refueling methods in flight with the help of tanker aircrafts, unique flying tankers. Therefore, scientists are turning to chemistry in searching for new fuels for airbreathing-jet engines, first of all, for fuels with more energy productivity.

Does contemporary chemistry know, of substances, which can serve as more energy productive fuels for airbreathing-jet engines? Yes, such substances, not existing in nature, but synthesized, i.e., obtained by chemists, are well-known. In particular, definite prospects exist in this respect for a number of synthesized hydrocarbons and certain chemical compounds of one of the elements of the halide group – boron, for example, the so-called boranes – boron compounds with hydrogen expecially pentaborane, the chemical formula of which is B_5H_9. This substance liberates during combustion considerably more heat than the hydrocarbon fuels (approximately 16,000 kcal/kg instead of 10,000). But to use it as a propellant is impeded by high costs, operational difficulties connected, mainly, with the toxicity of pentaborane, the erosional action of the solid products of the combustion of boron on engine components, their deposition on these components, etc.

Incidentally, certain other boroderivatives, for example, triethyloborane, aluminum boronydride and others, and also certain other chemical substances can be used as so-called pyrophoric fuels, i.e., spontaneously inflammable in the first contact with air. This property can be very effective for the ignition of the basic fuel in a combustion chamber, in an afterburner of turbojet engine, in a ramjet engine, especially with supersonic combustion, in general, in all cases, when combustion should occur in an air stream of great velocity. Experiments with such application of pyrophoric fuels are being conducted abroad.

In the United States plants have been built for the production of boron hydride fuels and extensive experimental investigations are being conducted of their combustion in airbreathing-jet engines. However, in the way of the application of these fuels are serious obstacles, moreover, doubts have even been expressed about whether they will in time find general, practical application, so significant are the deficiencies of boron hydride fuels.

This does not at all mean that attempts to find new, more perfected fuels than hydrocarbons, are being abandoned. Chemistry is intensively continuing research both in the area of boron hydrides, and also of other compounds. If the importance of this research is great with respect to airbreathing-jet engines, then it is many times greater, when the discussion concerns rocket engines, whether, liquid or solid propellant engines. The fuels for such engines are no longer one chemical substance, but two or even several similar substances, and on the other hand, all the work of these engines and the characteristics of aircrafts with them to a still greater degree depend on the properties of the fuel, first of all, on its energy productivity. It is understandable, why this is so. After all onboard the rocket there must be the whole fuel reserve, whereas in the case of the airbreathing-jet engine there is onboard only a small part, frequently only about one percent of the total amount of working substance passing through the engine – the rest is scooped up from the atmosphere.

But the matter is not only in this. In aviation the energy productivity of a fuel determines its consumption and, consequently, the possible flying range of the aircraft with a given payload. If the required range is greater, then the aircraft lands for refueling and continues it flight to its destination, or refuels directly in flight from a tanker aircraft.

The circumstances in rocketry and astronautics are different; here rocket engines have their basic application. The ballistic flight of a rocket differs from the aerodynamic flight of an aircraft by the fact that the rocket engine does not work all the time, as does the engine of an aircraft, but only for a few minutes during the launch, i.e., during the short, initial, so-called powered section of the flight trajectory. It is precisely during these minutes that the rocket must acquire the great speed, which is necessary for accomplishing all the rest of the flight to its destination. But if the fuel does not possess sufficient energy productivity, then the required velocity will not be attained and, consequently, flight to the destination will not be possible.

There emerges, in this case that the energy producticity of the fuel determines not simply its expenditure for accomplishing the flight, i.e., the economy of the flight, but the possibility itself of one or another flight.

It is understandable that the "landing" of a rocket for repeated refueling has little meaning, since in such a landing the accumulated speed is lost. Regarding refueling in flight, as it is easy to see, this problem is much more complex than in aviation perhaps, even insolvable.

However, one possibility of such refueling in flight not only exists, but with it are connected the very great hopes of rocket technology. This concerns the refueling of space rockets, which have already attained orbital velocity, i.e., have arrived in the circular or elliptical orbit of an artificial earth satellite. There, in orbit, in principle it is possible to set up a meeting of the space rocket with an orbital "refueller," in order to fill from the tanks of this ser icer the emptying tanks of the rocket with the required amount of fuel. This would make it possible to considerably increase the possibilities of astronautics, and it is not surprising that in the United States, for example, they are very seriously preparing to carry out this concept of space refueling - a concept, expressed even by K. E. Tsiolkovskiy.

However, the problem of space refuelling is still not solved, yes and, furthermore, it only side-steps, and does not tackle all those limitations of rocket flight, which are connected with the energy productivity of fuels. This is why there is frequently mentioned the "barrier," which the insufficient energy productivity of fuel erects on the path of the development of rocket engineering and, primarily, of cosmonautics. And since for the rocket engine the energy productivity of the fuel is, first of all, the exhaust velocity of gases from the engine, then they talk about the "barrier of exhaust velocity," or about the "barrier of specific impulse," inasmuch as specific impulse is a value, proportional to the exhaust velocity.

Thus, the fate of rocket technology and cosmonautics is to a great extent in the hands of chemistry. How does chemistry respond to the hopes that are placed on it?

We will start with our story about fuels for rocket engines solid fuels, if only because this is the first of all known fuels used for jet engines.

Solid rocket propellants have travelled a long road in their development and have quite rapidly improved in very recent times.

Both at the dawn of the development of solid propellant rockets, and also even at the end of the past century the only fuel for such rockets was common black powder. Such a powder is a mechanical mixture of three basic substances - carbon, sulfur and saltpeter. During combustion it forms puffs of black smoke. But this is not the main deficiency of black powder, but its low energy productivity. Such powder is able to provide an exhaust velocity equal to a total of approximately 700 m/s.

For reader there involuntarily can appear the question - why doesn't the powder explode in the rocket engine, as it explodes, for example, in a high-explosive bomb? After all, of course, the engine could not work, if it turned itself into a bomb.

The secret here is in the combustion rate. When the so-called explosive effect must be attained, i.e., the explosive force of the powder is used, then the combustion rate should be very great; all the powder should burn practically instantly, or, so to speak, detonate. Such powders are therefore called high explosives.

And even in the barrel of an artillery piece the powder must burn very slowly, otherwise the barrel will burst. The function of artillery powder is different - it should form gases during combustions, which push the shell from the barrel at high speed. Such powders, in contrast to explosives, are called propellant powders. And also in this case the combustion rate should still be sufficiently great, or else the pressure of the gases in the gun barrel will be low and the shell will obtain low initial speed. If similar powder were used in a rocket engine, its chamber would burst during operation, or its walls would have to be made as thick, as the barrel of an artillery piece (if not thicker).

In a rocket engine there must be used even slower burning propellant powders. Certainly, if the combustion rate is very small, then not much gas will be formed in the engine and therefore the thrust of the engine will also be small. Obviously, it is necessary to make sure, that the combustion rate of the powder is very specific.

This is provided by the special technology of powder charge manufacturing for engines, in particular, by the selection of powder grain sizes, by the configuration of the grains, from which the charges is composed, etc.

The deficiencies of pressed gunpowder forced the scientists to look for a replacement for it and approximately 100 years ago so-called smokeless powder was invented. An important external distinction of the new powder from gunpowder is the fact that it does not form smoke during combustion. But incomparably more important is something else – smokeless powder is considerably more energy productive. This is why this powder starting with the second world war became a rocket fuel.

Smokeless powders are in most cases a mixture of two basic substances – nitroglycerine and nitrocellulose and therefore bear the name two-component of dibasic powders. Besides these basic component ingredients in this powder there are usually also different additives improving its properties. All component parts are thoroughly pulverized, mixed and gelatinized for the formation of a dense, uniform, gelatinous mass. If during the combustion of black powder there immediately occurs a chemcial reaction, in which all three component parts of the powder participate, then in the smokeless powder combustion – first of all the process of the explosive decomposition of its basic components. As a result of such decomposition oxygen is liberated, entering into the molecules of both nitrocellulose, and nitroglycerine, and then combustion occurs in association with this oxygen.

In recent years with the dibasic solid fuels there have successfully competed new fuels, obtaining the name composite or mixed fuels (sometimes they are also called compound). These fuels are an intimate mechanical mixture of an inorganic oxidizer and an organic polymeric fuel also playing the role of the binder. As oxidizers crystal inorganic salts have been successfully used, in particular, nitrates, i.e., salts of nitric acid, for example, potassium, sodium and ammonium nitrates, perchlorates, i.e., salts of perchloric acid, and picrates, i.e., salts of picric acid. They constitute approximately 70-80% of the whole fuel and liberate during decomposition a large quantity of free oxygen necessary for the combustion of the fuel. As for the fuels they are various rubber-like polymeric resins, for example, polyurethanes, polysulfides and others, the selection of such fuels is very great. A mixed fuel is by manufacture a viscous fluid mass, which in fused form pours directly into the combustion chamber of the engine, which gives great advantages (they were discussed in Chapter VII). It is necessary to note that this progressive method of the direct pouring of the charge into the engine is used now instead of the old method of pressing for dibasic fuels.

The most energy productive contemporary solid fuels provide exhaust velocity of gases from an engine of the order of 2300-2500 m/s. Even for the most promising combinations, for example, with the addition of certain metals to the fuel as combustibles (widely employed above), which liberate much heat during combustion (this idea of using metallic combustibles belongs to the pioneers of domestic rocket technology, to Yu. V. Kondratyuk and F. A. Tsander, in which Tsander carried out the first experiments on their combustion), it is doubtful whether the value of the exhaust velocity will exceed 3000 m/s. This value can be considered the maximum, so to say, limit of the possibilities of the chemistry of solid fuels.

Somewhat greater (approximately 3500 m/s) is the possible exhaust velocity in the case of mixed, "hybrid" fuels – liquid oxidizer and solid fuel, which were discussed in the preceding chapter. In these cases the fuel can be, usually, the very same polymeric rubber-like resins, and the oxidizer can be liquid oxygen, nitric acid and other oxidizers common to rocketry. The merit of such fuels – not only their somewhat greater energy productivity, but also their operational advantages.

Another combination of solid and liquid fuels, which abroad is also considered promising, is the so-called gelatinous fuel. This fuel is a suspension of a solid oxidizer (for example, ammonium nitrate or ammonium perchlorate with the addition of aluminum or magnesium powder) in a liquid organic fuel, for example, hydrocarbon, where a special gelating substance (for example, ethylcellulose and others) converts this suspension into a colloidal, gelatinous state. Engines, working on such fuel, still have not been developed; there are only some patents and design sketches, and the first tests have been conducted. The basic merit of the gelatinous fuel consists in the fact that it can be fed into the rocket with the help of a pump immediately after its installation on the launching site, which opens the possibility for the creation of powerful carrier rockets. It is true, the part of the fuel in the total weight of rocket is somewhat decreased, but the fuel can be somewhat more energy productive. The engine in this case has a sectional construction so that by varying the number and the dimension of the sections, it is possible to vary the thrust of the engine and the duration of its operation with their constant operation, i.e., total impulse.

A number of possible, promising improvements of solid fuel increasing its energy productivity has also been pointed out abroad such as two-component solid fuels, i.e., fuels, consisting of a separated oxidizer and fuel, which can make it possible to use more chemically active substances, and also a method of enclosing liquid fuel in hard fuel in the form of small isolated cells. However, in these cases, which are still far from realization, it is doubtful whether the exhaust velocity will significantly exceed 3,000 m/s.

And what are the possibilities of liquid rocket fuels?

At the present time the absolute majority of all known liquid-propellant rocket engines operate as was already mentioned in Chapter VI, on bi-propellants or fuels of separate supply. However, there are also engines, operating on so-called monopropellants, which are, essentially, liquid powders. These fuels – one liquid which is either a uniform chemical substance, as, for example, hydrogen peroxide, liberating heat as a result of decomposition in the engine (in this case the fuel is single-component), or a solution of several substances – two or more. In the latter case

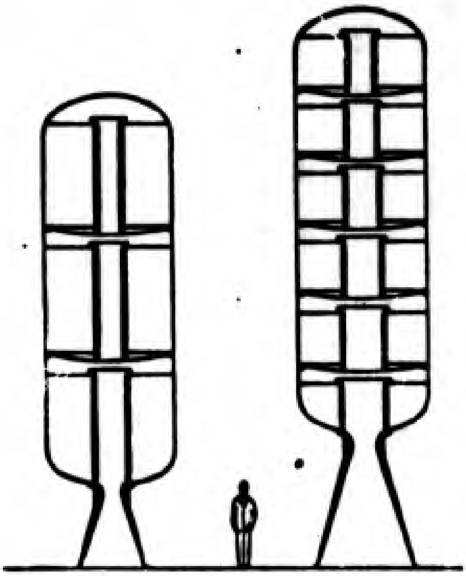


Fig. 65. Rockets for gelatinous fuel. Both engines shown on the figure have an identical total impulse of approximately 20,000,000 kg·s, but one (on the left) develops a thrust of 225 t for 90 s, and the other – 450 t for 45 s.

in the solution there are present the oxidizer, and also the fuel, so that in the engine during combustion the usual oxidation reaction occurs. Examples of such fuels, finding certain application abroad, are solutions of nitric oxide and ammonia, tetranitromethane and alcohols or various hydrocarbon combustibles, etc. Similar fuels possess absolutely obvious operational advantages as compared to fuels of separate supply, however, it is also just as obvious that they have to yield the latter with respect to energy productivity. After all high energy productivity is the result of great, so to speak, chemical affinity, i.e., high reactivity, the tendency to easily and rapidly enter in chemical reaction. It is clear that the retention in one solution, in such intimate contact of two substances readily and violently reacting with each other is fraught with the great danger of explosion. This also limits the possibility of the application of adequately energy productive monopropellants, although, nevertheless, the operational merits ensure such fuels indisputable prospects for application in the future.

It is obvious that the greatest potential possibilities with respect to energy productivity belong to fuels of separate supply. What in this respect are the resources of chemistry?

At the present time the main applied oxidizers, are, according to data published abroad, liquid oxygen and nitric acid which were

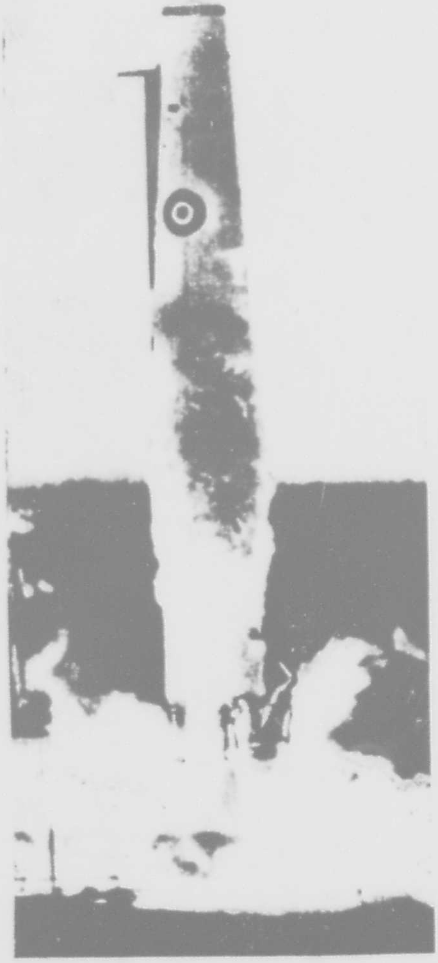


Fig. 66. One of the most broadly used oxidizers at present is liquid oxygen, which was proposed by K. E. Tsiolkovskiy. The American "Thor" rocket takes off, wrapped in a fur coat of hoarfrost — the first indication that in its tanks is liquid oxygen (its vaporization temperature is equal to -183°C.

also proposed by K. E. Tsiolkovskiy. Hydrogen peroxide and certain oxides of nitrogen are used (for example, tetroxide, or nitrogen tetroxide) and their solutions in nitric acid. Regarding fuels, the ones that have received the greatest application at present are hydrocarbon petroleum fuels — kerosene and others, which were also proposed by K. E. Tsiolkovskiy. Alcohol, aniline, ammonia, hydrazine and certain other substances are being used. The maximum values of the exhaust velocity of gases using these oxidizers and combustibles, for example, fuels, consisting of liquid oxygen and kerosene, are approximately 2700-3000 m/s. As can be seen, these values are significantly greater than in case of solid fuels. But they are far from necessary to cosmonautics. Are there possibilities of developing more energy productive liquid fuels?

As for the oxidizer, then, at first glance, it seems that such possibilities are absent. In fact, what oxidizer can be more ideal than - pure oxygen? However, in reality such an oxidizer, "more Catholic than the Pope in Rome," nevertheless exists, and there are even several of them.

First of all, a more ideal oxidizer is a close "relative" of oxygen - ozone. As is known, a molecule of ozone consists of the same atoms, as a molecule of oxygen, but in a molecule of ozone there are not two but three of these oxygen atoms. For the dissociation of a molecule of ozone into atoms it is necessary to expend less energy than for the dissociation of a molecule of oxygen. Naturally, the energy productivity of the same fuels during combustion in ozone is greater than in oxygen. If one were to consider that liquid ozone also possesses a greater specific weight than liquid oxygen (1.45 instead of 1.14), and also a somewhat higher boiling point (-112°C instad of -183°C), then the attractiveness of ozone as an oxidizer in rocket technology will become evident. However, the matter is far from being this simple, since in the way of the practical use of ozone stands one, but very extremely great obstacle - the extraordinary chemical instability of ozone. Ozone has a tendency to explode for any reason and even without any reason. With such an explosion, which is accompanied by the appearance of a powerful shock wave, few or no traces will be left of the engine or rocket. And yet scientists are intensely working on the "domestication" of ozone, so great are its other merits.

Nevertheless, for the title of "king of the oxidizers" there is another oxidizer with pretensions. Is this second pretender also from among the "relatives" of oxygen?

Not at all. Rather, on the contrary, it is a true enemy of the oxygen family, since if oxygen is able to oxidize any chemical substance from the total number, which enter into chemical reaction (we exclude, therefore, the inert gases), then our new oxidizer is not only not oxidized by oxygen, but it itself also... oxidizes. An oxidizer of oxygen, this would appear to be a real iconoclast! And yet one, truly the most powerful chemical oxidizer, exists – it is fluorine. It was no accident, apparently, that it received its name – phthorios (in Greek it means "disruptive"). Fluorine is also a cryogenic liquid, i.e., a liquified gas, its boiling point is equal to minus 188°C. In specific weight (1.51) liquid fluorine even exceeds ozone, in energy productivity it concedes slightly to ozone, but considerably exceeding liquid oxygen. But fluorine also has a very great shortcoming – it, like its compounds, in particular, the products of its combustion, are highly poisonous. And yet the prospects of using fluorine in rocket technology are great; in this direction extensive works are being conducted. Certain derivatives of fluorine can also find application as oxidizers, for example, oxygen fluoride, chlorine trifluoride and others, perhaps, possessing somewhat less energy productivity, but then having better operational properties.

Thus are the matters with respect to the best of all possible oxidizers, which are available to chemistry. Well, and what fuels can it offer?

Here, in first place stands, of course, liquid hydrogen. This is not surprising, after all as much heat, as hydrogen liberates is not liberated during the combustion of any other substance. This would make hydrogen the indisputable "king of fuels," if its deficiencies also were not rather numerous and serious. One of these deficiencies is especially unpleasant – the extremely small specific weight of liquid hydrogen: it is lighter than water, by approximately... 15 times! It is easy to imagine, how huge would be the volume of a rocket fuel tank, if in them is contained the liquid hydrogen necessary for a flight. This is why in the first place the use of liquid hydrogen is proposed for the upper stages of multistage rockets, where the fuel reserve is relatively small. But then in this case there shows up very strongly another great deficiency of liquid hydrogen as a rocket fuel – its extremely low boiling point. In order to transform hydrogen which is, as is known, a constant gas into a liquid, it is necessary to cool it to a temperature of minus 253°C, i.e., a total of 20°C above absolute zero! It is clear that such a low-boiling liquid evaporates violently, and since the engines of the upper stages work last, then the portion of hydrogen which has evaporated can be extremely great.

And yet these deficiencies of liquid hydrogen do not decrease the interest in it as a fuel for liquid-propellant rocket engines. Although some time ago in scientific journals there were the usual articles proving that such application of liquid hydrogen would be ineffective and will not take place, life has refuted these assertions. So great is the importance of the extremely great energy productivity of rocket fuels based on liquid hydrogen that its deficiencies recede into the background, which promotes, in particular, the successful development of new, perfected types of thermal insulation, providing minute losses of hydrogen due to evaporation.

Recently abroad, especially in the United States, there has appeared a number of rocket engines, operating on liquid hydrogen and liquid oxygen. This remarkable combination of oxidizer and fuel provides an exhaust velocity of an order of 4200 m/s, i.e., almost one and a half times greater than for the usual contemporary fuels, for example, liquid oxygen and kerosene. Oxygen-hydrogen engines have been tested in the United States for a long time on test stands and are even being mounted on a number of new space carrier rockets. Work on such engines is also being conducted in England. Fluorine-hydrogen engines are also being tested; incidentally, this fuel combination is hypergolic.

Among the number of other promising fuels (by their energy productivity) there also must be included certain chemical compounds of hydrogen, and also light metals, which were proposed, as was indicated above, by Kondratyuk and Tsander. Certainly, metals liberate considerably less heat during combustion than hydrogen: the heat of combustion of hydrogen with oxygen is 28,800 kcal/kg, and for the most energy productive metals it is less than one and

Fig. 67. The LR-115 rocket engine operating on liquid oxygen and liquid hydrogen (the first "hydrogen" engine in the United States): a) external view of the engine, its thrust is equal to 6800 kgf; b) a diagram of the engine. The difference is the operation of the turbopump assembly on hydrogen heated in the cooling "jacket" (without a gas generator). 1 – oxygen pump; 2 – hydrogen pump; 3 – turbine; 4 – fuel intake; 5 – oxidizer intake; 6 – thrust chamber.

a half times more and is equal for beryllium to – 16,100 kcal/kg and for boron – 14,400 kcal/kg. But then metals are incomparably heavier than hydrogen; their specific weight is more than the latter by approximately 30 times (for beryllium it is equal to 1.85, and for boron – 2.3).

But the trouble is not only in the specific weight. When we talk about energy productivity, then we have, after all, in mind the exhaust velocity of gases.

The exhaust velocity is directly determined by the energy productivity of the fuel: it is proportional to the square root of the calorific value of the fuel (it is worth emphasizing – fuel, and not of the combustible). This is a very important distinction. Is it true that from that, that 1 kg of any combustible during combustion liberates very much heat, if for such combustion a very large amount of oxygen is also necessary? After all we have to relate the liberated amount of heat to the total weight of the burning combustible and of the oxygen expended on such combustion (and the oxygen must be stored onboard the rocket)! This is why, for example, the extremely high energy productivity of hydrogen still does not say anything directly; we must furthermore, answer such a question: and how much oxygen will be needed for the combustion of one kilogram of hydrogen?

It turns out that taking into account the indicated circumstance the energy productivity of a fuel consisting of hydrogen and oxygen will be equal to 3400 kcal/kg, and for beryllium - 5850 kcal/kg, for lithium - 4850 kcal/kg, for boron - 4560 kcal/kg. Consequently, not only in specific weight, but also in energy productivity fuels based on light metals are better than those based on hydrogen. And actually, the ideal exhaust velocities will be equal to, respectively, for hydrogen - 5300 m/s (the actual exhaust velocity will be, as was noted above, approximately 4200 m/s), for beryllium - 7000, lithium - 6400 and boron - 6200 m/s. The advantage of metals is obvious.

Thus, what's holding the matter up? It is necessary, obviously, to broadly use such metallic combustibles in rocket engines.

It turns out this is not at all so simple to do. First of all, the application of such metals as fuels for liquid-propellant rocket engines is practically completely excluded since under normal conditions they are in a solid state. Actually, what kind of liquid-propellant engine would this be if it operated on solid fuel? Certainly, it is possible to first fuse the metal in a special crucible, or to prepare a suspension of the metal in some other liquid fuel. Both of these methods were proposed long ago and have already been partially tested, but their practical application is still not taking place, yes and it is doubtful whether it soon will.

Another deficiency of metallic combustibles is, usually, their high cost. One more deficiency consists in the fact that the products of the combustion of such fuels have great molecular weight and contain solid particles of metal oxides, which hinder the exhaust process and decrease the specific thrust. And yet, of course, it is possible to depend on the fact that metals will serve as combustibles in the liquid-propellant rocket engines of future. Their inclusion in the composition of solid rocket propellants – matter of still more recent time; this is being done now. As one of the attempts to use the merit of metallic combustibles in liquid-propellant rocket engines and to avoid the deficiencies connected with them it is possible to point to the proposals expressed abroad about the creation of liquid-propellant rocket engines, operating not on two, but on three working substances. In this case the energy producing metallic fuel, burning with liquid oxygen, is used for heating a third substance which best of all can be liquid hydrogen. The small molecular weight of the latter can provide an extremely high exhaust velocity.

We will limit outselves to the above mentioned promising oxidizers and combustibles for rocket engines, although they do not exhaust all the chemical possibilities. At present in various countries the most intensive research and investigations are being conducted of all possible chemical substances, capable of claiming the role of ideal rocket fuels. In certain cases these are still very rare substances, at other times at the disposal of the chemists are several grams (quite recently this also touched on such substances, as certain boranes, liquid fluorine and others), however they are sufficient for a complete determination of the physical, chemical properties. For this it is necessary to carry out complex and laborious theoretical and experimental investigations, in which electronic computers are beginning to play an ever greater role.

However, it is already becoming clear now that whatever the fortunate findings about rocket fuels will be in the future, it is doubtful whether the maximum values of the exhaust velocity will exceed 4500-4750 m/s. This, probably, is the limit of the possibilities of the chemistry of rocket fuels. It cannot be greater, since such is the order of the maximum value of chemical energy liberated during the combustion of fuels in a rocket engine. This value of chemical energy is determined by the properties of the electron shells of the atoms and molecules, by the value of forces of the bond of the electrons on this shell with the atomic nuclei.

Certainly, the achievement of the values of maximum exhaust velocity mentioned above, which by approximately one and a half times exceed the best contemporary values, will represent a great step forward in the development of rocket technology and cosmonautics. With help these "ideal" chemical fuels remarkable new victories will be gained over the elemental forces of nature, particularly, in conquering space. And yet, it is obvious that the fuels set a limit to the further development of rocket engines. Chemistry is powerless to overcome this barrier.

However, it would be unjust with respect to chemistry, if we looked down on certain of its possibilities, which perhaps, it will not manage to realize due to overwhelming difficulties, but which, at the same time, must be subjected to the most thorough study, so remarkable are they.

If one is to consider airbreathing-jet engines, then here, in the first place, it is necessary to note the remarkable fuel, stored in the upper layers... of the terrestrial atmosphere. As is known, at heights of more than 90-100 km the shortwave solar radiation splits the molecules of oxygen located in the atmosphere into atoms so that above approximately 150 km there are already no more oxygen molecules; only atomic oxygen exists there. At heights of the order of 250 km there are also no molecules of the second gas making up air, nitrogen, since it is also only in the atomic state there.

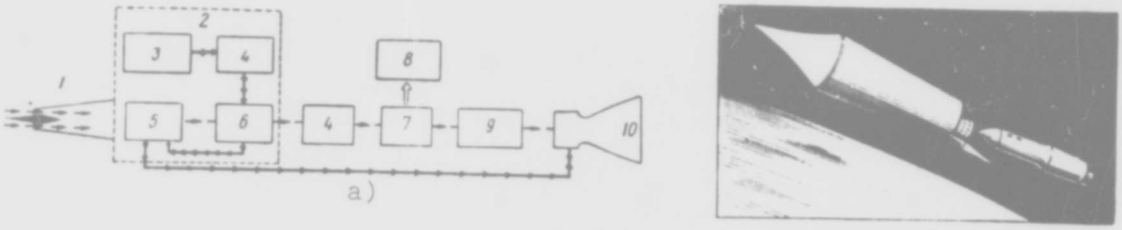
But if the splitting of molecules of nitrogen and, primarily, of oxygen occurs due to the absorption of the energy of solar rays, then, obviously, the reverse reunification, the recombination of molecules leads to the liberation of the earlier expended energy.

This is very great energy and with its help practically unlimited "free" flight in the upper layers of the atmosphere could appear possible. This is a very outstanding possibility, isn't it?

Unfortunately, it is very difficult to realize it, perhaps, it will not be managed at all. First of all, the reverse reunification of the molecules from atoms occurs very slowly at high altitudes. It is true, it can be accelerated artificially with the help of special chemical substances – the accelerators of this recombination reaction, the so-called catalysts, are for example, nitrogen oxide, certain metals, in particular, gold and others. Such a possibility has already been checked and confirmed experimentally with the help of high-altitude rockets. Consequently, this obstacle could be overcome. But it is impossible, unfortunately, to bypass another difficulty – the extreme rarefaction of those upper layers of the atmosphere, in which atomic air is contained. As a matter of fact, it is precisely due to this rarefaction that the existence itself of atomic gases is possible for a prolonged time. But this rarefaction does not permit the using of this desirable "free" energy of the atomic gases of the atomosphere simply because the amount of these gases is so insignificantly small. As tentative calculation show, the thrust, which can be developed by an engine operating on the atomic atmospheric gases, cannot provide independent flight for the lightest possible aircraft. It is true, the results of these calculations cannot be considered final; a direct experimental check will be required here, but still it is necessary to recognize, that the odds for the possibility of using the unique chemical energy of the atomic gases of the atmosphere do not seem too real.

This does not at all signify, of course, that the whole idea should be completely cancelled. Even if such "free" flight in the terrestrial atmosphere appears impossible or irrational, the situation can be otherwise, for example, during flight in the atmosphere of Mars or, especially, of Venus. It is not excluded that communication between a satellite of Venus, into which a spaceship arriving from earth will be converted, and the surface of the planet itself will be carried out with the help of precisely such "chemospheric" engines.

Incidentally the dissociative energy of atmospheric gases can be not only not useful, but even harmful. There are designs for a power system for flight in the upper layers of the atmosphere, which is also a unique "hybrid" of jet and liquid-propellant rocket engines. According to these designs only liquid hydrogen will be found on the aircraft for fuel. The air coming into the hypersonic air intake of the engine will enter a condensation system, where it will be liquified. The liquid oxygen will be separated from the nitrogen and either accumulated in the tanks for subsequent transfer to the tanks of a spaceship taking off from earth, or used in the liquid-fuel rocket hydrogen-oxygen engine. The heat liberated during the recombination of atomic atmospheric gases, will in this case, obviously, hinder liquefaction, i.e., cause damage.



a)

b)

Fig. 68. Designs of engines with air condensation (liquefaction) for flight near the boundary of the atmosphere (the United States): a) diagram of a liquid-propellant rocket engine, in which liquid hydrogen burns with liquified atmospheric oxygen; b) the transfer in a low-altitude orbit of a satellite of atmospheric liquid oxygen, accumulated in its tanks as a result of the prolonged operation of its condensation device, to the tanks of a spaceship. 1 – hypersonic air intake; 2 – condensation system; 3 – liquid hydrogen; 4 – pump; 5 – preliminary cooler; 6 – condenser (liquifier); 7 – separator; 8 – liquid nitrogen; 9 – liquid air enriched with oxygen; 10 – thrust chamber.

But if the atomic gases of the atmosphere are difficult to use because they are sparse there, then is it impossible to create such gases artificially? After all if this is possible, then it simply remains to fill the tanks of the rocket with such liquified atomic gas so that then in the combustion chamber of the engine the reaction of the recombination of atoms into molecules would occur with the liberation of a great quantity of heat, as a result of which from the nozzle of the engine there would emanate a stream of heated gases at high speed. Moreover, during such artificial formation of atomic gases it would not be at all necessary to be concerned with oxygen and nitrogen. It would also be possible to select more suitable substances, liberating more energy during recombination and, in particular, possessing less molecular weight, since, as we know, the exhaust velocity increases with the decrease of the molecular weight.

In this connection it is natural to think about hydrogen – the substance with the least molecular weight. Is it impossible to convert atomic hydrogen into a rocket fuel? Experience and theory show that, indeed, such fuel could become phenomenal due to the magnitude of its exhaust velocity and, consequently, of its specific thrust: its exhaust velocity could reach to 15,000 m/s. Whereas contemporary engines and fuels provide as exhaust velocity of 3000 m/s. Actually, here is something to think about.

But contemporary science considers it doubtful whether this idea can be practically carried out. And not, of course, because it is impossible to obtain atomic hydrogen – methods for obtaining it are known. The main difficulty is something else; it is connected with the exceptional chemical activity of hydrogen atoms and therefore the extreme instability of gaseous or liquid atomic hydrogen. In insignificant fractions of a second after the disintegration of molecules of hydrogen (yes and other gases) into atoms, these atoms are again reunited into molecules. In order to decrease the recombination rate it is necessary to greatly decrease the density of the gas – then the collisions of the atoms leading to their unification into molecules will be rare (recall the atomic gases in the upper, rarefied layers of the atmosphere). But who needs rarefied atomic gas? After all we dream about liquid atomic hydrogen, and in the liquid the interactions between atoms are very intense.

Is it impossible, however, in another way, not decreasing the density, to decrease at the same time the number of atomic collisions?

Such a way exists – for this it is necessary to greatly decrease the speed of the atoms, their mobility, i.e., consequently, to lower their temperature. And indeed, by cooling almost to absolute zero it has been possible to experimentally obtain relatively stable solid atomic hydrogen. But also it is doubtful whether this way can be successfully used, so insignificant are the quantities of the atomic substance obtained in this way, yes and, as is indicated, its specific weight is less than water, by – 50 times.

Thus, science does not as yet know a method for the prolonged preservation of atomic hydrogen, as well as other liquified atomic gases, which is necessary for their use as rocket fuels. This does not mean, however, that all investigations in this direction have ceased, no indeed, they are being conducted abroad and very in intensively; different ways are being studied, but as yet there has been no success. As can be seen, physics, which in this case is attempting to come to the aid of the chemistry of rocket fuels, has also as yet not achieved anything.

It is necessary to note that this is not the only possible way of assisting chemistry, which physics can render to it in its present situation. Thus, for example, in principle the imparting of great energy to the atoms of a substance by physical methods is possible; i.e., the energy connected with the so-called electron excitation of these atoms, i.e., the shifting of electrons from their normal orbits to orbits of an electron shell more distant from the nucleus. During the transition of the atoms from this excited state to the initial, unexcited state (i.e., in returning the electrons to their normal orbits), the energy expended can be liberated under certain conditions in the form of heat. If this occurs in the thrust chamber of the rocket engine, then the gases emanating from it can acquire colossal speed. Thus, for example, if helium will serve as such a "fuel" for the rocket engine (here this inert gas, which does not, generally enter into chemical reactions, turns out to be nearly the most ideal "fuel"), then the exhaust velocity can reach 30,000 m/s! But also these are still only ideas, in the way of the realization of which stand difficulties, which now seem to be insuperable.

We have given several examples of the unique "exotic" possibilities in the field of developing perfect rocket fuels, which chemistry has gained by itself and also in collaboration with physics. The number of such examples could be greatly increased. Science is persistently investigating such possibilities, discovering ever new things and not sparing the efforts and means on this, since it is difficult to overestimate value of any significant success in this direction. After all the discussion concerns the decisive condition of accomplishing interplanetary flights; here indeed the road is opening into the cosmos. And yet at the present this is only a quest and there is no certainty in its success. Actually rocket technology must be considered from the firmly established possibilities of the chemistry of rocket fuels, about which there was discussion above. To expect an exhaust velocity greater than 4500-4750 m/s there are no serious bases.

Thus, there appears the most important barrier in the way of developing rocket technology and cosmonautics, the "fuel" barrier, the barrier of the insufficient energy of available fuels. How science is attempting to overcome this barrier, which has been turned over to chemistry, will be related in the last three chapters of this book.

CHAPTER X

AID FROM THE ATOM

It is obvious that in the search for fuels or, more precisely, working substances (inasmuch as we have decided not to use the services of chemistry) with increased energy and productivity, science is turning its attention, primarily, to the energy of the atomic nucleus. After all, in these microscopic "storerooms" there is colossal energy, many billions of times exceeding chemical energy. If this energy could be usefully used in jet engines, i.e., convert it into the kinetic energy of the gases emanating from an engine, then the obtained exhaust velocity would be tens and hundreds of thousands of times more than is possible for the best chemical fuels.

In order to create such atomic jet engines, it is necessary to solve at least two key problems — how to free the energy in the nucleus, and then learning to convert this gigantic nuclear energy into the kinetic energy of the flow emanating from an engine. What is the status of this now?

As we know, science can already free the energy of the atomic nucleus by two methods. One of these is connected with the chain process of nuclear fission of the metal uranium or another metal, plutonium; it is realized in the explosions of atomic bombs and in so-called atomic reactors, or piles. With such a disintegration of complex nuclei into less complex, a part of the potential energy stored in the nuclei is released, mainly, in the form of kinetic energy of the newly formed nuclei, i.e., products of the fission of the initial nuclei.

This kinetic energy, in turn, very quickly, in fractions of a second, turns (as a result of the numerous collisions of fast-moving nuclei of fission with other atoms) into the energy of the disorderly, chaotic movement of all these atoms, i.e., into thermal energy, or heat. Only a comparatively small part of the nuclear energy is lost here in the form of various radioactive emissions.

In principle the same method of releasing intranuclear energy is realized during the so-called radioactive decay of nuclei, i.e., a spontaneous process, proceeding without interference from without; as a result of this process, from the unstable atomic nuclei electrons, alpha particles (the atomic nuclei of helium) and other particles escape. As a result of such decay the initial nucleus becomes simpler and lighter, and, finally, stabler; the separated intranuclear energy will be converted basically into heat. A drawback of this process of radioactive decay, from the point of view of its practical use for the separation of intranuclear energy is its complete uncontrollability — the speed of the process cannot be accelerated, slowed down, stopped or started again. The energy of radioactive decay has already found practical application, even in missile technology, for which special small "atomic batteries" with different, (most suitable for this purpose) radioactive isotopes are being created. In such "batteries" it is possible to directly transform the intranuclear energy into electrical energy, which is quite profitable. However, the power of such "atomic batteries" is usually so low that they can only be used for different auxiliary needs, for example, for feeding electrical current to the onboard equipment of a rocket or space vehicle. When high energy is needed, as occurs in the case of rocket engines, the process of radioactive decay (as a rule) cannot be used. Here only the chain process of fission is useful, with which there are practically no limitations of the amount of power.

We must stress that during the fission chain reaction of nuclei, in which the atomic "fuel" is uranium or plutonium, in all approximately one thousandth part of all of the potential energy of the atomic nucleus is released. During radioactive decay this part is considerably smaller. And yet the fission energy of nuclei is so great in comparison with chemical energy that it is sufficient to produce exhaust velocity from a rocket engine a thousand times greater than in a conventional engine. Consequently, it is a matter only of the second part of the problem — developing a method of converting the separated energy into the kinetic energy of the jet stream.

But before we can move on to this, we must clarify the possibilities of the second method of freeing the intranuclear energy; this is connected with a physical process which is diametrically opposed by its character to the first, i.e., not with the decay of complex atomic nuclei into simple nuclei, but vice versa, with a merging of the simplest nuclei into the more complex. It is exactly this so-called process of thermonuclear fusion which is the source of solar and stellar energy. It is artificially realized in a thermonuclear explosion, i.e., the explosion of a hydrogen bomb. By the amount of energy released per kilogram of nuclear fuel, the reaction of nuclear fusion exceeds the fission reaction and, consequently, its use in a jet engine would be more profitable. Thus, for example, if it were possible to create an atomic rocket engine in which intranuclear energy were used fully to create jet thrust, and this energy were released during the nuclear fusion of hydrogen atoms into an atomic nucleus of helium (so-called stellar reaction, realized in mineral resources of the sun and other stars), then the exhaust velocity would be approximately 2.5 times more than in an atomic rocket engine with a uranium reactor (considering, of course, that which emanates from the engine is the same substance, being the product of a nuclear reaction, i.e., disregarding the possible difference of properties of such a substance). This is explained by the fact that 1 kg of hydrogen nuclei, completely turning (in the course of nuclear fusion reaction) into nuclei of helium, releases approximately 7.5 times more intranuclear energy than 1 kg of completely separated uranium nuclei in the course of a nuclear chain reaction of fission.

Use in rocket engines of the reaction of thermonuclear fusion is more profitable for other reasons. In particular, it is possible to think that thermonuclear rocket engines would be connected with significantly less radioactive radiation than engines with a uranium reactor; after all, this dangerous (for those around it) radioactive radiation of the atomic engine is one of the most serious difficulties in the path of its creation and practical use. The use of thermonuclear fusion is more profitable in connection with the practically inexhaustable reserves of thermonuclear fuel in nature.

And yet the chances of the possibility of the appearance of a thermonuclear rocket engine as yet are still infinitely small. This is simply explained — up to now it has not been possible to find actual means for the realization of a controlled thermonuclear reaction, i.e., for the creation of a thermonuclear reactor, or pile, similar to the existing uranium or plutonium reactors. An uncontrolled, i.e., explosive thermonuclear reaction has been artificially carried out in a hydrogen bomb, but the separation of thermonuclear energy constantly, not by explosion, in such a manner that its value could be limited and controlled, is still not understood by scientists.

It is known that in the direction of "domesticating" thermonuclear energy, in many countries, including the USSR, steady investigations and experimental works are being conducted. The value of these efforts is understandable; after all, solving these problems would give mankind a practically unlimited source of the energy so necessary to it — the raw material for thermonuclear fuel can be ordinary water. However, scientists are still quite distant from their target. In order to support thermonuclear reaction for a prolonged period, hydrogen must be heated to a temperature of millions of degrees. Science has found a method for heating gas by transforming it into plasma, i.e., an almost completely ionized mixture of the nuclei of hydrogen (protons, deuterons and tritons — for ordinary, heavy and superheavy hydrogen) and electrons. For this the combined influence on gas of powerful electric discharges and magnetic fields is used. Here it has been possible to solve such, one would think, insolvable problems as containing million-degree plasma in a vessel without its walls instantly evaporating — this was aided by the same magnetic field, the lines of force of which create an invisible vessel woven from them, which keeps the plasma away from the walls. In the Siberian branch of the Academy of Sciences of the USSR plasma has been produced with a temperature of 100 million degrees!

There is one unsolved problem remaining, but this problem, without which there is no final solution, has turned out to be extraordinarily insidious. It consists of the need to ensure the stability of plasma, or, as the scientists say, that of the "plasma column" — that usually rectilinear or annular gas volume, in which (by a magnetic field) the plasma is held inside the vessel, far away from its walls. As it turned out, the plasma column is simply phenomenally unstable; the plasma attempts by any method to escape from this column, to slip away from the grid of magnetic power lines braiding the column, and to make a hole in this grid. For only insignificant fractions of a second does the column with its incredible temperature exist; it then disintegrates, and the plasma temperature sharply drops, so that the thermonuclear reaction cannot be carried out. If it were possible to extend the period of life of the column somewhat, even to several seconds, then it would be possible to cause a stabilized thermonuclear reaction and the problem would finally be solved. But up to now this has not been done.

Certainly a controlled thermonuclear reaction will be carried out; there cannot be any doubt of it. Then thermonuclear jet engines will be created. But for now scientists sketch only the possible schematic diagrams of such engines, readying themselves for that cherished day when their creation will be real. Therefore, being limited to the existing possibilities, it will be necessary to recognize that the only type of atomic jet engine which can now be created is an engine which is based on the use of a uranium or plutonium atomic reactor of any type as the source of thermal energy.

However, the same nuclear reaction of the decay of complex atomic nuclei, which is the basis of the uranium reactor, could have been tried in a jet engine. Here are possible, or, more precisely, are proposed, two other alternative solutions.

One of them is the idea of using a conventional atomic bomb in rocket technology.

A thermonuclear bomb does not fit here; the bomb should possess low power, and the force of its explosion (for example, like the "Orion" project, developed in the United States) does not have to exceed approximately 1000 t (i.e., equivalent to the explosion of one thousand tons of trotyl). If one were to detonate similar bombs one after the other, at certain intervals behind a spaceship which is protected from the direct action of these explosions by a strong steel plate, then the force of the explosion will push the plate and, together with it, the whole ship, driving it to a great cosmic velocity. Suppose this project could be carried out, and this in principle is fully possible; then this would be one of the few fully applicable forms of peaceful use of the force of a nuclear explosion. It is necessary to say, however, that such a method of movement in space can be applicable and, all the more so, profitable only in very rare cases, and it cannot compete with atomic jet engines.

The other alternative to the rocket atomic reactor in principle is immeasurable more attractive, although, as we will see below, it also can be used quite rarely. The attractiveness of this alternative solution is due to the fact that it manages without the conversion of intranuclear energy into heat, which is obligatory for any existing atomic reactor. This means that an attempt is being made of direct transition of intranuclear energy into the kinetic energy of the jetstream. The benefits here are evident: besides the fact that each conversion of energy is connected with its losses, the use of thermal energy, i.e., its conversion into mechanical energy is always connected with great difficulties.

How can one imagine the direct transition of intranuclear energy into the kinetic energy of a jetstream? For this it is necessary to remember the fact that we spoke above about the direct manifestation of intranuclear energy after its release — it is found basically in the products of nuclear fission and constitutes their kinetic energy. Actually, the fragments of the uranium nucleus,

Fig. 69. An interplanetary ship, movable by the force of atomic explosions. Weight of the ship is 75,000 t, the force of each of a thousand atomic explosions is 1000 t of TNT (drawing from the United States).

formed after fission, rush in the mass of remaining uranium atoms at great, supercosmic velocity (15-20 thousand kilometers per hour). True, on a very short route for the considered instants they are braked and their motion is delayed as a result of the collisions with the atoms — the kinetic energy of the fragments is lost and is imparted to all of the atoms in the form of heat.

But is it impossible to try to avoid this deceleration, and instead of it "organize" the chaotic motion of the fragments of the nuclear fission in such a manner that they moved "friendly," in one direction common for them all? After all, then the goal would be attained and there would be an atomic rocket engine, since the fragments moving in one direction would form a jetstream with an exhaust velocity of up to 20,000 m/s. And why can't this be done? After all, is it possible in the jet nozzle of a conventional rocket engine to organize the previously chaotic thermal motion of gas molecules? Now, instead of molecules, there will be atomic nuclei...

In general, the devices necessary for this purpose probably can be created, although they don't yet exist, and they will be quite dissimilar to conventional jet nozzles. After all, the products of nuclear fission are charged particles, and for controlling their motion, obviously, electrical and magnetic fields will be needed, and not the limiting hard surfaces like the walls of a nozzle. It is obvious that in this case nuclear fission need not occur in a solid medium, because then along the way (by length) into microns the rapidly rushing nuclei-fission products will lose their speed. Here gas is more appropriate, and even better — rarefied gas.

But the main obstacle in the way of creating an atomic rocket engine is not this at all. Let us imagine that such an engine has been created and that in it every second there "burns," i.e., is fissioned, a considerable mass of nuclear fuel — uranium or plutonium. If we desire that the engine develop a great thrust of hundreds of tons, like contemporary powerful rocket engines, then the per second amount of expended fissionable material should be, indeed, considerable — on the order of hundreds of kilograms. This means that in the engine every second there will be released a vast amount of intranuclear energy — after all, 1 kg of uranium is equivalent (with respect to energy production) to approximately 1700 t of aviation gasoline. Engine power will equal tens of millions of kilowatts, like several gigantic hydroelectric power plants taken together. It is easy to see that the working substance in such an engine and its walls will be subjected to such a huge amount of heat that the engine will evaporate instantly, but drawing off this heat and cooling the engine will be practically impossible. This is why such an atomic rocket engine is often called a pseudorocket, stressing thereby its unreality and the impossibility of its creation.

Nonetheless, the pseudorocket engine, despite its frightening, nihilistic name, can be and probably will be created. But only, obviously, such an engine should develop extremely low thrust, the amount of which will be limited by the engine power which is the highest possible from considerations of its thermal load. Here, for the first time we encountered the problem of the interconnection of engine thrust and power, which leads to the limitation of the amount of thrust. In greater detail, this especially important problem (for the entire future of jet engineering)will be examined in the following chapter, which is devoted to the jet engines utilized in the conquest of space, since for exactly these engines this problem becomes especially acute. There we shall discuss the possible fields of application of both pseudorocket and other rocket engines of extremely low thrust.

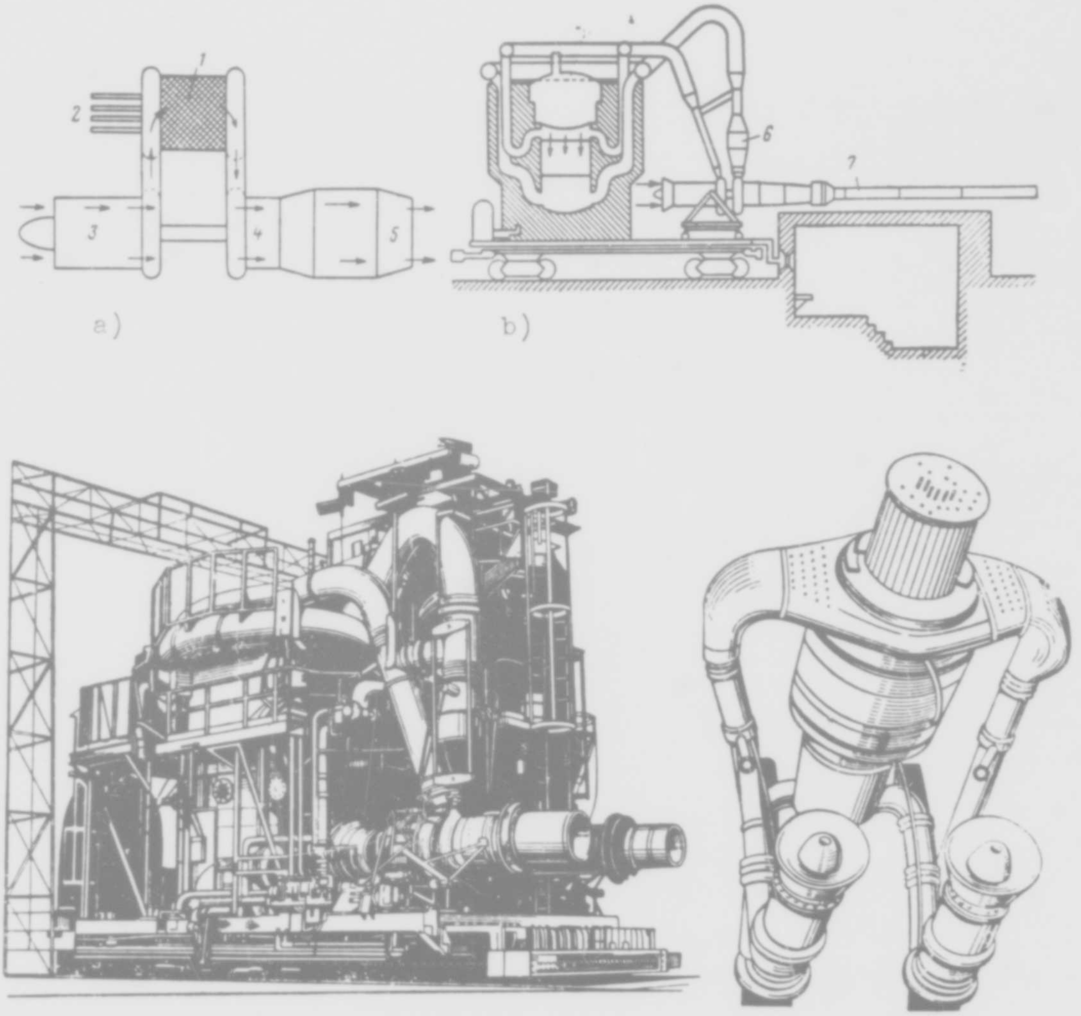
Thus we have clarified that essentially the only type of atomic jet engine which can be created at present should be based on the application of an atomic uranium or plutonium reactor. Obviously, the heat which is freed in such a reactor should be used for heating some working substance, the exhaust of which from the engine will create jet thrust.

In at least one case the character of such working substance is predetermined beforehand — in the air jet atomic engine it is, obviously, atmospheric air. Two cases are possible — either atmospheric air directly flows through the channels of the atomic reactor, cooling it and being heated (so-called direct cycle), or cooling of the reactor is carried out with the help of an intermediate heat-transfer agent, liquid or gaseous (for example, molten metal or helium), and this heat-transfer agent in a special heat exchanger transmits heat obtained by it in the reactor to the working substance — atmospheric air (indirect cycle).

Judging by materials of the foreign press, abroad there is being conducted work on atomic aviation jet engines of both diagrams, where there are being developed both atomic turbojet and atomic ramjet engines.

In the atomic turbojet engine developed in the United States by General Electric for aircraft, direct cycle is used. In tests of this propulsion system there were used two ordinary turbojet engines J47, and also an experimental atomic reactor in which there was carried out preheating of working air of the turbojet engines. Thus, the place of the combustion chamber of the engine "conveyer" in this case is occupied by the atomic reactor itself.

Another American firm, Pratt Whitney, is developing an indirect cycle atomic turbojet engine. In this engine there are used two closed circulation loops, in which intermediate heat-transfer agent — melted metal (for example, alloy of sodium and potassium) circulates. The metallic heat-transfer agent of the primary contour removes heat from the atomic reactor and transmits it in the intermediate heat exchanger to the metallic heat-transfer agent of the secondary circuit. In turn, this secondary heat-transfer agent transmits heat obtained in the heat exchanger replacing the combustion chamber of the engine to its working air. The firm intends to change to a simpler engine diagram with one circulation loop for intermediate heat-transfer agent.



a) b)

c) d)

Fig. 70. Direct cycle atomic turbojet engine (General Electric, the United States): a) diagram of engine; b) diagram of testing; c) appearance of testing unit with experimental atomic reactor and two J47 turbojet engines; d) reactor with engines, 1 — reactor; 2 — control rods; 3 — compressor; 4 — turbine; 5 — nozzle; 6 — combustion chamber; 7 — exhaust pipe.

An atomic ramjet engine is being developed in the United States in the "Pluto" project. The engine consists of an intake diffuser, an atomic reactor for heating of air (replaces combustion chamber) and a jet nozzle. The atomic reactor for this engine was named the "Tory." An experimental model of the reactor subjected to tests

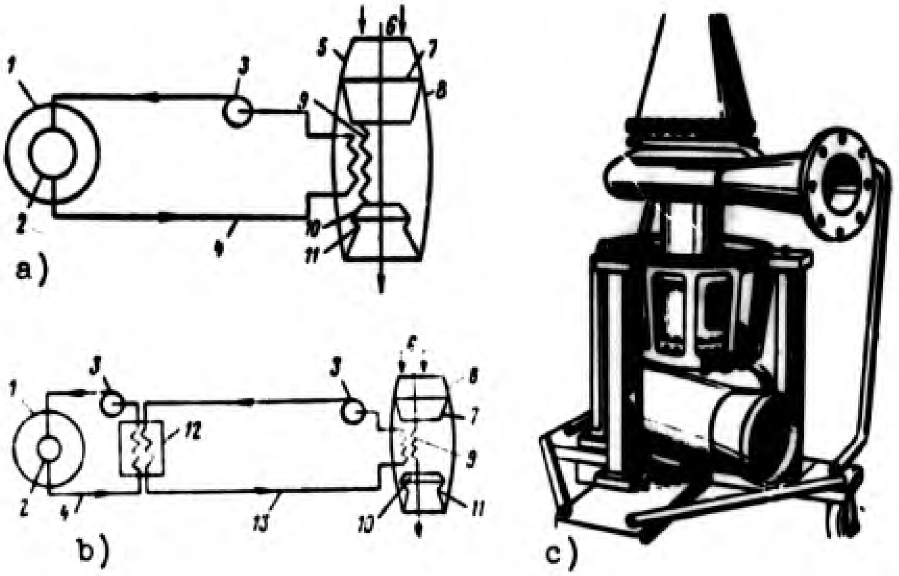


Fig. 71. Indirect cycle atomic turbojet engine (Pratt Whitney, the United States): a) perspective diagram of an engine with one circulation loop for liquid metal; b) diagram of engine with two circulation loops for liquid metal; c) turbopump assembly for liquid metal. From above there is located a pneumatic turbine for driving the pump shown from below. The total length of the aggregate is approximately 1.2 m. 1 – shielding; 2 – active zone of reactor; 3 – turbopump; 4 – contour of liquid metal; 5 – diffuser; 6 – air; 7 – compressor; 8 – atomic turbojet engine; 9 – radiator (heat exchanger); 10 – turbine; 11 – nozzle; 12 – intermediate heat exchanger; 13 – secondary contour of liquid metal.

("Tory IIA") has a thermal power of 155 MW and 315 kgf/s of air, which is heated to 1080°C in the reactor flows through it. The diameter of the active zone of the reactor, containing about 100,000 ceramic fuel elements with nuclear fuel, is equal to 810 mm and its length is 1210 mm. The natural reactor for the atomic ramjet engine "Tory IIC" is being tested. As is shown, the thrust of the "Pluto" is 2250-4500 kgf. The engine is intended for unmanned aircraft traveling at three times the speed of sound able to fly continuously at this speed approximately 3 days.

The fundamental advantages of atomic aviation jet engines over ordinary jets are quite evident. Inasmuch as an atomic jet aircraft expends insignificantly little nuclear fuel in flight, the duration of such a flight is practically without limit. And the most essential thing is that this flight can take place at high supersonic speed, which is absolutely beyond the capabilities of ordinary jet aviation. After all the higher the speed at which the aircraft flies, the more powerful its engine has to be and consequently, the more fuel is expended every second. Therefore supersonic flight is limited to a short time, even in record-breaking cases – approximately two hours. If the flight of the usual jet aircraft is to be prolonged, then it is inevitably carried out at relatively low speed.

The atomic jet aircraft is another matter. The high power of the atomic turbojet or ramjet engine is not conjugate with high fuel consumption, and in this case supersonic flight can last for an arbitrarily long time. Furthermore, naturally, atomic engines do not need air for their work, air serves in this case only as a rejected working substance, in consequence of which there are eliminated many problems and difficulties of high-altitude flight of ordinary jet aircraft, in particular, for example, those connected with unreliability of combustion in rarefied air.

The potential possibilities of application of atomic airbreathing-jet engines in aviation are evident. If such engines are not yet in use, it is not because they are not being worked on but because of serious technical difficulties which have arisen.

First of all in this connection one should mention a problem which never appears in the usual "chemical" engine and is complex when the discussion concerns atomic engines – the problem of radioactive radiation of the working atomic reactor. This radiation, both electromagnetic (gamma rays, rigid X-rays) and corpuscular (protons, neutrons, electrons, and others), is extraordinarily dangerous for people and all life. Disease processes caused by it in the organism are given the general name "radiation sickness." It is not only extraordinarily dangerous, inasmuch as it is connected with striking a number of vitally important organs, but frequently ends with the destruction of the sick organism. Not less dangerous is the fact that the consequences of radiation sickness frequently have an effect on the posterity of the sick organism, even in several generations.

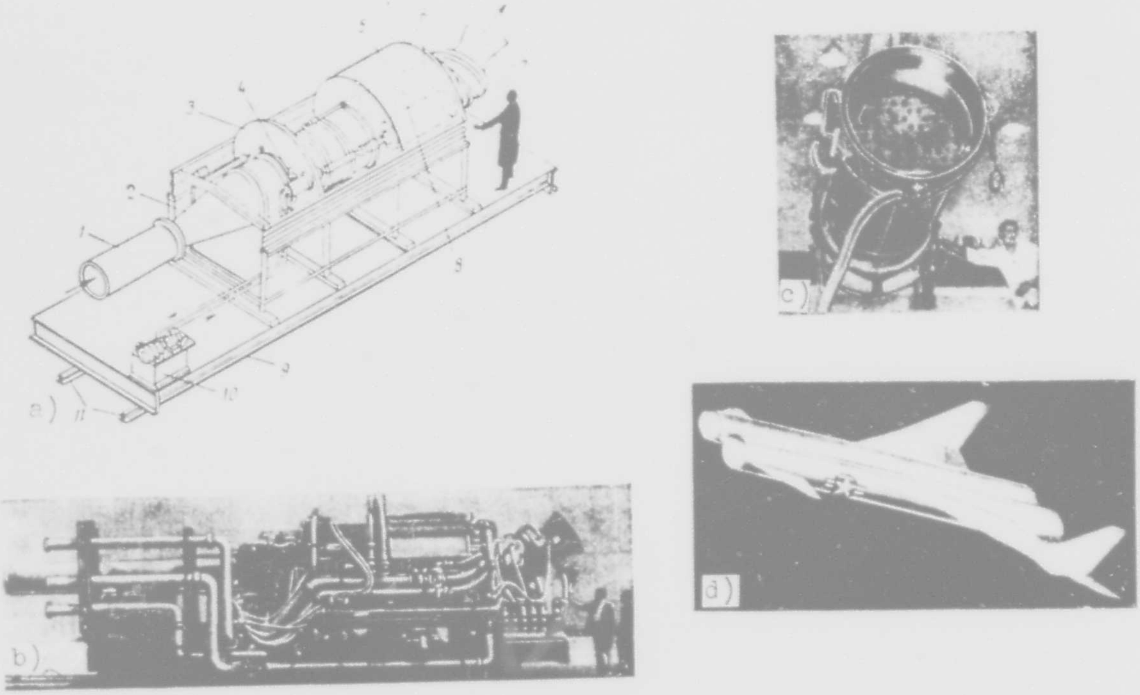


Fig. 72. Atomic ramjet engine: a) diagram of experimental atomic reactor "ToryIIA," developed for experiments in the "Pluto" program; b) appearance of the reactor of the "Tory IIA"; c) active zone of reactor; d) figure of supersonic bomber with atomic ramjet engines (the United States). 1 — air inlet; 2 — diffuser; 3 — protective screen; 4 — hydraulic drive for regulating cylinder; 5 — rod of exact adjustment; 6 — regulating cylinder; 7 — nozzle; 8 — active zone of reactor, where heating of air takes place; 9 — platform for installation of engine; 10 — hydraulic pump; 11 — track.

The human organism has no organ with which it can sense the influence of dangerous radiation; it has an effect only after some time. Another very unpleasant biological peculiarity of radioactive radiation is its cumulative effect, i.e., accumulation during a certain time of invisible results of radiation until they appear already in strong form. These peculiarities require reliable shielding of man from radioactive radiation of the atomic reactor. In stationary installations, at atomic electric power stations or in research laboratories and also on the atomic vessel "Lenin" or atomic submarines, people servicing reactors are protected by a powerful shielding shell, inside which is the reactor. It is obvious that

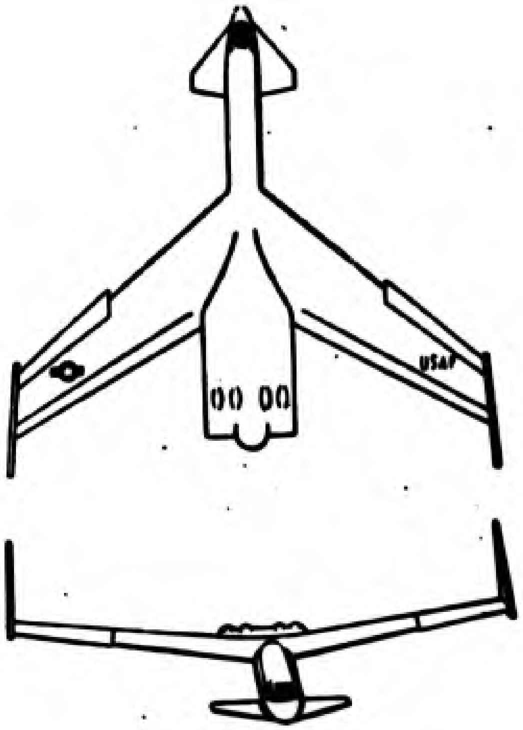


Fig. 73. The atomic aircraft developed in the United States by Convair will have the diagram of a canard so that the crew are as far as possible (more than 30 m) from the engines. The aircraft (its model is shown on the figure) will be subsonic, its takeoff weight will exceed 200 t, and the first flight is planned for 1965.

such heavy shielding cannot be used on aircraft; the aircraft simply will not lift it. But even the minimum necessary protective biological shielding is very heavy; it weighs tens of tons, in consequence of which atomic aircraft have to possess very high takeoff weight. In a word you will create neither atomic fighter nor light atomic airplane; however, they are not needed.

But the need for a massive protective shell-shielding is not all that matters. It is extraordinarily important that in case of an aircraft accident or a forced landing radioactive products can "escape" from the protective cage in which they were enclosed. This will be very dangerous for all nearby. Development of means of decreasing such danger is obviously a very complex problem. The same goes for such engine maintenance as replacement of nuclear fuel which has been working some time (unfortunately, it is impossible to use up to full "burning out," since it is "contaminated" by products of nuclear fission, in consequence of which the fission chain reaction is delayed, and then stops all together). As can be seen, radioactive radiation is the main obstacle, truly the Rubicon on the way to creation of an atomic jet engine for aircraft.

There are many other obstacles. Thus, for example, the dimensions of an atomic reactor have to be small, although its power must be considerable. This creates a number of design problems and, in particular, the problem of transmission of large quantities of heat through relatively small surfaces of the reactor. To solve such a problem it is necessary to increase temperature gradient on surfaces of heat transfer, i.e., increase the operating temperature of the reactor. This is all the more important since the air cooling the reactor (and all the more so the intermediate heat-transfer agent) should have sufficiently high temperature; otherwise, engine thrust will be small. Therefore, reactors of aviation atomic jet engines have to be, so to speak, high-temperature reactors, which essentially complicates their design as compared to ordinary existing reactors.

It will probably not be long before the first atomic aircraft takes off. In the United States flight has already been accomplished by aircraft with an experimental atomic reactor on board, and turbojet and ramjet engines have already worked without combustion chamber; it was replaced — directly or with the help of a heat exchanger — by an atomic reactor.

And how is it with atomic rocket engines?

Here the advantage of an atomic engine over ordinary "chemical" rocket engines is not so obvious. After all if airbreathing-jet engines scoop their working substance from the atmosphere, rocket engines expend from reserves on board the aircraft. Therefore, regardless of what rocket engine is set on the aircraft — chemical or atomic — all the same working substance should be on board. The fact that in one case this substance is, at the same time, fuel, i.e., the source of energy, and in other it is not, does not fundamentally change things — atomic energy makes it unnecessary to have chemical fuel on board, but cannot make it unnecessary to have working substance on board.

It is true that the quantity of working substance on board the aircraft, which, when it comes right down to it, is decisive, will be the same only if exit velocity is the same (the weight of the engine itself will not yet be considered). In this respect cannot an atomic engine be better than a chemical one?

In order to answer this question, it is necessary to remember that exit velocity depends on two values – temperature of gases emanating from the engine and their molecular weight. As indicated above in the preceding chapter, exit velocity is proportional to the square root of the ratio of these two quantities. Therefore, to increase exit velocity it is necessary as much as possible to increase the temperature of the gases and decrease their molecular weight.

And here is the first and, probably, the most essential advantage of the atomic rocket engine over ordinary chemical ones. If temperature and molecular weight of gases of chemical engines are mutually connected, since gases are products of combustion of any fuel with a given energy productivity (and everything depends on it), in the atomic engine there is no such interconnection. This makes possible heating various working substances to an assigned temperature in an atomic reactor and, thus, selecting the most advantageous, i.e., the one possessing minimum molecular weight. However, we already know such a substance; it is, of course, hydrogen. If in a chemical hydrogen-oxygen engine the products of combustion of hydrogen, i.e., water vapors, have molecular weight 18, then in the outflow from an atomic engine, the molecular weight of the hydrogen itself will be equal to 2. Since molecular weight in our example was 9 times less, then, consequently, at the same temperature of emanating stream exit velocity will be increased $\sqrt{9}$ or 3 times. Huge progress!

Besides hydrogen there are a number of other substances with molecular weight less than that of water, so that the range of possible working substances for the atomic rocket engine which can be selected turns out to be sufficiently great. But, as we now see, the possibility of heating working substance in an atomic engine is in much worse straits.

Actually, so that the atomic rocket engine will exceed the usual chemical one in this respect it is necessary to heat gases in it to a temperature higher than 3000-3500°C since such is the temperature of products of combustion of a number of fuels used in contemporary liquid-propellant rocket engines. But this means that the surfaces of the atomic reactor, which are cooled by the working substance and heat it themselves have to be still hotter. If there is an intermediate heat-transfer agent heating the working substance in the heat exchanger, as was mentioned above with respect to jet atomic engines, then, obviously, exothermic surfaces of the actual reactor have to have still higher temperature. But fissionable materials which remain solid at such temperatures does not exist in nature. The most refractory of materials — uranium carbide — melts at a temperature of 2450°C. Consequently, the working substance of an atomic rocket engine, let us say hydrogen, can be heated in it to a temperature of not more than 2000°C, i.e., essentially less than in the usual rocket engine. But then exit velocity will fall accordingly, approximately 30%. As a result of joint change of temperature and molecular weight, exit velocity from an atomic rocket engine will be approximately 2-2.5 times as large as that of the usual chemical rocket engine. This is the advantage which application of an atomic reactor instead of the combustion chamber of an ordinary rocket engine can give.

It must not be forgotten, however, that this is gained at the price of considerable increase in engine weight and dimensions. Instead of a light and small dimension "chemical" engine on the rocket it will be necessary to set a bulky and heavy engine with an atomic reactor. Things will be especially bad if reliable shielding is necessary, i.e., if there are people on the rocket. It is obvious that this additional weight worsens the indices of the atomic rocket engine.

However, the superiority of the atomic rocket engine with respect to exit velocity is so essential that it makes it understandable why efforts to create such an engine are being made abroad, in the United States. There these works are being fulfilled in program "Rover" and with them scientists of the United States have high hopes of realizing various space flights. For the rocket engine "Nerva" weighing 5 t there is being developed the atomic reactor "Kiwi," the active zone of which consists of graphite plates with uranium carbide. The working substance of the engine is hydrogen. Reactors of the "Kiwi" type were tested at a special installation, starting from 1959. The reactor is approximately cylindrical in form with a diameter and altitude of about 1.5 m. The thermal power of the reactor is 200-1000 MW, and engine thrust is up to 22 t. The other reactor for the same engine is the NRX, the first "hot" tests of which were conducted in September, 1964. For a new modification of the engine "Nerva II" there is being created the reactor "Feb," etc.

Forced work on creation of an atomic rocket engine in the "Rover" program (with a solid active zone) does not mean, of course, that this type of engine is possible. Thus, for example, with the use of an atomic reactor in which fissionable nuclear "fuel" was not in the solid state, the limitation with respect to maximum temperature of working substance could be dropped, and exit velocity, accordingly, could again increase. It is possible to imagine, in particular, such a reactor, in which a nuclear reaction occurs in liquid or gaseous "fuel" mixed with working substance. It is clear that in this case the temperature of the working substance could be considerably higher. However, it is far from easy to create such a reactor. First of all, it would be necessary to see that the nuclear fuel did not emanate together with the working substance through the nozzle of the engine, otherwise, the expenditure of nuclear fuel would be excessively high, and the jetstream mortally dangerous due to its radioactivity. For this it is possible to use, for example, a gas vortex created in the reactor. In such a vortex the lighter hydrogen will be concentrated in the center – along the axis – and emanate through the nozzle, and the heavier uranium molecules will be along the periphery of the vortex and will not emanate. But this is not the only difficulty; it turns out that such a gas-cooled reactor should possess excessively large dimensions (the minimum, or so-called critical mass of nuclear fuel necessary

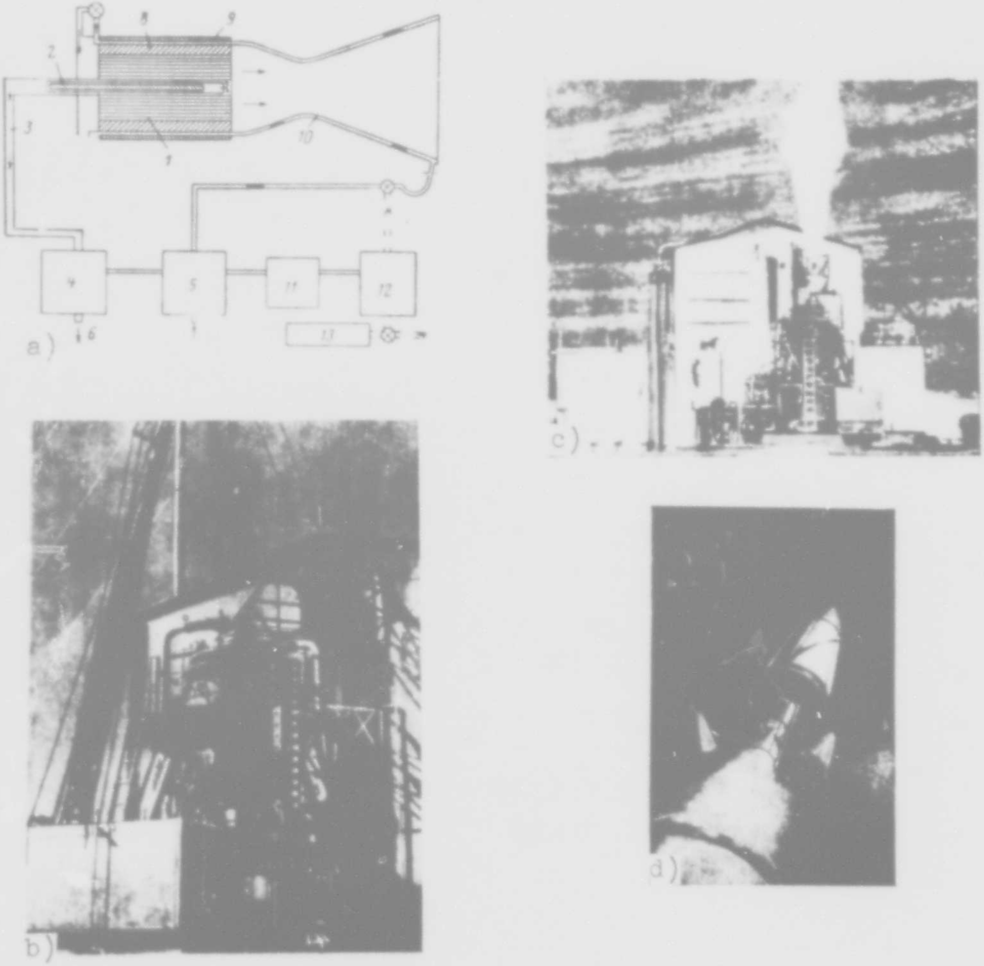


Fig. 74. Atomic rocket engine. a) diagram of engine with solid active zone of reactor ("Kiwi" type); b) "Kiwi" atomic reactor for "Rover" atomic rocket engine (the United States; c) test of "Kiwi" reactor; d) atomic rocket in flight (figure). 1 — active zone of reactor; 2 — control rod; 3 — gas in turbine; 4 — turbine; 5 — pump; 6 — exhaust from turbine; 7 — fuel feed; 8 — reflector; 9 — body; 10 — cooling jacket; 11 — auxiliary drive engine; 12 — auxiliary pump for refrigerant; 13 — battery.

for realization of the chain process of fission in the case of gas acquires great volume). For a rocket such dimensions turn out to be clearly unfit, although it is possible to decrease them in a number of ways.

There are other ideas on creating an atomic rocket engine in which the temperature of the working substance could be lifted

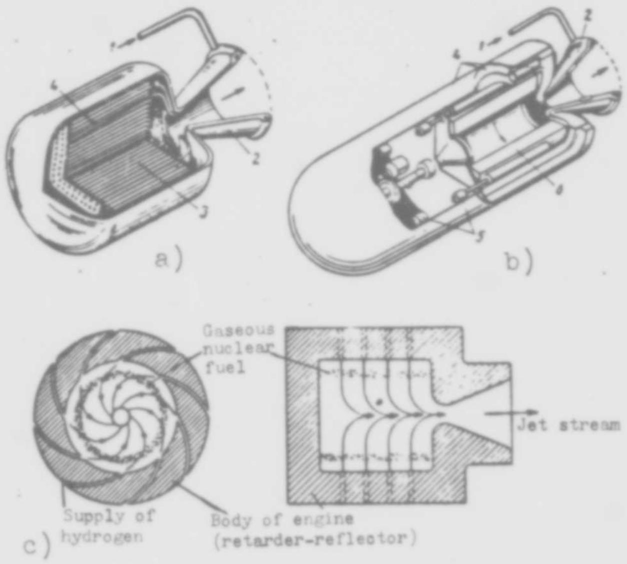


Fig. 75. Diagrams of atomic rocket engines: a) engine with solid active zone of atomic reactor (graphite-uranium); b) engine with liquid active zone of atomic reactor or so-called fluidized bed (melted carbide of uranium is held on the walls of the container as a result of its rotation under the influence of centrifugar force); c) engine with vortex gas-cooled reactor (in the engine there is created a gaseous active zone — a stabilized gas vortex of uranium and hydrogen). 1 — supply of fuel; 2 — nozzle; 3 — active zone of reactor; 4 — circulating fuel; 5 — control rods; 6 — rotating liquid.

considerably higher than in a "Rover" type reactor. And although all of them are still very far from realization, it is doubtful whether we will err if we express confidence that in the future such engines will be created and will find wide application.

However, help given to jet engineering by atomic energy is by far not limited to creation of the atomic jet and rocket engines described above. There is one more important region of jet engineering, one more large group of rocket engines, sharply needing help from the atom. These engines are so unusual, so unlike those existing at present, and in general, they are all well-known to us, and, at the same time, they are so promising and so important for all future jet engineering that the whole next chapter deserves to be dedicated to them.

CHAPTER XI

JET ENGINES IN SPACE

The engines which were spoken of at the end of the preceding chapter are intended for use in outer space.

Space flight is so different from those flights, on which aircraft engines had been used till now that naturally the question arises concerning the expediency and even necessity for the creation of special engines. Such engines, while they still do not exist, are being developed intensively, and indeed are just as dissimilar to their "terrestrial" colleagues as the earth, surrounded by its atmosphere, is to the gloomy vacuum of space.

Certainly the distinction of conditions of space flight from flight in the atmosphere does not amount to the color of the sky and the number of stars in it. The main differences are probably two: absence of atmosphere as a medium which exerts a drag on flight, and achievement of speeds of flight which exceed orbital velocity, i.e., which make it possible to overcome the gravitational field of earth without the help of specially created lift. It is easy to see that the second of these two peculiarities is also a result of the first, i.e., a result of absence of drag in the medium in which the flight is carried out. Thus, it is namely the vacuum of outer space which is the fundamental principle of the chief characteristics of space flight.

How will these peculiarities influence the performance of engines for space aircraft and their construction?

First of all, it becomes clear that under these conditions there is no need for the collossal thrusts which are so characteristic, as we saw, for standard contemporary jet engines. Actually, if one were to talk about aircraft, then their engines have to develop huge thrust for overcoming the drag of an aircraft which is flying in a dense atmosphere. The greater the speed of such flight, the more thrust necessary, and it increases much faster than the actual speed. If, however, we are considering rockets, then their engines should ordinarily possess still greater thrust, so that a multiton rocket is able to overcome the force of terrestrial gravitation and in a short time (the shorter the better, since this decreases the expenditure of fuel for acceleration) attain the tremendous speed required.

Under conditions when the medium which exerts drag is absent and space speed is already attained, thus making it possible to preserve a constant altitude of flight with the engine turned off (in orbital flight), even the most microscopic thrust applied to a massive spaceship will change the law of its motion – it will accelerate it or slow it down. It is true that this acceleration or deceleration of the ship will be insignificantly small, but it nevertheless will be. If even such a small force acts for a sufficiently long time, then the change of speed, and consequently also the trajectory of the ship, will be fully visible, significant, and, if desired, even very considerable, which is necessary for realization of any conceivable interplanetary flight.

So looms the main, principle distinction between engines for space flight[1] and those already known to us – their thrust can be

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[1] Certainly the standard rocket engines on contemporary space rockets are also space engines – with their help much has already been done and still more will be attained in the attack on space. Here the discussion concerns such space engines of the future which will ensure flight in its basic section, i.e., between the orbits of planet after the 1st space speed is attained.

very small, but then they have to be in state to develop it over long intervals of time – many days, weeks and even months on end.

Compare the characteristics of these engines and rocket engines, used at present for the attack on space: the first develop thrust in fractions of a kilogram, the second – in hundreds of tons, the first work hundreds of hours on end, and the second – for calculated minutes. Is it not clear that the first can never be like the second?

In particular, incidently, new conditions can make it possible to consider the use of an atomic engine, called pseudorocket in the preceding chapter. But, of course, this will concern only quite rare cases, since usually even under these conditions insignificant thrust of such an engine turns out to be nevertheless excessively small, as a consequence of which the periods for acceleration of the ship are excessively great. Another matter are space rocket engines of a special type, about which we will speak in greater detail below, since it is to them to which the present chapter is devoted.

But before switching to the story about these engines, one question which very naturally appears should be answered. Actually, if under conditions of space flight small thrusts of the engine are possible during its prolonged operation, and this is not like the conditions of operation of standard jet engines, then why is it impossible to adjust these standard engines to the new conditions?

After all if one were to produce, for example, a liquid-propellant rocket engine which is specially designed for work with low thrust, then it probably will be able to function for many hours on end. Actually similar examples already exist. Several unstressed rocket engines of low thrust have already functioned very long. Such engines are used, in particular, in systems of flight control and orientation in space of rockets and spaceships.

Indeed similar rocket engines can be produced and they will develop low thrust for hundreds of hours. But what is the price? In order to ensure such high reliability, the engines should be namely unstressed, i.e., first of all the temperature of gases in their combustion chamber should be lowered. However, as we know, decrease of temperature of gases signifies deceleration of exhaust velocity.

Meanwhile, it is well-known that the main deficiency of contemporary rocket engines, preventing the further development of rocket technology and, especially, cosmonautics, is exactly the insufficiently high exhaust velocity. And even this insufficient velocity has to be decreased further. Certainly this in no way can be called progress.

At the same time those engines of the new type, which we will be speaking of below and which also are able to work continuously for a prolonged time while developing little thrust, are characterized not only by a decreased, but a very significantly increased exhaust velocity. Here is the main merit of these engines – for them decreased thrust, which is possible under conditions of space flight, is not an end in itself, but a means for a considerable increase of exhaust velocity. Therefore, to precisely such engines belongs the future in the area of space flights. After all we already know that only an increase of exhaust velocity permits a decrease in the necessary reserve of fuel on rocket, inasmuch as here fuel consumption is reduced per 1 kilogram (force) of thrust, developed by the engine. Consequently, only an increase of exhaust velocity permits an increase of payload of a spaceship, and very frequently only such a method of increasing exhaust velocity opens up the possibility for realization of any complex space flight.

However, how is it possible to essentially increase exhaust velocity, if we know that neither chemistry nor atomic energy are able to ensure this?

The fundamental path for the solution of this problem is obvious and also already known to us. Inasmuch as chemical energy, included in the working substance of the engine, is insufficient for imparting a high movement velocity to this substance, then obviously it is necessary to divide the source of energy and working substance. If the supply of energy to the working substance is from without, then it is obvious that this opens the possibility, let us assume at least fundamental, to considerably increase the amount of energy supplied. In any case it becomes clear that potential chemical energy of a working substance is no longer a natural limitation of energy supply. This means the main matter is to separate the source of energy from the working substance, which thus begins to play only one role — namely the role of the working substance and not of the fuel, serving, apart from this, as the source of energy for the acceleration of inherent products of combustion.

In the preceding chapter we already spoke of one such method for separation of the source of energy from the working substance, namely about atomic rocket engines. As we know, even with the help of these engines, in spite of their organically inherent limitation on the temperature of heating of working substance, the exhaust velocity can be increased by 2-2.5 times. Are there no other methods for a more successful solution of this problem?

Such methods exist, and even not in single numbers. All of them are based on the use of the wonderful power of electricity. That is why rocket engines founded on similar methods are usually called electrical. It is exactly electrical rocket engines which have a future in cosmonautics.

But before talking about electrical rocket engines, we have to have a distinct concept of why these engines are inevitably characterized by little thrust. While conventional chemical rocket engines can have as much or as little thrust as desired, electric motors with as much thrust as contemporary powerful rocket engines cannot be. Why?

Here we again return to a problem which was already touched on once above in connection with the pseudorocket (and still earlier — in connection with the turbojet engine). This is the problem of the connection between exhaust velocity and power of the engine. Now we will gain somewhat more detailed knowledge of this interconnection which is very essential for an understanding of the actual essence of work of jet engines.

We know that the thrust which is developed by a rocket engine is nothing else but the momentum of the jet stream of gases emanating from the engine, i.e., product of mass flow per second of gases by the speed of their escape. And the power of the engine is equal to the per second kinetic energy of the jet stream, i.e., the intermediate product of mass flow per second by the square of exhaust velocity. Consequently, the power of the engine is the intermediate product of thrust by exhaust velocity.

Incidentally, very frequently in popular scientific literature about rocket engines they speak of their power as the product of thrust by speed of flight. As can be seen, this expression for power is not similar at all to that mentioned above. After all only in one absolutely special case is the speed of flight of a rocket equal to half of the exhaust velocity (here both values of power, as is easy to note, coincide). Which of them is true?

Solely true is the expression given in the text, according to which power is the kinetic energy of mass of gases, emanating from the engine in a second. In fact it is precisely into kinetic energy of gases that the chemical energy of fuel, burning in any rocket engine, is converted. This is true of any other energy which is imparted to the working substance inside the engine. If the engine possesses ideal perfection and there are no losses of energy in it (this, of course, is impossible), then expended, or supplied, energy is accurately equal to effective power, i.e., kinetic energy of the jet stream. In reality, of course, kinetic energy of the stream will always be less than this ultimately possible, which is determined by the value of the efficiency factor of the engine.

But after all the product of thrust of the engine by speed of flight of the rocket also constitutes power, moreover effective power exactly, since after all this is the product of force which is accomplishing work on a path which has passed in the direction of action of force. Actually, if an engine is operating and developing thrust, but otherwise remains fixed, as during a bench test or during launching of a rocket for example (until it separated from the launching pad), then the engine does not accomplish any effective work: there is force but the path is equal to zero. At that same time the power of the engine, determined by kinetic energy of the jet stream, naturally does not equal zero — after all gases are emanating from the engine.

It is obvious that the power of the engine, the value of which does not depend on the speed of flight, can be expended in various ways on the accomplishment of useful, or tractive, work in the advance of the rocket. When the rocket is stationary, then all the power of the engine is expended uselessly — on heating up ambient air. However, it is useless only in the case when the engine is mounted specifically on a rocket or some other aircraft. But now we know cases of quite another use of jet engines, when the jet stream created by them does not serve to create motion, i.e., not as a propelling agent. Thus, for example, there is great promise in the use of thermodrills. These are used for drilling wells with the help of a supersonic stream of heated gases and for all practical purposes, constitute liquid-propellant rocket engines. Here in these cases the stream accomplishes effective work, although the thermodrill itself never shifts.

But we will return to rocket engines. The greater the speed of flight of the rocket, the greater (at constant thrust) the effective work accomplished by the engine. Finally, at a speed of flight equal to half the exhaust velocity, useful or tractive power turns out to be exactly equal to the power of the engine. And what will occur with a further increase in speed of flight? Tractive (useful) power still increases and will become greater than the power of the engine. Consequently, effective work will turn out to be greater than expended energy! This looks like a direct violation of the law of conservation of energy.

But in reality, of course, there is no contradiction in this apparent paradox. The whole point is that useful or tractive power essentially constitutes work, not accomplished by the engine, but by the flying rocket; this is the power of the rocket. Therefore, expended energy is not only the chemical energy of fuel which is burned in the engine, but also that kinetic energy of fuel which it possesses and which is on board the speeding rocket. Of course this kinetic energy of fuel was obtained as a result of acceleration of the rocket, i.e., at the expense of chemical energy of those portions of fuel which were burned before this. But the fuel which is burning in every given second possesses two forms of energy – chemical and kinetic. And this whole reserve of energy it expends when the products of its combustion flow out of the engine. This is why tractive power at high speeds of flight (greater than half the exhaust velocity) can turn out to be greater than the power of the engine into which only chemical energy of fuel passes. We know a case when all the energy of the stream of gases converts into effective work, i.e., both the expended chemical energy of fuel and its kinetic energy – this is the case of flight with speed equal to exhaust velocity. Actually, in this unique case gases, emanating at high speed from the engine, do not possess any speed relative to the ground, they turn out to be static and, consequently, expend their whole reserve of energy (not considering, naturally, the internal thermal energy of hot gases, which they possess because not all the chemical energy of fuel will be converted in an engine into kinetic energy of gases, i.e., due to imperfection of the engine). In this unique case effective work of the rocket, or its tractive power, is composed of two equal values – power of the engine which is equal to the kinetic energy of the jet stream, and kinetic energy of the fuel.

We dwelled in such detail on this quite delicate question not only because it is usually not expounded quite truely by authors of many popular science books and articles, but also in connection with the importance of correct presentations about energy ratios of rocket flight. Without such presentations it is impossible to understand thoroughly the physics of this flight.

Thus, we came to an important conclusion – the power of a rocket engine is numerically equal to the product of tractive force by exhaust velocity, divided in half. Consequently, the same power can be obtained during great thrust and small exhaust velocity (in this case the mass of emanating gases will be large), or with little thrust and high exhaust velocity. We will see now what important consequences this interdependence of power and exhaust velocity leads to.

As long as we examined only conventional chemical rocket engines, the question of their power never interested us. Everything was solved by thrust and, of course, specific fuel consumption. In fact, does it really matter what the engine's power is? After all, this power is developed as if by itself during combustion of fuel in the engine.

But now, when the discussion concerns engines in which the source of energy is separated from the working substance, the problem of power of the engine is advanced to the first level. After all, in this case the magnitude of engine power determines that energy which should be supplied from without to the working substance. Obviously on board a flying craft there should be a power plant which generates the necessary energy. Inasmuch as we are considering electrical rocket engines, then such a power plant should be an electric power station. Is it not clear that power and, consequently, dimensions and weight of such a rocket electric power station become of paramount importance, that precisely they can limit the power of the engine?

Indeed, we will assume for a minute that on the carrier rocket which put the spaceship-satellite "Vostok" into orbit there were no conventional chemical rocket engines, but electrical. Inasmuch as the power of the engine of this rocket, as it is known, is equal to

20 million horsepower, then obviously the power of the electric power station for the rocket in the event that electrical rocket engines were installed on it would have to have been still greater (considering different very considerable losses in the engine). But how can one imagine an electric power station of such tremendous power on a rocket? After all this is the total power of almost ten of the largest hydroelectric power plants in the world, plants such as the Volga hydroelectric power plant imeni V. I. Lenin!

But even this is small. Really the entire venture with electrical rocket engines is connected with only one factor — the possibility of a significant increase of exhaust velocity. If it is assumed that this velocity can be increased by 10 times, then at the previous value of thrust (and thrust should remain approximately as before inasmuch as it is determined by the weight of the rocket and its necessary terminal velocity) the power of the rocket also increases by 10 times. It turns out that the power of the electric power station should in this case be equal to hundreds of millions of kilowatts. The conclusion is absolutely clear — electrical rocket engines inevitably have to be characterized by very little thrust. The less it is the greater the exhaust velocity. And not because these engines are not in a state to develop a high magnitude of thrust — everything is decided by the power of the electric power unit. It is precisely it which determines the possible thrust of the engine since it is clear that at the contemporary level of technology a superpowerful electric power station has to possess a huge mass which is unacceptable for flying vehicles.

We see that for electrorocket engines little thrust is not a caprice, is not chance, and is not an arbitrary solution. In this case little thrust is a sad necessity. If it were not for the circumstance that in space little thrusts are acceptable, then electrical rocket engines could not be considered for use. This would be sad, since essentially with them, and only with them, is connected the sole real possibility of a significant increase of exhaust velocity which is necessary for increasing the payload on space vehicles.

In a number of cases augmentation of thrust of electrorockets would be very desirable, first of all, for reducing the duration of space flight, and also in the fulfillment of different maneuvers in the course of such a flight. If this turns out to be impossible, then again it is due only to the electric power station of the rocket and its insufficient power, which is limited by mass requirements.

In order to finish up the problem of rocket power plants which generate the energy necessary for functioning of the electrical rocket engine, we will clarify how such an installation can appear and what are its arrangements and principle of operation. Although these questions do not have a direct relation to the electrical rocket engines themselves (to them it makes no difference by whom and how the electric power consumed by them is generated) the importance of the power plant for the future of these engines and the very prospects of their application is absolutely obvious.

First of all, of course, the question arises about sources of energy for power supply of electrorocket engines. It is obvious that for this chemical energy of fuel can also be used, i.e., something is created which in principle is a thermal electric power station. It is also possible to use those which supply energy to the electrical bulbs in our apartments. But it is doubtful whether this is a rational path. Certainly, in this case with the help of chemical energy of fuel it is possible to obtain a much higher rate of exhaust than in conventional rocket engines, but at what price? The entire propulsion system will be immeasurably more complex, bulky, and heavy (here already it is naturally difficult to make a comparison with a conventional rocket engine), and inevitably the limited reserve of fuel on the craft will sharply limit the possible duration of work of the engine.

It is understandable that in the beginning, when the first electrorocket engines will be tested and developed in flight, their electric power station will possibly be thermal — they have been studied well and can be made easily. Furthermore, definite prospects open here for different means and methods being studied at present for the immediate direct conversion into electric power of the chemical energy of fuel or just of the thermal energy which is given off during its combustion. By using such methods it would be possible to completely exclude the necessity for the most troublesome mechanical equipment for transformation of heat into mechanical work. No matter how this equipment improves from year to year, all the same it requires excessively large dimensions and weight; too much metal is expended on this equipment. Here there is probably nothing to be done; such is the nature of thermal energy that it is difficult to convert it with the help of thermal machines into mechanical work.

Regarding methods of direct conversion of chemical energy of fuel directly into electrical then of course it is especially alluring that one such method was well-known long ago. We are talking about batteries which are in wide use. From a school course in physics we know that in an electrical battery and in any other battery or element the current is generated as a result of a chemical reaction occurring in it which leads to the expenditure of some chemical substances and the formation of others. No one whould be surprised at what similar electrochemical processes in principle are possible — after all chemical energy itself has an electromagnetic nature; it is connected with electromagnetic forces which are acting inside the molecules and atoms. However, great deficiency of batteries, if one were to talk about their possible use as rocket electric power stations, is the fact that they work only as long as they still have a reserve of initial chemical substances. After these are expended the battery has to recharge (and many electrochemical elements are simply discarded), i.e., to restore the reserve of initial chemical substances at the expense of the expenditure of substances which are formed during the functioning of the battery. For this electrical current from an outside source is passed through the battery, i.e., electrical energy is expended again. It is as if "stored" in the storage battery, which is how it got its name. But on board a rocket such a recharge is naturally impossible, which makes the battery itself unfit as a source of electrical energy for supplying the electrorocket engines.

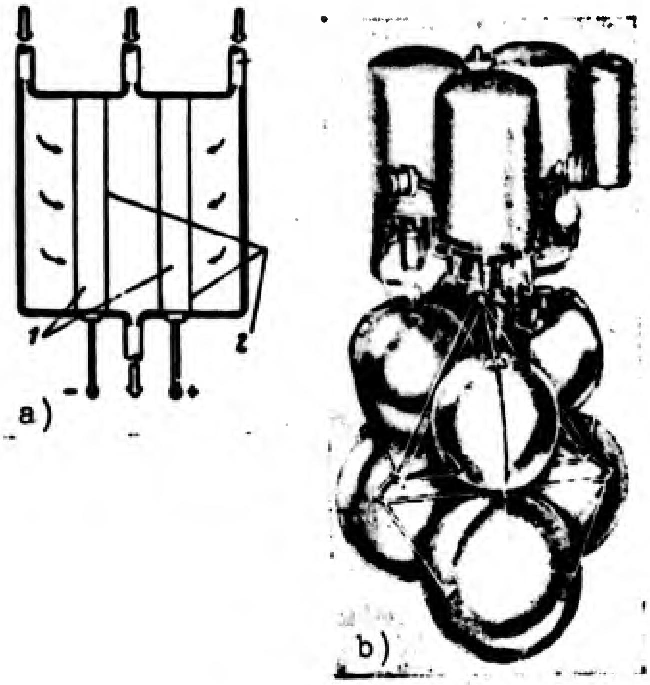


Fig. 76. Diagram of the arrangement of an electrochemical fuel element, working on oxygen and hydrogen (a) and a mock-up of a fuel element (the United States) for a spaceship (b): 1 — porous electrodes; 2 — on these surfaces ionization occurs.

GRAPHIC NOT REPRODUCIBLE

However, recently the idea of an electrochemical generator of electrical energy has received extraordinarily fruitful development in the form of so-called electrochemical fuel elements. Based on principle of work the fuel element is no different from a battery; in it the initial chemical substances are also expended so that the reaction taking place leads to the liberation of electrical energy, which is removed. The only essential difference is that the substances expended for supporting the reaction are not stored beforehand in the fuel element, as this is done in the case of a battery, but are continuously supplied to it. It is understandable that these substances have to be liquid and gaseous; particularly widely known is a fuel element working on hydrogen and oxygen. These gases "burn" invisibly, with a flameless "fire," in the element, which continuously generates electrical energy at the expense of chemical energy which is liberated during such "combustion." It can be expected that this and certain other fuel electrical elements will be used with success on the first electrorockets. However, in general their extensive application on motor vehicles, tractors, etc., is still waiting. But, as was already said, for use on a prolonged space flight chemical sources of energy are not suitable.

Another possible source of energy for power supply of electrorocket engines in space is solar energy, which is continuously radiated by it in the form of electromagnetic waves of different length, from the least – for γ-rays and X-rays, to the largest – for radio waves. As is known, this energy is the primary source of life for us on earth, but the earth receives only a grain, less than one billionth of the entire ocean of energy emitted by the sun. Circumsolar outer space is very rich in solar energy and it is perfectly natural to think of using this energy for conversion into the electrical energy which is required by the engine.

Many methods are known for the conversion of solar energy into electrical. The most attractive, naturally, are methods of direct conversion. One of them is based on the so-called photoeffect and has already found quite extensive application on artificial earth satellites and space rockets. The semiconductor photoelectric solar batteries which are mounted in them ensured the supply of electric power to airborne instruments and radio equipment for many months on end. Some of the satellites with such batteries are still now in orbit. When the batteries are exposed to the sun, then incident solar rays dislodge electrons from the surface layer of their substance in such a way that further in the semiconductor substance of the battery a whole rain of such electrons appears, i.e., electrical current. It is true that usually less than one tenth of all incident solar energy is converted into electrical energy, but the maximum simplicity and small weight of photoelectrical generators makes them very profitable for use in space. Furthermore, they continuously improve and in this respect there are still considerable possibilities.

Another method of direct conversion of solar energy into electrical is the so-called thermoelements or thermoelectric generators. These devices make use of the difference in temperatures of two junctions of metal or, which is better still, two surfaces of a semiconductor thermoelement, one of which is irradiated by solar rays and the other is in the shadow. Under the impact of such a difference of temperatures in the element electrical current

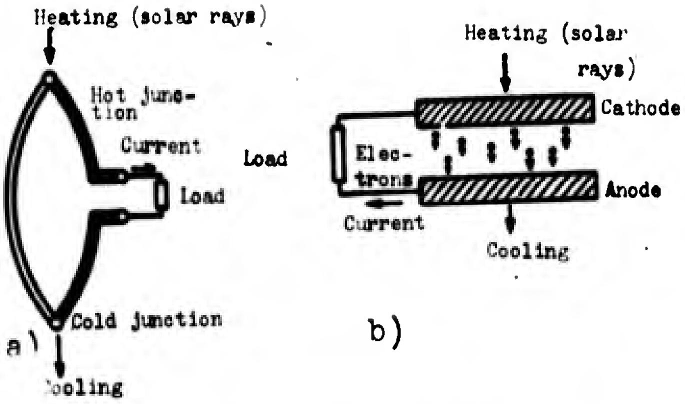


Fig. 77. Diagram of thermoelectric (a) and thermoelectronic (thermoionic) converters (b) of thermal energy in electrical.

starts to flow. In thermoelements also approximately one tenth of incident solar energy will be converted into electric power and considerable possibilities for their further improvement also exist.

In the future there are definite prospects of using the so-called thermoelectronic, or thermoionic, method of direct conversion of solar energy into electrical.

In this case, just as in the case of the thermoelectric generator, the difference of temperatures of two metallic surfaces is used. But only this difference is used in another manner. In the thermoelement the difference of temperatures creates a thermo-electromotive force in the junction of two various metals or in a specially selected semiconductor. In the thermoelectronic generator a hot plate emits electrons (so-called thermoemission), which pass through a vacuumized space between this plate, serving as the cathode, and a cold plate – the anode, thus exciting current in the circuit. It all turns out to be very similar to an ordinary electron tube – a diode, only there the electrons are emitted, i.e., are emitted by the cathode and rush to the anode as a result of application of electrical potential difference to them, but here this difference will be formed under the impact of difference of temperatures. Still better results are obtained in the case when the space between cathode and anode in the thermoelectronic generator is filled with vapors of easily ionized alkali metals, cesium for example. This will increase electron flow in the generator and also the current in the circuit of a similar so-called plasma (since between the electrodes plasma will be formed; this will be dealt with in greater detail below) thermoelement or plasma diode.

However, at present all the above-indicated methods of direct conversion of solar energy into electrical still cannot yet compete at any considerable powers with machine conversion of the conventional or, so to speak, thermodynamic type. In such machine converters the energy of solar rays vaporizes some liquid working substance, mercury in a boiler, for example, and then the vapors of this substance are expanded in the turbine, setting in motion the electric generator, and again are liquefied in the condenser, which drains heat from the working substances and radiates it into outer space. Incidentally, such radiators of heat are necessary in all cases, with all converters of energy. Therefore a characteristic peculiarity of all future space vehicles with electrical rocket engines will probably be the presence of some radiating surface with a very large area (large because the temperature of the surface inevitably will not be very high). This is why on all figures and on all plans of such vehicles it is possible to see large planes (similar to that on the wing of a conventional aircraft, gigantic umbrella which is opened in space), or other, not flat, radiating surfaces.

Whatever the method of conversion of solar energy into electrical on board a rocket or space vehicle, in all cases the power of such a solar airborne electric power station will inevitably not be very large, rather it will even be small in comparison to that required for operation of an electrorocket engine. This is explained simply – such is the intensity of solar radiation in the orbit of the earth. Actually, at this distance from the sun the full magnitude of solar energy falling on 1 m^2 of surface perpendicular to the rays of the sun equals approximately 1.35 kW. If it is considered that not all incident radiation is absorbed, but only a relatively small portion of absorbed radiation is used

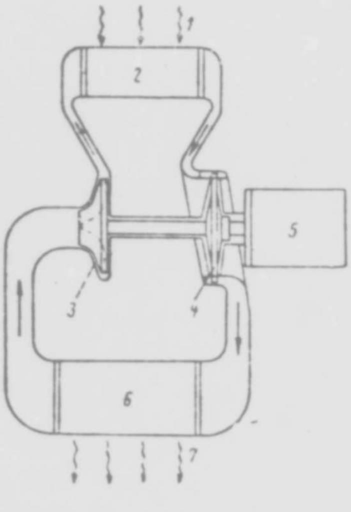


Fig. 78. Diagram of a thermodynamic (machine) converter of solar (or other thermal) energy into electrical: 1 — heat addition; 2 — boiler; 3 — pump; 4 — turbine; 5 — electric generator; 6 — condenser; 7 — heat removal.

usefully, then there is a clear necessity for very large surfaces of irradiation to ensure a considerable power of electrical current.

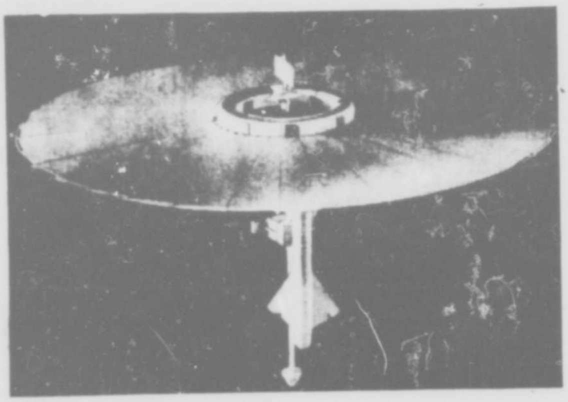


Fig. 79. An electrorocket can be easily recognized by the huge surface of the space radiator which is radiating waste heat (based on the plan of Stuhlinger USA).

Foreign scientists consider that solar electrical propulsion systems on space vehicles can be used with powers no greater than 100 kW, perhaps even less. However, the advantage of using "free" solar energy is so great, especially in prolonged space flight, that subsequently an increase, even a considerable one, is not excluded for the maximum power which can be developed by solar rocket power plants. In particular, a very effective means of increasing their power is considered the use of concentrators of solar energy — mirrors, collecting incident energy from a large surface and reflecting it on receiving elements of the installation - boiler, thermoelements, and so forth. Such concentrators under conditions of space can have very little weight with a huge surface, for which it is possible to use the finest metallized organic films, inflatable constructions, and others. The creation of such a type of concentrators of solar energy is being worked on abroad by many scientists and designers.

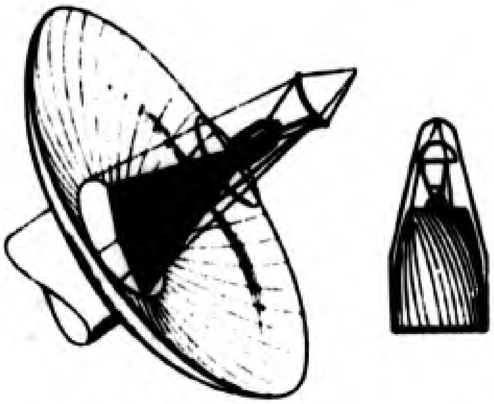


Fig. 80. Solar rocket power plant (Sunflower) (United States) with machine converter. The parabolic mirror is a concentrator of solar energy. It has a diameter of 9.8 m and during takeoff of the rocket is folded (figure on the right). Power of the installation is 3 kW, its weight 316 kilograms. In the focal point of the mirror at a distance of 6 m from it is a mercury boiler and turbogenerator.

But, probably the most promising is the use of <u>atomic energy</u> for the power supply of electrorocket engines, the creation of atomic electric power stations on board space vehicles. After all, atomic propulsion systems are in a state to work for many years on end. They can have practically unlimited power, in any case larger than for all the other possible sources of energy. And, at the same time, these installations can be sufficiently compact and light, even taking into account the biological shield, which we spoke of in the preceding chapter. It is true such a conclusion is based not so much on the level of development of atomic propulsion systems which has already been attained, as on the possibilities of their further improvement. In particular this concerns the prospects of direct conversion of heat, given off in a nuclear reactor, into electricity with the help of thermoelectric or thermoionic converters. It is true in this case for the first time a machine turbogenerating converter will probably remain basic; such converters are used, in particular, in the first installations of such a kind which were developed in the United States in the "Snap" and "Spur" program. This is conditioned mainly by the still insufficient mastery of direct methods of conversion. However, in the future doubtless priority will shift to these direct methods which make it possible to manage without complex, bulky, and relatively not very reliable machine equipment — high performance turbines and others. The first attempts of such kind have already been started. As is known, in our country we have created the first atomic power plant in the world (so-called "Romashka") with such a direct conversion of nuclear energy into electrical with the help of thermoelements. Its electrical power is equal to 500 W and it has already performed successfully for hundreds of hours. Attempts are being made to develop such installations abroad.

It is necessary to mention the attempts to create atomic electric generators with direct conversion of intranuclear energy into electrical, which of course, is most tempting. This is possible to achieve with the help of so-called atomic batteries, in which the radioactive decay of atoms is used. Such batteries contain a certain quantity of specially selected radioisotopes, for example, promethium-147, strontium-90, cerium-144 (the "Beta-1" installation which was developed in the USSR, works on it), and others, which during disintegration emit electrons, or so-called beta-rays (radioactive beta decay). It is sufficient to collect these electrons on a metallic plate-collector, so that it receives a negative charge, and the radiator itself — positive.

Thus is obtained the necessary potential difference, under the impact of which current can flow in the circuit of the electrorocket engine. In other atomic batteries the heat of radioactive decay will be converted into electric power (with the help of thermoelements or thermoionic converters). However, atomic batteries are usually created only for the power supply of different airborne instruments, since they still develop very small power, in fractions of a kilowatt. For electrorocket engines this is clearly insufficient.

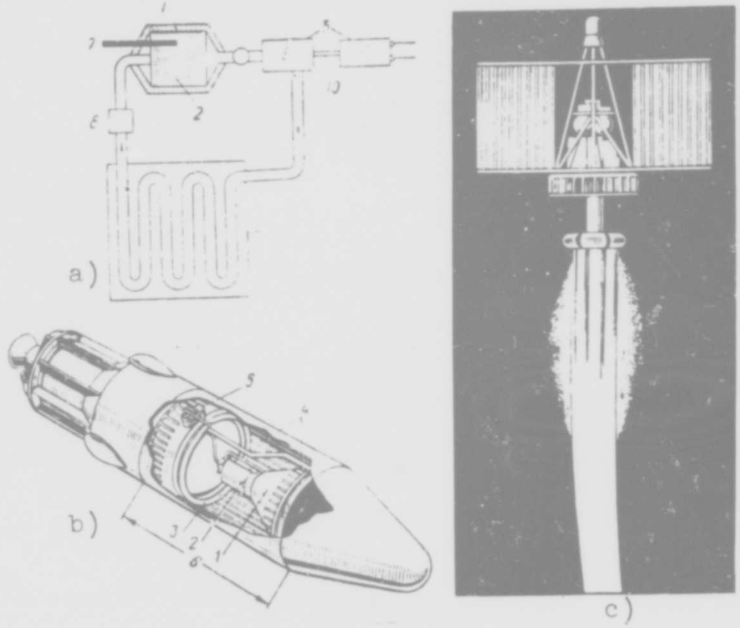


Fig. 81. Atomic airborne rocket electric power stations with a machine (turbogenerating) converter: a) diagram of atomic power plant with reactor and machine converter (turbogenerator); b) drawing of space vehicle with atomic power plant "Snap-2." Unit with a power of 3 kW with uranium reactor, cooled by melted sodium, and with a turbogenerator working on mercury vapors; c) drawing of electrical spacecraft in flight. Mounted on it is the airborne atomic electric power station "Snap-8" with a turbogenerator with a power of 30 kW. 1 — shielding; 2 — reactor; 3 — boiler; 4 — condenser-radiator; 5 — turbogenerator; 6 — length 2.1 m; 7 — control rod; 8 — pump or compressor; 9 — turbine; 10 — shaft.

But let us assume that one way or another the necessary electric power is obtained. Now the matter rests on the electrorocket engine; it should use this electric power in order to create a jet stream of high speed and thus the jet thrust driving the spaceship. How can this be done?

One path for achieving this goal seems quite evident. After all we know that exhaust velocity is determined by the temperature

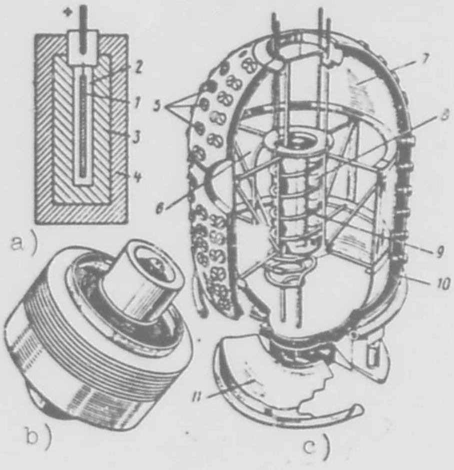


Fig. 82. Atomic radioisotope "batteries": a) diagram of the arrangement of an atomic element which utilizes beta decay; b) exterior view of element; c) radioisotope electric generator "Snap 1-A." In it 277 thermoelements convert the heat of radioactive decay of cerium-144 into current with a voltage of 28 V and power of 125 W. Weight of the generator is approximately 80 kg and it can work for more than a year. 1 — beta-emitter; 2 — clearance; 3 — battery; 4 — body; 5 — thermocouple; 6 — radiation heat reflector; 7 — space for mercury screen; 8 — rod of cerium-144; 9 — cooling coil; 10 — insulation; 11 — heat screen.

of effluent gases; it is directly proportional to the square root of this temperature. This means that for increasing the exhaust velocity it is sufficient to warm up the gas more strongly, to increase its temperature. With the help of chemical fuels this is impossible to achieve. Is this within the power of electricity?

Yes, it is within the power. Everyone has probably seen the dazzling fires of electric welding. In the brightly luminescent column of electrical high-voltage discharge, which has received the name of electrical arc, the temperature of the gases reaches 5000°C and even higher. Not one chemical reaction is capable of producing such a temperature. Meanwhile, the temperature of the arc can still be increased easily. For this it is sufficient, for example, to compress it, encasing it in a water or gaseous shell. If this shell is subjected to rapid rotation, i.e., a swift vortex is created around the arc, then not only will the arc be compressed and its temperature strongly increased, but there will be an increase in the so-called stability of the arc, it will be stabilized (without such stabilization the arc frequently starts to fluctuate and even dies out). Temperature of gases in such a stabilized arc can reach 10-15 thousand degrees.

At such temperatures gas already ceases, as a matter of fact, to be gas, it is turned into plasma. Plasma, as it is known, is the name given to a substance in such state when it no longer consists of neutral molecules and atoms, as in the other three states (solid, liquid and gas), but is a mixture of electrically charged particles – ions and electrons. Furthermore, in plasma it is also possible to find a certain quantity of neutral atoms and molecules, if the plasma is not completely ionized. On the whole all plasma is neutral, i.e., the number of positive and negative charges in it is equal (since plasma is formed from neutral substance), but its separate particles have an electrical charge of one or the other sign.

Plasma, this fourth basic state of matter, has long been of interest to astronomers, especially astrophysicists, since a large part of all substance in the universe constitutes primarily plasma – this includes the gigantic nebulae and all the stars and interstellar matter. In recent years plasma became the most urgent subject of scientific interests for scientists of the "earth" specialties, mainly those working in the area of nuclear physics. After all, through the mastery of high-temperature plasma lies the path to a controlled thermonuclear reaction, which for practically forever will satisfy the rapidly growing needs of humanity for energy. Plasma is also of great interest to scientists who are engaged in radioelectronics, since the study of the secrets of plasma and its practical use promises to considerably expand the possibilities of this truly ubiquitous science. And now plasma joins the armament of rocket technology.

However, it is not enough just to have high-temperature plasma, it is necessary yet to force it to emanate at high speed outside in order to obtain a rocket engine. To carry this out is simple; for this it is sufficient in just one of the electrodes of the arc to organize an opening which is located exactly along the axis of the column of the arc. Then the heated, blindingly luminescent, stream of plasma will emanate outwards under the impact of the increased pressure existing inside the arc chamber. In order to completely use the possibility of conversion of the huge potential energy of plasma into kinetic energy the discharge of plasma should obviously occur through a profiled jet nozzle. Thus basically is the electrorocket engine which is usually called arc. In principle of operation, at the basis of which lies heating of the working substance up to a high temperature with the help of electricity, such an engine is electrothermal in the same way as conventional jet engines can be called thermochemical.

It is interesting to note that the above described arrangement for production of a high-speed stream of heated plasma, which we called an arc electrothermal rocket engine, in reality has been created and is being used now, though still not at all as an engine. It is true that engines of such a kind already exist, but still only in experimental laboratory models, whereas for the first time similar arrangements, which have been given the name of plasmatrons, have been developed and are now used quite widely for other purposes. Thus, here the matter is diametrically opposite to that which takes place in the case of conventional rocket engines, developed precisely as engines but then gradually obtaining other uses. Plasmatrons are used abroad and here in our country for different industrial purposes for example, putting on of heat-resistant coverings, cutting of metal and so forth. They are sometimes used also for simulation of flight at great supersonic speed, during which the vehicle is subjected to intense aerodynamic, or so-called kinetic, heating. With their help it is possible to study, in particular, conditions of reentry of a space vehicle into the earth's atmosphere.

The arc-jet engine, which we just now met, is by no means the only possible representative of the "family" of electrothermal engines. Other electrothermal engines are possible, and some have even been proposed and partially tested. These are engines in which heating up of the working substance to high temperature is attained with the help of electrical energy. This heating up of gas can be carried out by various so-called electrodeless methods, i.e., those when the arc between two electrodes is absent. Examples

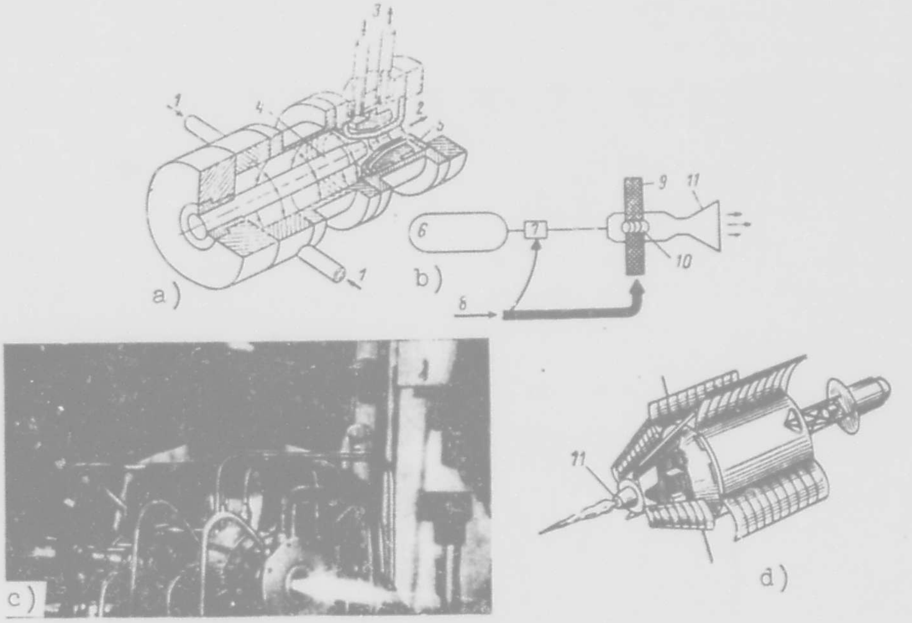


Fig. 83. Electrothermal (arc) rocket engine: a) structural diagram of engine with stabilized arc; b) schematic diagram of engine; c) laboratory installation of a "plasmatron" with a stream temperature of 10,000° (Avco Firm, United States); d) drawing of space vehicle with electrothermal (arc) engine from the Avco Firm. The working substance is hydrogen and the electric power station is atomic with a turbogenerator on mercury vapors. 1 — supply of working substance; 2 — exit of jet stream; 3 — cooling agent; 4 — electrode; 5 — nozzle-electrode; 6 — working substance; 7 — pump; 8 — power supply; 9 — electrodes; 10 — arc; 11 — traction chamber.

of such electrodeless heating are, in particular, various kinds of units for high-frequency induction heating — metallurgical furnaces for melting of different metals, furnaces for casehardening of metals, medical units (many have received it, and after all this is also ultrahigh-frequency heating), contemporary high-frequency "miracle kitchens," and many others. The same method of high-frequency electrical heating is also being tried out in electrothermal engines. Other methods of high-temperature heating of working substance in these engines are possible.

Incidentally, the use of solar energy makes it possible to create a space rocket engine in which the heating up of working substances to a high temperature will be carried out directly by concentrated solar rays, without preliminary conversion of solar energy into electrical. This of course will not be an electrothermal, but a unique heliothermal engine. It is easy to see that it is especially profitable in this case to use liquid hydrogen as the working substance of the engine. Abroad a number of plans for such a solar-hydrogen engine have been proposed.

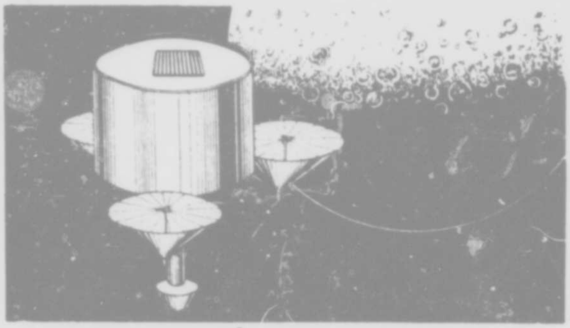


Fig. 84. Space vehicle "Heliodyne" with heliothermal rocket engine, working on liquid hydrogen (a cylindrical tank holds 800 kg of hydrogen). Heating of hydrogen is carried out by three mirror concentrators of solar rays.

Abroad a number of designs of experimental electrothermal engines have already been developed. These are mainly arc rocket engines, some of which have already been subjected to multihour laboratory tests. As was already said above, these engines, just as all other electrorocket engines, develop very little jet thrust. It is true that the thrust of an arc engine is slightly more than for all the others, but nevertheless it also is usually less than 1 kilogram (force). Inasmuch as the development of an arc engine leans on the vast experience of electric welding technology, and also on the not so great, but then very valuable experience of application of different plasma-arc torches — plasmatrons, plasmajets, and so forth as laboratory and technological installations, then frequently the opinion is stated that these engines will be brought to a state of readiness for use earlier than electrorocket engines of other types. However, followers of these "other types" usually do not hurry to agree with this.

But then with regard to maximum attainable exhaust velocity arc engines clearly yield, sometimes somewhat and frequently very considerably, to other electrical rocket engines. Inasmuch as the main goal and, if desired, the very assignment of electrorocket engines is increased exhaust velocity, then it would have been possible to think that arc engines are in principle less perfected and can be calculated for use only on account of the absence of finished improved electrorocket engines. However, such a concept is incorrect.

The essence of the problem here again is connected with the very idea of a rocket engine in which the source of energy is separated from the working substance. We already mentioned above that in this case the power of the rocket power plant at a given engine thrust will be directly proportional to exhaust velocity. The greater the exhaust velocity, then the greater the power. But this also means the greater the weight of the power plant. Taking this fact into account will any increase of exhaust velocity be justified for all possible cases of application of the engine in space? It is easy to see that this is not so.

An increase of exhaust velocity is profitable because it decreases the necessary reserve of fuel on the vehicle and, accordingly, increases its payload. It is obvious that an increase of velocity is indeed profitable only in the case when it does not lead to such an increase of weight of the engine itself and, consequently, the vehicle, which overlaps the gain in reserve of fuel. After all in another case the weight of the payload will not be increased, but will decrease! It is obvious that in every concrete case, for every given space flight an exact calculation should be performed in order to establish what is the most advantageous velocity of exit, which indeed corresponds to the greatest possible payload.

Such calculations are very labor-consuming and in carrying them out a great role falls to the share of electronic computing technology. But certain conclusions are so evident that they can be made without its help. Thus, for example, in general it is clear that the longer the duration of work of the electrorocket engine in flight, the more important it is to decrease fuel consumption and, consequently, to increase exhaust velocity, whereas the increase of weight of the propulsion system starts to play a relatively smaller role. This is why it is possible to assume that arc-jet engines will be used for relatively simpler and close space trips, but engines with greater exhaust velocity will be needed on spaceships for "distant movement."

When we talk about the relatively low exhaust velocity for arc-jet engines, then this should not be misleading. In reality, of course, based on its absolute value this speed is very great, it is simply colossal. It is considerably greater than exhaust velocity in the best contemporary and best possible future chemical rocket engines, but after all in these engines the exhaust velocity attains unusually high values of three kilometers per second and higher. Even in the first, still far from perfect, arc-jet engines exhaust velocity on the order of 10-12 km/s has been achieved. In the future it will be increased up to approximately 20 km/s. In comparison to this phenomenal speed what trivial examples there are of high-speed movement - the speed of an aircraft, a bullet, and even a space rocket still by far yield to it in magnitude. And this is the "lowest speed" engine of all the electrorocket engines.

Well what else can be said during this first acquaintance with the first of the electrical rocket engines - the arc engine? What are its dimensions and weight? Actually this question is not only appropriate, but also the most important for all transport engines, all the more so for aviation, rocket, and space engines. All, but not for electrorocket engines. And this is why. The dimensions and weight of the engines themselves are absolutely lost against the background of the power plant for their power supply - a rocket electric power station which is so much larger and heavier. Therefore the insignificant difference in dimensions and weight of electrorocket engines of different types, and it is indeed insignificant, does not have any significant importance. In general these engines are small and weigh little, but naturally with their characteristic low thrust.

Here is indeed what is important for any electrical rocket engine (we omit here the already noted obligatory reliable operation for a prolonged time), that is its efficiency factor, its omnipotent efficiency. Very frequently precisely on it depends the very future of this or that electrorocket engine, which it would seem is very attractive in everything else. And such a "might" of efficiency is easy to explain. After all the extent of efficiency shows what part of electrical energy which is expended for the operation of the engine will be converted into the kinetic energy of the jet stream, i.e., is used usefully. Imagine that efficiency decreased twice – this means that the power of the electric power station which is supplying the engine should increase twice so that the thrust of the engine remains as before. But after all this power, as is known, is very great and the actual electric power station obtained is bulky and heavy, and here it is still necessary to increase it. Yes indeed, in the first place from an electrorocket engine it is necessary to require a high degree of economy, high values of efficiency.

Unfortunately it is precisely on this front that the situation is still far from good, and here electrical rocket engines probably cannot yet compete with chemical. If for chemical engines usually more than half of the chemical energy of fuel is converted into kinetic energy of the jet stream, then for electrorocket engines this usefully utilized part of expended electric power usually turns out to be approximately half as much and more. It is true, in contrast to conventional rocket engines electrorocket engines possess considerable resources for improvement of economy and it is possible to think that the first years of improvement of these engines will lead to their efficiency being comparable with the efficiency of chemical engines and then exceed them. In regard to extent of efficiency different electrorocket engines usually differ little from each other, and arc engines here also have nothing to brag about. Now in these engines as a rule approximately 1/4-1/5 of all the expended electrical energy is converted. But already ways are known for essentially increasing this share, perhaps even up to 3/4. This is already unattainably for conventional chemical rocket engines.

However, it is time to speak of other types of electrorocket engines besides the arc and electrothermal in general, all the more so because they are probably of greater interest, both for the reader, and in regard to prospects of their application.

Of all the other electrorocket engines electrothermal engines are the closest to conventional chemical. This is even expressed in the name - some are thermochemical, others are electrothermal, in both cases thermal, i.e., heat. The only difference is in the fact that in one case the thermal effect of a chemical reaction is used and in the other - the thermal effect of an electrical current. Other types of electrorocket engines differ from conventional chemical much more radically, since in them the creation of a high-speed jet stream is generally not the result of heating of working substance. Here quite other means enter into play.

We will first turn again to the arc or some other electrothermal engine. As a result of thermal action of a current the working substance in it is turned into plasma and is discharged at high speed from the engine, thus creating the jet thrust. Is it possible to increase exhaust velocity more, to accelerate the plasma without increasing its temperature more? Doesn't physics know of any way for achieving this goal?

It does. For this it uses the remarkable properties of plasma, namely its electrical conductivity. In contrast to usual gases which are insulators, i.e., do not conduct electrical current, in this respect plasma is similar to metal in that it is such a good conductor of current. But if this is so, then it is a natural thought to use methods of acceleration which are well-known in physics and very widely used in technology - the acceleration of electrical conductors. Is it not so that all electric motors are based on this? If one were to place a conductor in a magnetic field and start a current through it, then it will start to shift in this field (remember the school rule "left hand," indicating the direction of this shift?). But obviously plasma which has been placed in a magnetic field will start to move in the same way if a current is started through it. The speed of plasma flow can thus be made very great, much greater than the speed of the stream which emanates from a plasmatron or arc engine. Thus stands out the scheme for an electrical rocket engine of a fundamentally new type. It is fundamental because here already an electrical or, more exactly, and electromagnetic field itself accelerates the plasma, the jet stream. Here for the first time we encounter a case when the stream emanates, not under the impact of pressure in the engine (as in all thermal engines, including electrical) or not only under this influence, but as a result of the action of electromagnetic forces. It is not surprising that such rocket engines received the name of electromagnetic. However, they are also called plasma, which does not require explanation, or magnetohydrodynamic. Here this last term should be explained.

A science which bears the name of hydrodynamics and its sisters – aerodynamics and gas dynamics – have been widely known for a long time. Hydrodynamics studies laws of motion of liquids, aerodynamics – air and gases at relatively low speeds, and gas dynamics – at high speeds. Essentially, inasmuch as gases and air are also liquid, but only compressible (in other respects from the point of view of their motion there are no differences), then the last two sciences – aerodynamics and gas dynamics – can be considered only as branches of hydrodynamics.

But what is this "magneto"? This addition to the word "hydrodynamics" is explained by special properties of a flowing liquid, which is studied in magnetohydrodynamics, i.e., plasma. When a flowing liquid conducts electricity, for example, it constitutes a gaseous plasma or melted metal, then it begins to interact with electromagnetic fields. This requires the introduction of new members into equations describing the motion of a liquid, a calculation of new properties – so hydrodynamics becomes magnetohydrodynamics.

Until recently magnetohydrodynamics did not have either great importance or specially significant development. This was explained simply – when it had a basically purely theoretical or, as they sometimes say, academic nature it was a curious, interesting, but in general a practically useless branch of knowledge. Here only some astronomers and astrophysicists constructed their concepts of motion of space matter based on positions of magnetohydrodynamics. But even these investigations could hardly be considered as having practical value, and to check them was still impossible.

In recent years the position changed sharply. Initially this was assumed by atomic power engineering, in connection with the solution of a number of its practical problems. And then newer and newer important problems began to appear which required for their solution the rapid development of magnetohydrodynamics. An honorary place in the circle of such new problems was occupied by magnetohydrodynamic rocket engines.

Incidentally, in the same way that in the area of electrical machines we know about the existence of two huge, frequently mutually reversible classes – electric motors and electric generators, then here also along with magnetohydrodynamic engines it is possible to easily visualize magnetohydrodynamic generators of electrical current. And here also they are identical in principle of arrangement and can be converted one into the other, i.e., can be rotated. As it is easy to see, a magnetohydrodynamic generator, or, as it is frequently abbreviated, MGD-generator or even simply MGD, serves for the generating of electrical current by exactly the same method of shifting of a conductor in a magnetic field as in conventional dynamo electric machines. Only the conductor in this case is not the metallic winding of a revolving armature, but a stream of rapidly flowing plasma. Such generators of current, by not having revolving and other moving parts and by possessing potentially significantly greater efficiency than their usual colleagues – dynamoelectric machines, are very promising. Their development has been worked on intensively by scientists of many countries – this is one of the most important areas of application of magnetohydrodynamics. Undoubtedly in the future the MGD will find widest application at electric power stations, on various transport devices, and on electrical rockets, where they will supply electric power to various electrorocket engines, including magnetohydrodynamic. And what is surprising here, perhaps in daily practice conventional electrical generators do not supply current to electric motors just as two peas are similar.

Here also the magnetohydrodynamic rocket engine in principle repeats the circuit of the MGD arrangement. While in the MGD the stream of plasma flows between two magnetic poles which are situated on both sides of the stream in one plane, and two laminated electrodes, from which current is carried off, in another plane, then in a magnetohydrodynamic engine which is similar in arrangement current is already supplied to the same electrodes and the jet of plasma begins to accelerate rapidly up to very high speeds. This is very simple "inversion."

But magnetohydrodynamic or electromagnetic, as they are more frequently called rocket engines can have quite another arrangement and be completely different from the MGD. Many of the most schematically diverse rocket engines of this type have already been built and tested, and still more proposed circuits for such engines are well-known.

Some of them work constantly, a stream of heated plasma emanates from them continuously, just as from the arc engine or plasmatron. They include, in particular, the above described magnetohydrodynamic engine of the type of inverted MGD. Others work under so-called pulsed conditions, i.e., plasma emanates from them periodically - a "shot" with a clump of plasma, then an interruption, again a "shot," etc. It is not surprisingly that such engines are sometimes called "plasma guns," although of course they never resemble conventional artillery pieces. Yes, and the "shells" in them are quite different. Incidentally, these "shells" can have the most diverse form - they can constitute a shapeless cluster, then a stream, and then plasma "rings" with definite outlines, the so-called plasmoids which are very similar to rings of smoke made by experienced smokers.

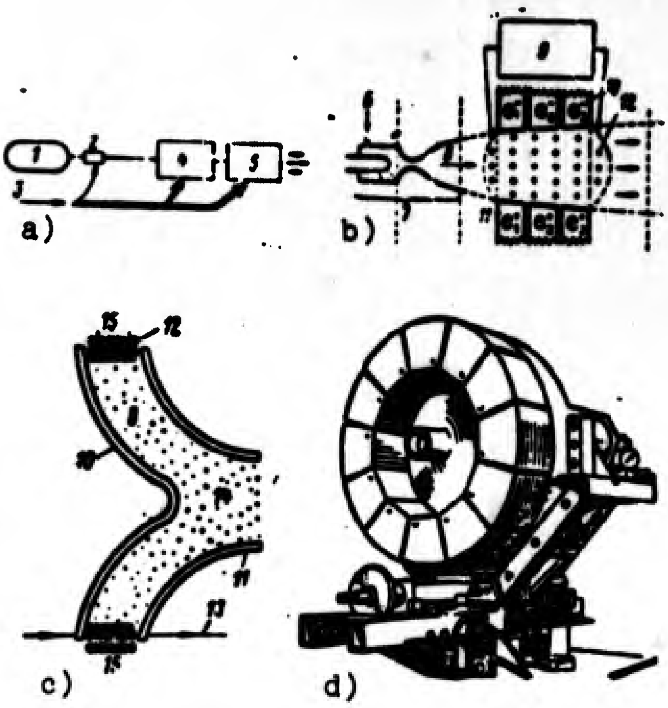


Fig. 85. Electromagnetic (or plasma) rocket engine: a) schematic diagram of engine; b) diagram of continuously working plasma engine with lattice-type electrical and magnetic fields; c) and d) diagram and external view of a "pinched" plasma engine of the pulse type from the firm Republic Aviation (the United States). Around the nozzle are located 12 capacitors, the discharge of which creates the "pinched effect" in the plasma. Thrust of the engine is on the order of 50 g, escape velocity in the range from 10 to 70 km/s. 1 – working substance; 2 – pump; 3 – power supply; 4 – generator of plasma; 5 – accelerator of plasma; 6 – input of working substance; 7 – arc generator of plasma; 8 – flow of plasma; 9 – zone of coverage of magnetic field; 10-11 – electrodes; 12 – magnetic lines of force; 13 – current of capacitor; 14 – nozzle; 15 – compressing forces.

It is interesting to point out as an example the pulsed electromagnetic engine which is usually called "pinched." Interest toward this engine is connected not so much with the prospects of its application as with the very physical process of electromagnetic acceleration of plasma. This process, based on the so-called pinch effect, after the sensational report of academician I. V. Kurchatov in England in 1956, became famous in recent years thanks to work in the area of controlled thermonuclear reactions. The first successful experiments on the obtaining of high-temperature plasma, carried out in the course of this work, were conducted primarily using the pinch effect. "Pinch" in English means to compress, to constrain. In this case the actual plasma is compressed, and it is precisely the plasma which compresses itself. This is what also occurs in installations for the study of thermonuclear fusion, and in pinched rocket engines.

The original cause of everything is the powerful electric discharge along the pole of plasma. As soon as such a discharge occurs, immediately the plasma column is compressed into a narrow cord along the axis of this discharge. What forces produced such compression? Electromagnetic. More precisely they converge together, the matallic conductors along which electrical current flows in one direction draw near — many readers will still remember a similar experiment from a school course in physics. And if one were to pass a powerful current along a thin-walled metallic tube, then it will be flattened by the same invisible electromagnetic hand. This "hand" is an electromagnetic field of cylindrical form which develops during passage of a discharge pulse.

As a result of discharge and subsequent compression of pole of plasma the pressure and temperature in the plasma column which is forming are increased sharply. Thermonuclear physicists try to bring the temperature thus obtained up to many millions of degrees which are needed for the onset, or as it is said, "ignition" of a thermonuclear reaction. In case of an electrorocket pinched engine similar temperatures are not required. Much lesser ones are fully suitable. If plasma is to flow somewhere from the region of discharge, for example, along the axis of the plasma column, a hole in the electrode — a jet nozzle is foreseen for this purpose, then compressed and heated plasma will rush into it with great speed — the pinched engine is ready.

Electromagnetic engines are also distinguished according to how plasma is formed in them. Here, as in electrothermal engines, it is possible to use either arc or electrodeless, radio frequency for example, heating. They are distinguished according to the method of acceleration of plasma, which was already spoken of above. They are distinguished, naturally, by construction, dimensions, thrust, working substance, exhaust velocity, etc. Probably no other type of electrorocket engines have so many varieties. Incidentally, abroad they have proposed not only rocket, but also jet magnetohydrodynamic engines, which may find application on certain "low-flying" artificial earth satellites and should use as the working substance the rarefied air of the upper layers of the atmosphere.

Regarding thrust of electromagnetic rocket engines, then it naturally is very low, and usually approximately the same or even less than for electrothermal engines — grams, dozens, from a force of hundreds of grams. Possibilities for augmentation of thrust exists, but they are small. Efficiency of both types of engines is approximately identical.

But then in regard to exhaust velocity electromagnetic engines are considerably better than electrothermal. Exhaust velocity in them is ten times greater and reaches 50-200 km/s. Generally speaking it can be even greater — such are the potential possibilities of the electromagnetic acceleration of plasma.

It is obvious that relatively high speed of exit makes the application of electromagnetic engines profitable for more complex, distant, and prolonged flights, in particular, for example, to Mars, Venus, and other planets of the solar system.

It is obvious that an electromagnetic engine in principle and design is more complex than electrothermal, since essentially it constitutes the same electrothermal engine with additional devices for electromagnetic acceleration of plasma. A general deficiency of both types of engine is the presence of high-temperature plasma, since it is not simple to make engine components which come in contact with such plasma reliable and long working, and after all this is an obligatory requirement for all electrorocket engines. Therefore the question naturally arises, doesn't the very rich arsenal of physics contain means for the electrical acceleration of substance without its preliminary strong heating up? The answer to such question comes to mind immediately, since electricity, as is known, does not have to be "hot."

As is known, electrical repulsive or attraction forces act between any two charges or charged particles - this is the so-called electrostatic or coulomb force. It stands to place a charged particle in an electrical field, since now under the impact of these forces the particle will start to move in a definite direction. This motion will be accelerated if the force of interaction of field and charged particle is preserved, as a result of which the velocity of a particle can be as great as desired. Is it not true that this is all that is necessary for an electrorocket engine?

But such a method of electrostatic acceleration of working substance is suitable only in the case when this substance, its particles are electrically charged. Meanwhile, all substances, their molecules and atoms, in their normal, usual state are electrically neutral. Consequently, if we want to create an <u>electrostatic jet engine</u>, then first of all one should see to it that particles which were previously neutral obtain electrical charges of this or that sign. As is known, the process of transformation of an atom or molecule into an electrically charged particle bears the name of ionization, and such a particle itself is called an ion. This is why the first most important part of any electrostatic rocket engine should be the ionizer or ion source - neutral atoms and molecules (or other initial particles of working substance) which earlier were neutral in it become ions; they acquire an electrical charge. Therefore the electrostatic rocket engines themselves are usually called <u>ionic</u>.

After ions are obtained it remains to accelerate them in the electrical field. Therefore the second most important element of any electrostatic, or ion, rocket engine is an accelerator of ions. From this accelerator a jet stream will discharge outside at great speed. This, as is known, is the final "product" of work of any jet engine. Does this mean that the electrostatic rocket engine has all told two most important component elements, two posts on the "conveyer" of changes of working substance occurring in it?

This noes not mean that. It turns out that in an ion engine it is not enough to create a jet stream, it is necessary further to care about this stream so that it is preserved. This is one of the unusual properties of an electrostatic engine, distinguishing it from all other known jet engines. It is obvious that such peculiarity deserves a more detailed account.

The essence of the problem is that in contrast to other engines the jet stream of an ion engine consists of electrically charged particles, where all these particles – ions – have charges with an identical sign. That the sign of charge of ions should be identical is obvious, since only in this case will the electrical field of an ion accelerator accelerate ions in one general direction for all of them. Without this a jet stream will not be obtained.

But then two questions immediately arise. Here is the first of them: where do the particles of the other, opposite sign go to? Actually we will trace changes in the state of working substance beyond the "conveyer." A neutral working substance enters the engine. In the ion source it is transformed into ions, i.e., all the previously neutral particles are divided into two: into two ions with an opposite sign. Particles of one sign are accelerated in the ion accelerator and form a jet stream. And what happens to particles of the other sign?

Obviously these particles also have to be removed from the engine to the outside, otherwise they will be stored in it, and the engine and together with it the whole vehicle will acquire a large electrical charge. This still perhaps was not so terrible but the fact is that the sign of the charge on the engine is opposite to the sign for the charge of the jet stream. Consequently, electrostatic forces, appearing in this case, will prevent the stream from escaping and very soon outflow will cease altogether. The engine will not work. This means that particles of the other sign also have to be led out of the engine so that it remains neutral.

This is why beyond the ion source the "conveyer" is divided in two – along one move the ions of one sign, forming the jet stream further down the line, and along the other – ions of the other, opposite sign. Do they also form a jet stream? Yes, the reaction of these particles, emanating from the engine is usually used, but this does not have to be done since the jet thrust obtained by this is insignificantly small in comparison to the thrust of the basic stream. This is explained simply. The formation of ions in the ion source of the engine is usually connected with the fact that from previously neutral particles one electron is detached. Then the particle becomes a positive ion and the jet stream consists primarily of such ions, i.e., it has a positive charge. So that the engine does not acquire a negative charge, the free electrons formed also have to be, as this was stated above, removed to the outside. Certainly their escape in the same direction as the basic ionic stream will create an additional jet thrust. But what will it be in value? If it is considered that exhaust velocities are identical, then thrust will be determined only by the mass of emanating particles, since after all the number of these particles is also equal. But the mass of electrons is tens and hundreds of thousands of times less than that of positive ions. It is clear that they are not in a state to create any significant thrust during escape. An "electron" rocket engine hardly has any meaning.

But this is still not all. There is no answer to the second question. The engine, as we clarified, now remains neutral during operation, but does this mean that the presence of a positive charge on the jet stream will not influence the operation of the engine? Unfortunately it does not mean this. And this is why. This stream, creating as if a cloud of positive charges beyond the engine, i.e., the so-called volumetric or spatial charge, will interact with its own electrical field with all the new positive ions emanating from engine and entering into this cloud. But obviously such an ineraction will be none other than the deceleration of emanating ions. The stream will as if impede the new ions from flowing out, prevent their escape, or decrease its velocity. With time outflow may cease altogether.

This is why it is necessary to exert an influence on the jet stream in order to "neutralize" it, to eliminate its ruinous influence on the operation of the engine. The method of solving the problem here is obvious, it is sufficient to neutralize the stream, i.e., to deprive it of electrical charge. But how is this realized? If the first post of the "conveyer" - the ion source - is only occupied in creating ions for imparting an electrical charge to particles of the working substance, then the last post of this "conveyer" should be engaged in a diametrically opposite matter - to again neutralize the particles of working substance. This is exactly how it is done. For such a neutralization in the very end of the "conveyer" there should be provided a source of electrons or other negative ions, which have to be introduced into the positive jet stream as near as possible to its beginning. It is necessary to admit that this neutralization of jet stream gives almost the greatest troubles to the designer of an ion engine.

How will the basic elements of an electrostatic ion engine look?

We will start with the first post of the "conveyer" - the ion source. In principle the ionization of working substance does not present any considerable difficulties. In science and technology many different methods are used for such ionization. Certainly, far from all of them are useful for use in an ion engine. Most frequently in foreign designs of such engines they use the method of so-called surface or contact ionization. In this case the working substance is ionized, i.e., its atoms or molecule lose electrons as a result of collision with a heated surface of some solid substance, usually metal. During such a collision the atoms located on the surface of the metal as if seize an electron, strip it from the shell of the atom or molecule which is hitting against the surface. So that this is possible it is obviously necessary to have a specific combination of properties of both substances, the ionizer and working substance. Atoms of working substance should give up their electrons easily, and atoms of the ionizer - absorb them readily.

Therefore, in the majority of foreign-built ion engines the working substance is usually any alkaline metal, most frequently cesium or rubidium - the atoms of these metals part readily with the outer electrons which are weakly bound with the nucleus. It is true that prior to putting these metals in the ion source it is necessary

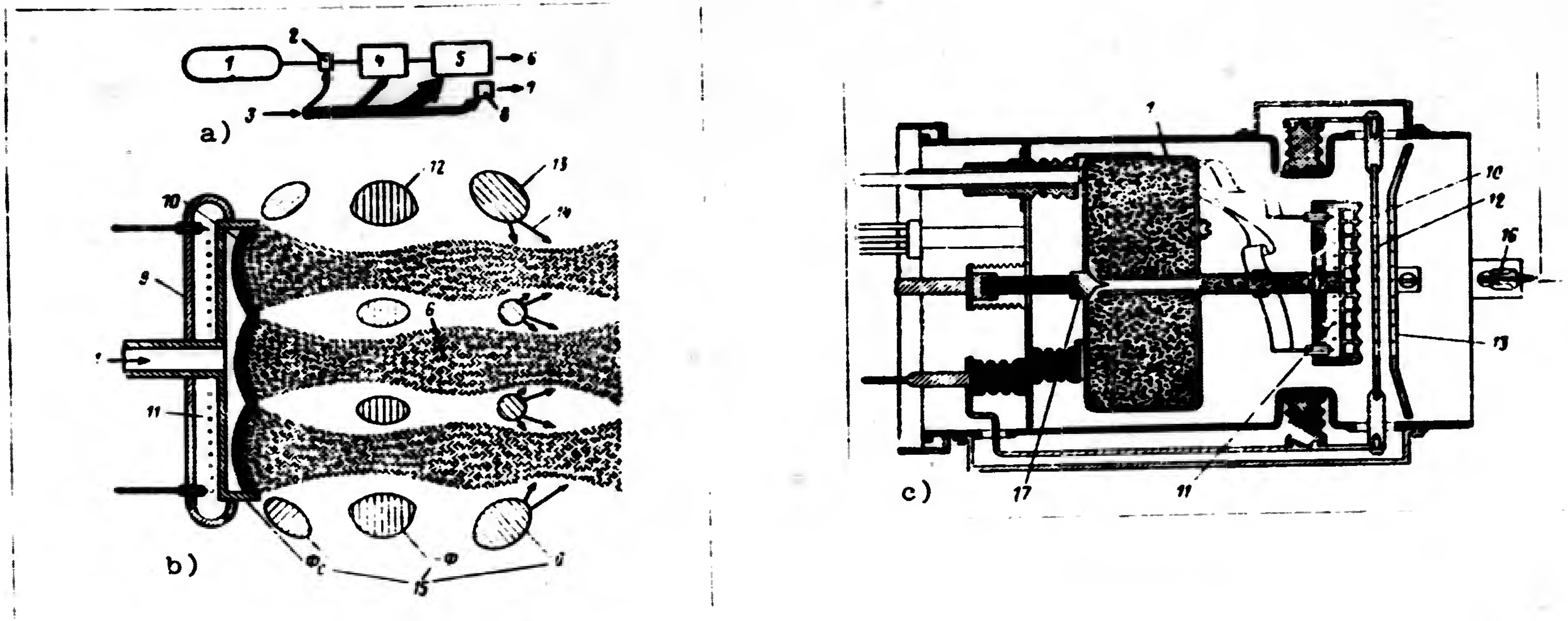


Fig. 86. Electrostatic (ion) rocket engine: a) schematic diagram of engine; b) diagram of cesium ion engine (ion accelerator); c) constructional diagram of cesium ion engine from the firm Electro-Optical Systems, Inc. (USA); 1 – working substance (cesium); 2 – pump; 3 – power supply; 4 – ionization chamber; 5 – electrostatic accelerator; 6 – ions; 7 – electrons; 8 – emitter of electrons; 9 – radiation screens; 10 – tungsten ionizer; 11 – heater; 12 – accelerating electrode; 13 – delaying and neutralizing electrode; 14 – electons; 15 – value of potential; 16 – nozzle for neutral streams; 17 – flow valve for cesium vapor.

to vaporize them, since under ordinary conditions they are solids. To do this, however, is not complicated, their vaporization temperature is relatively low. But then both of these metals possess several other merits as the working substance of ion engines, in particular a sufficiently high atomic weight (remember what was said above about the necessity for great mass of effluent particles; more exactly it is necessary to have a high ratio of mass to charge). Therefore, in most cases the ion engines which have been built are cesium or rubidium.

Regarding the material from which the ionizer is made, then it usually is tungsten, though it is possible to use rhenium, carbon, and certain other substances. They tenaciously hold the electrons of cesium or rubidium which were captured and do not return them (in these cases they say that the substances possess high "work function," i.e., for breakaway of electrons a great deal of work has to be expended). But this is not the only necessary property for the material of the ionizer. For example, it was pointed out above that the surface of the ionizer should be white-hot, heated to a very high temperature; it is clear that not every substance is suitable for this. But why is high heating needed?

Here we run into a typical engineering problem of finding the optimum solution, the optimum compromise between oppositely effective factors. One of these factors is electrostatic attraction between electrons which have been pulled from atoms which are hitting against the surface of the ionizer and are "trapped" in the ionizer, and these atoms which are transformed into positive ions. This is the usual attraction between charges of opposite sign. But due to it the ions start to "adhere" to the ionizing surface, disturbing the normal operation of the ionizer, and then stopping it in general. How can we eliminate such harmful "adhesion" ions?

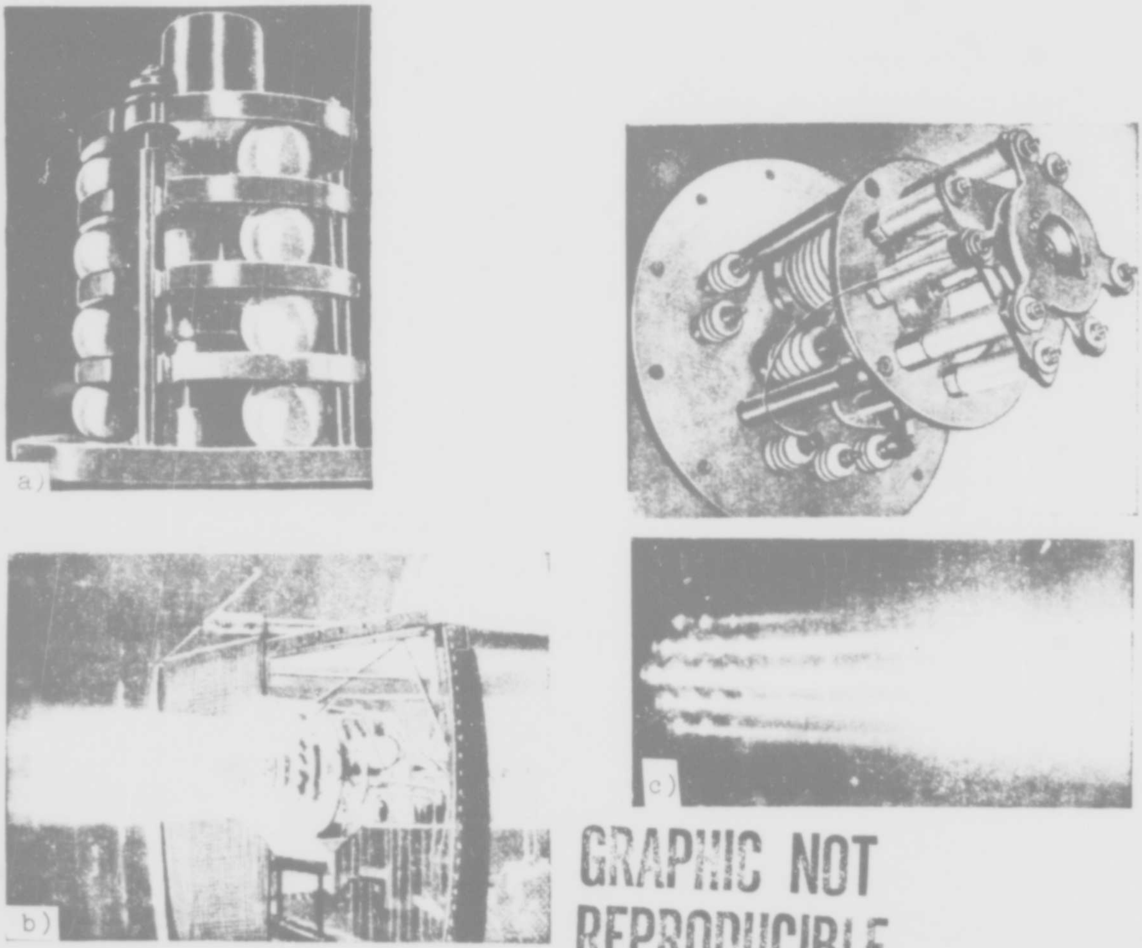
It is due to this that the ionizing surface has to be heated. In acquiring the temperature of surface, the ions which collided with it receive at the same time a kinetic energy which is sufficient for overcoming the electrostatic field of attraction of this surface, in the same manner that a rocket picks up escape velocity as it flys away from the earth. It is obvious that in this meaning the greater the temperature of the ionizer, then the less the possibility of ions settling on it. But then there is a lowering of "work function," as a result of which not only do ions no longer remain in the ionizer, but also electrons which are trapped in it start to fly away. And this naturally also worsens the work of the ionizer. Therefore it is necessary to select the most advantageous temperature of heating for each concrete case. It turns out to be quite high, usually higher than 1000°K, which places additional limitations on the selection of material for manufacture of the ionizer. For cesium as the working substance a tungsten ion source turns out to be best. It is usually organized in the form of thick layers of a thin tungsten grid or the same porous plate, through which electrical current for heating is passed and vapor of cesium are forced under pressure, so that from the source a flow of cesium ions already emanates.

As was indicated, other methods of ionization are possible, in particular with the help of the same electrical arc or electrodeless high-frequency heating which produces a plasma. But this method obviously returns all deficiencies connected with high temperature. Certainly, while it is still quite impossible to consider the construction of an ion source for electrostatic rocket engines as conclusively worked out here there are still many interesting possibilities and there are long, persistent searches for the best solution ahead, but after all this concerns, without exception, all other elements of such an engine, which is essentially still in the embryonic stage.

But let us turn to the second post of the "conveyer" – the accelerating system of the engine. Here ionic flow, coming out of post No. 1 – the source, should be accelerated up to the necessary high exhaust velocity and focused, i.e., turned into a dense cylindrical stream in which all the particles have one general direction for all. Acceleration in an electrostatic field is used widely in technology in the most diverse devices. Thus, for example, the simplest electron tube – the diode – also constitutes an accelerating system, only not ions, but electrons are accelerated in it, which is not a fundamental distinction. The same "diode" is also the simplest accelerating system of an ion engine. It consists of a pair of electrodes, located along the axis of the engine so that the first of these electrodes truely is the ion source – it "emits" ions in the same manner as in a tube the first electrode emits electrons. In accordance with such a distinction the ion source is the anode, and the emitter of the tube – the cathode. The second, accelerating electrode in the tube is the anode, and in the engine respectively the cathode. Under the impact of accelerating potential difference between the anode and cathode the ions which are formed on the anode, i.e., in the ion source, start to move more rapidly to the cathode. They pass through the opening in this cathode (or the cathode is organized in the form of separate plates with a clearance between them) and in the form of ion beam emanate outside.

Certainly this is only the simplest arrangement. In reality, the accelerating system usually has not one, but two electrodes besides the anode – the ion source. Thus it constitutes not a "diode," but a "triode." Furthermore, the traction chamber of the engine, in which the jet stream is formed, besides the accelerating system also has a focusing system which forms the ion beam, i.e., a unique "ionic optics." Usually very high voltage is applied to all these electrodes, they should not be easily put out of action by the impact of ions which are bombarding them, and the dimensions of the entire traction chamber have to be small. In general its creation requires considerable engineering talent.

Finally, at the exit from the traction chamber is disposed the last post of the "conveyer" – a device for neutralization of the ion beam. It was already mentioned above that realization of this process of neutralization is a very involved matter, since it should be performed as close as possible to the engine (otherwise the stream will be expanded rapidly and thrust will decrease) and in such a way as to not spoil the ion jet stream which is formed in the traction chamber. Meanwhile, introduction of electrons into this stream



GRAPHIC NOT REPRODUCIBLE

Fig. 87. Views of an ion engine: a) engine from the Goodrich firm (United States). Porcelain spheres serve as insulators; b) testing of the engine from the Hughes firm (United States with annular ion beam; c) engine from the firm Electro-Optical Systems, Inc. (USA) with 19 ion beams.

disturbs its flow, can make it unstable, and leads to losses of energy. Theoretically the best results can be attained in the case of introduction into the stream, for its neutralization, not of electrons but of negative ions of the same mass and speed as for the positive ions in the stream. Experiments of such a kind are being conducted abroad.

One of the methods for reducing the difficulties in the formation of ion jet streams is the creation of multisectional ion engines, i.e., having several traction chambers united in one construction, similar to how this is done in the case of clusters of conventional chemical rocket engines. A number of such multisectional ion engines have already been developed and are being tested (in the United States in particular). One large-diameter ion beam in place of several thinner ones would be unavoidably expanded (after all it consists of mutually repulsive particles of one sign of charge) and therefore connected with loss of thrust.

It was already noted above that in contrast to conventional chemical engines, in which the mass of molecules in the jet stream should be as small as possible, in ion engines it is expedient to have it as large as possible, since this decreases the necessary number of particles with the same thrust and, consequently, decreases the dimensions of the engine or increases the thrust of the engine with the previous dimensions. This is why sometimes a proposal is made concerning the development of an electrostatic engine in which not ions would be discharged, but much more massive charged particles consisting of thousands and millions of molecules. Such particles can be, for example, microscopic charged drops of oil and other liquids (molten metal in particular), and also different colloidal particles, which is why such engines are usually called colloidal in contrast to ion. Actually such engines would be more compact and light, which makes their investigation and development promising. However, they have a serious deficiency – for acceleration of more massive particles it is required to have greater accelerating voltage, and this strongly complicates the construction of the engine in connection with the danger of disruptive discharge.

The thrust of ion engines already developed abroad is as small, if not less, than for the other electrorocket engines described above, but then based on value of efficiency they are better, which makes them especially attractive. This partly explains the increased interest shown toward ion engines abroad. Regarding exhaust velocity, then in this respect ion engines outstrip the majority of others – in them it reaches many hundreds of kilometers per second. Obviously such engines are the most suitable for distant and prolonged space flights.

It is difficult to say now what types of electrorocket engines will be used first on actual space flights. At present intensive preparation is being made for flight tests of electrorocket engines of various types on rockets and artificial satellites. These tests are especially important because ground tests under conditions simulating space flight are very complicated and frequently do not give sufficiently exact results. One way or the other there is no doubt that the future of cosmonautics is connected to a great degree primarily with electrical rocket engines. In this connection it cannot fail to cause justified pride in the Soviet reader that for the first time in the world one of the types of electrorocket engines, plasma to be exact, was mounted on a space vehicle and successfully tested in action in space in December 1964 by Soviet scientists. As is known, such engines were used in the orientation system of the interplanetary automatic station "Zond-2," lauched in Soviet Union on 30 November 1964 and directed to Mars. In the United States up to now only two tests of electrorocket engines on ballistic missiles have been conducted.

CHAPTER XII

TO THE SPEED OF LIGHT!

The possibility of creation of electrical rockets, i.e., rockets with electrical rocket engines, was written about even by the founders of rocket technology – Tsiolkovskiy, Goddard, Oberth, and Eno Pel'tri. The first such statement published in print belongs to K. E. Tsiolkovskiy. In his article "Investigation of Outer Space by Rocket Instruments"[1] in the division about the future of these instruments Tsiolkovskiy wrote:

"Maybe with the help of electricity it will be possible in time to give great speed to particles ejected from a rocket instrument."

Tsiolkovskiy also first, in a work published in 1926, noted the fundamental possibility of use in space flights of rocket engines of very small thrust. Tsiolkovskiy more than once returned to all these and other adjacent problems in his subsequent works.

However, in those times the idea of electrorocket engines could not be realized, and it was not urgent – the conquest of space had not yet begun. Then there was no need of electrorocket engines nor the technical possibilities of their creation, and there was no theory of such engines.

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[1] Journal "Herald of Aeronautics," 1911, Nos. 19-22 and 1912, Nos. 2-9.

But then now, when man has begun his victorious conquest of space, when into the ocean depths of outer space there have already been sent hundreds of different spacecrafts and the first astronauts have accomplished their trips around earth, interest in electrorocket engines has increased and continues rapidly to increase. Continuously there is being published newer and newer theoretical research of these engines — their working process, working substances, characteristics and others — there are carried out different experimental investigations, there are developed projects of rockets and spacecrafts with electrorocket engines, and there are calculated routes of their flight in space.

Along with other problems there are examined regions of most advantageous use of electrorocket engines of various types — electrothermal, electromagnetic, and electrostatic. The point has already been made in the preceding chapter that these regions are determined, basically, by the most advantageous value of exit velocity for every given space flight. In many cases it will be possible to use engines of various types and only thorough analysis can show which of them will be the most profitable, allowing taking on board the biggest payload. Until now "specialization" of different electrorocket engines can be shown only in very general features, and even that not always sufficiently well founded.

One of the possible and, naturally, first priority regions of use of electrorocket engines is artificial earth satellites. Certainly, it is not a question of getting satellites into orbit; this, as is known, requires powerful carrier rockets and here, probably, there will be used with success usual chemical engines — liquid and solid fuel. They can be thrust by airbreathing-jet engines for use on the first stages of a multistage rocket and atomic rocket engines, probably, for the second (not first, so that the engine is not worked from earth), and maybe the third stage. Electrorocket engines with their diminishing thrust do not fit here. But then, once the satellite is already in orbit, electrorocket engines on it can fulfill numerous functions, and it is doubtful whether any other rocket engine can compete with it in this area. It will be especially profitable to use electrorocket engines in those cases in which on the satellite without that there should be a sufficiently powerful electric power installation for feeding of airborne equipment, radio equipment (in particular, for connected relay satellites), etc. After all such an installation can if necessary, from time to time, be switched to feed electrorocket engines of the satellite, which, essentially, takes away the main obstacle on the road to using such engines.

Electrorocket engines on the satellite can serve to control its orientation in space, i.e., preserve the assigned position of the satellite with respect to earth, sun, and moon, which is absolutely necessary for satellites of many assignments. They can be used for correction of satellite orbit, i.e., its correction and compensation of various perturbing influences distorting this orbit (atmospheric drag, nonsphericity of the earth and eccentricity of its field of gravitation, influence of the moon and others). Electrorocket engines can also serve to change satellite orbit – its apogee, perigee, and average altitude, attitude, etc.

In particular, with their help it is possible to shift a satellite from a low-altitude orbit, where it is put by a carrier rocket to a higher one, including, for example, a daily orbit, i.e., one having a 24-hour period of rotation; this orbit is at an altitude of approximately 35,800 km and is very important for many practical uses of satellites. The duration of such a shift will depend on the acceleration which the engine can impart to the satellite, i.e., on the ratio of engine thrust to mass of satellite. But very frequently in such cases time will not play a special role.

It is possible to imagine a special "transport" installation with electrorocket engines which will constitute a unique "migrating" satellite-tug. This space tug will convey other satellites from orbit to orbit and do nothing else. Such a method can, of course, be used also for cargo shipments between satellites and space orbital stations. For passenger communication, obviously, such hardly moving "crews" are not useful.

But if electrical rocket engines can perform good service in outer space near earth, i.e., in space "surburban" communication, then, obviously, their role is even greater in distant, interplanetary space trips. After all we already know that effectiveness of application of electrorocket engines is especially great in those cases in which very high speed of outflow turns out to be most advantageous, and it increases with lengthening and complication of route of space flight.

Electrical rockets will accomplish cargo trips from circumterrestrial to circumlumar orbit. This cargo communication will be at first especially important after landing of astronauts on the moon and creation there of a permanent scientific station — after all at first these lunar colonies will be completely dependent on earth for logistics. Cargoes will be transferred from earth into circumterrestrial orbit and from circumlunar orbit to moon, of course, with the help of ordinary chemical rockets. The same goes naturally for flights to all planets — electrorockets cannot cope with a strong gravitational field.

In flights to the moon, which will probably be accomplished with the help of unmanned, automatic electrorockets, there will be transported a larger payload than is possible with the help of chemical rocket engines at the same total weight of rocket, but also duration of flight will be somewhat longer. This seems justified — win one, lose one, that's the way it usually goes. But here in realization of trips to planets, even the nearest, and especially distant ones, the gain can be already both in size of load, and in duration of flight.

Thus, for example, a flight to Mars on an electrorocket can last approximately 300 days, and the return trip can be even shorter, approximately 260 days, i.e., almost as long as and in the flight of an ordinary chemical rocket. It is true that chemical rocket engines will work minutes in such a flight and electrorocket engines will work the whole time of flight, i.e., more than one and one-half years. But then the payload of the electrorocket can be more than one third of its full weight, which is considerably more than the maximum possible value for an ordinary chemical rocket.

In this example exit velocity from electrorocket engine is equal to 120 km/s. In such a flight there can already be people on the ship.

If, however, flight is more distant, for example, to Saturn, then it will be not only much more profitable with respect to payload (assuming that up to now it has been totally unrealizable with the help of ordinary rocket engines) but also of much shorter duration if an electrorocket is used. Instead of 6.5 years necessary for flight of the usual rocket, an electrorocket will accomplish such flight in only 2.5 years. Huge difference! Here we are already getting into an area in which electrorocket engines have essentially no competitors.

Thus, electrorocket engines permit expecting to "conquer" the whole solar system and realizing flights to the most distant planets and even reconnaissance trips in orbits of these planets and into the zone of the possible 10th planet of the solar system and hypothetical mysterious belt of freezing comets slowly revolving around the sun at gigantic distances from it.

Well, what else? Will electrorocket engines be able to open a path to other stellar worlds and ensure flight to distances incommensurably larger than the diameter of the solar system?

As is known, the stars nearest to the sun are in the creation of Centaurus; these are the closest of all stars to us, also called "nearest" or, in Latin, "Proxima Centauri," and a second one much brighter and a little bit further distant — "Alpha Centauri." The distance to these stars is approximately four and one quarter light years, i.e., a ray of light travels all the way from them to our eye in more than 4 years.

From the earth to the sun it is one hundred fifty million kilometers, but a solar ray covers this distance in approximately 8 minutes. More than four years is an entirely different scale.

If, duration of journey is disregarded and it is accomplished at the speed with which electrorockets fly inside the solar system, i.e., on the order of tens of kilometers per second, then such interstellar flight is fully within the powers of space electrorockets. But it will last tens and hundreds of thousands of years! At worst such flight of automatic, unmanned spaceships will be possible in future, but it is doubtful whether it will organize space science: publication of scientific results of such an experiment will have to wait too long. Flight of ships of such duration with a crew on board are completely out of the question.

How can duration of flight be decreased. The obvious way is to increase ship speed. But here two obstacles immediately pop up, although electrorocket engines in principle can provide immeasurably higher speed of flight than the speed of contemporary rockets — for this it is necessary only that they work long enough. The first difficulty is connected with the fact that speed increase necessary to solve or at least facilitate the problem should already be very great. After all increasing speed ten or even one hundred times (such an increase is not dreamed of with ordinary chemical rockets) does nothing to solve the problem — duration of flight will still be many thousands of years. Only approximation of ship speed to the velocity of light in vacuum, equal, as is known, to 300,000 km/s and constituting, in accordance with the ideas of contemporary physics, the highest possible speed in nature, decreases the duration of interstellar flight to several years or tens of years at the shortest. As can be seen, even huge increase of ship speed does not solve the problem by far. And, at the same time, such increase of speed requires colossal consumption of the working substance of the electrorocket engine, so large that it makes the flight itself practically unrealizable — this is the second fundamental difficulty.

How is it possible to surmount both difficulties; what ways does science see for this?

If one talks about decrease of expenditure of working substance, then the method of achievement of this target is obvious; we already know it; increase exit velocity. It is obvious that exit velocities of hundreds of kilometers per second, characteristic for electrorocket engines most perfected in this respect, already turn out to be insufficient here. Now there is already needed very high speed, approaching as close as possible to the velocity of light.

Is it possible in electrorocket engines to chase particles of working substance to such sublight speeds? Fundamental methods of solution of such problem are known from experience with accelerators used in nuclear physics laboratories. In such accelerators — proton synchrotrons, bevatrons, and cosmotrons — there are attained just such speeds, especially high in the case of less massive particles — electrons — and lower for protons and heavier atomic nuclei. Thus it is possible to imagine an electrorocket engine similar to any of these accelerators. It is true that all of them have very large dimensions, making them unfit for installation on aircraft, but technology of development of accelerators is developing so fast that it is possible to imagine accelerators of generally acceptable dimensions.

This is not the main thing. In any accelerator the number of accelerated particles is relatively insignificant, and the bundle of such particles coming out of the accelerator exerts influence on it with so small a reaction force that to talk about the practical use of such force as moving thrust makes absolutely no sense at all. This means the number of emanating particles must sharply increase in order to obtain any noticeable, sufficient thrust. And this cannot be done since it is prevented by the known relationship between tractive force, exit velocity, and the power feeding the engine of the power plant. If one increases exit velocity from an electrorocket engine, let us say, 100 times so that consumption of working substance in interstellar flight decreases, then at the former value of thrust the required power of the power plant will also increase 100 times. The necessary increase of exit velocity as compared to attained values for contemporary electrorocket engines can be not 100 but 1000 times. We are again confronted with a problem solution of which forced decreasing thrust of electrorocket engines to fractions of a kilogram. It is doubtful whether smaller values of thrust can be used; this will disproportionately increase duration of flight. This means it is necessary to increase engine power and the power of the whole propulsion system.

With a power of hundreds of thousands and even millions of kilowatts the engine will develop thrust of fractions of a kilogram. Truly, a mountain is borne by a mouse! And all that is why this mouse is already very swift; its speed is close to the velocity of light.

In order to accelerate the ship to near the speed of light speeds necessary for realization of interstellar flight practically conceivable in duration, the electrorocket engines of the ship have to work a very long time, the best of all, all the way, so that during the first half of the trip they accelerate the ship, and starting from halfway decelerate it. It is easy to imagine what colossal energy content stored on the ship should be expended – after all, an engine of great power should work for many years and decades in succession.

Calculation shows that the only energy feasible in interstellar flight, i.e., intranuclear energy, is grossly insufficient for realization of such flight. There is no point in talking about chemical energy.

Thus necessary energy once again becomes an obstacle on the way to space. The first barrier which it erected is connected with small value of energy of chemical fuels. This barrier will be surmounted by electrical rocket engines. Now again it is necessary to look for new ways, this time a way of surmounting the weakness of electrorocket engines. Is it possible to create new engines in principle different from electrorocket engines which would combine two, one would think, incompatible qualities – maximum possible exit velocity and new sources of energy?

Science knows such engines up to now only in theory. They are photon, or quantum, as they are still called, rocket engines, engines of interstellar ships.

A quantum is the smallest fraction, "particle," the minimum amount of energy. Contemporary physics considers that all known forms of energy have to have a certain minimum, limiting value, a unique "atom" of energy. Energy smaller than a quantum is inconceivable; such a value of energy does not exist. Any amount of energy is, therefore, a whole number of quanta – halves of quanta do not occur. Physics knows how to determine the theoretical value of a quantum in every given case. A quantum of sound energy is usually called a phonon, and a quantum of electromagnetic energy a photon. The value of the latter is determined only by frequency of radiation – it is directly proportional to frequency. Therefore, for example, a quantum, or photon, of blue light is larger than a quantum of red light, and a quantum of X-rays is much larger than a quantum of infrared radiation or radio beams.

The photon is one of numerous elementary particles, which are so much the concern of contemporary physics, trying with their help to penetrate into the deepest secrets of the universe. In contrast to other elementary particles the photon does not possess rest mass, i.e., it is impossible to stop a photon; it either moves with the velocity of light or vanishes and does not exist.

And here are such electromagnetic quanta – photons are to be used as working "substance" of new engines. There is no doubt that photons can be rejected in a beam to one side; the best evidence of that is the ordinary searchlight feeling the night sky. It is clear that a rejected light ray should create force of reaction, since experimental confirmation of pressure of light was obtained for the first time more than half a century ago by our remarkable compatriot, Moscow physicist P. N. Lebedev.

But the experiment of Lebedev was outstanding because he had to measure minute disappearing forces — so insignificantly small is the pressure of light rays. Actually, solar rays press on an ideal 1 m^2 mirror (i.e., reflecting rays) surface perpendicular to them with a force of approximately 1 mg, slightly less. Even a square kilometer surface would be acted on by a force of less than 1 kg (if the surface absorbs all incident rays, then the force will be half as much). This force is so small that to use it as jet thrust during the study of light is practically, of course, very complicated. However, calculations show that even such a small force can sometimes be used in space. In particular, the idea of creation of a so-called solar-sail spacecraft for flight in circumsolar space can be completely justified. The force of pressure of solar rays on large and very light "sail" surfaces of a craft can impart to it, as is evidenced by strict calculation, very high speed.

And yet for a starship such a force of pressure of radiated light is very small. In order to increase recoil force of emitted light rays to an acceptable value the temperature of the radiator has to be incredibly high, equal to many millions of degrees. Obviously, this way does not work, so a photon engine will not be created.

There is one more fundamental difficulty on the way to creating such an engine. It consists in the necessity of creation of a reflector for direction of the beam of photons emitted by the engine in one direction common for all of them. This problem is never complicated when the rejected beam of light does not possess high energy — in such a case any sufficiently good mirror parabolic reflector like that of an ordinary searchlight is useful. It is true that such a reflector even in the best case does not reflect all photons falling on it; part of the light energy is absorbed by the material of which the reflector is made and becomes heat — the reflector is heated. But since this part is very small, the heating obtained is practically imperceptible.

The photon engine is another matter. Here the "mirror" should reflect a huge flow of light energy (although we do not yet know how to create it). With the best known and even conceivable mirror it will nevertheless absorb so much energy that it will instantly evaporate. Here, obviously, there will be needed quite another type of "mirror," unlike usual viewing mirrors of searchlights. In order to imagine, at least as an illustration, what kind "of mirror" scientists call in their theoretical searches, we will refer to the well-known German scientist E. Zenger — he proposed using for this purpose an electronic cloud in a powerful magnetic field.

And, finally, the third fundamental difficulty, the last to be given here, but probably the most important and difficult to surmount. No matter how complicated it is to create a source of light radiation of necessary colossal power and no matter how difficult it is to concentrate a beam of this radiation with the help of a reflector, these problems, nevertheless, can probably be solved. Thus the first part of the problem of creation of an interstellar rocket engine will be solved — exit velocity will be the maximum exit velocity possible. But what can be done about the second part of the problem, what should the source of huge energy necessary for flight be? After all for an interstellar engine there is needed not only highest possible exit velocity but also highest possible use of sources of energy stored on board the ship.

Let us assume that, for example, there is created a source of radiation feed from an ordinary atomic reactor or even thermonuclear reactor, a not yet existing reactor. Does this solve the problem? No, since in the best case this will mean use of only approximately one thousandth of all potential energy stored in nuclear fuel. As you see, only one thousandth is very far from the full exhausting of all potential energy which we required. This is why usual sources of atomic energy are no good here; interstellar flight cann

Fig. 88. Circumsolar space of the future will be plowed by solar-sail spaceships.

be accomplished with them; it is necessary to have too much atomic fuel on board even with maximum possible "outflow" speed, which is that of light.

But what does one thousandth mean? What reserves of potential energy of atmoic fuel are in question?

We have in mind that potential energy which is included in any substance, but never in only one atomic fuel, where all substances with respect to the value of this energy per 1 kg of mass are absolutely identical. This potential energy, in accordance with opinions of the theory of relativety, is determined by the well-known Einstein equation, according to which potential energy is equal to the product of the mass of the substance by the square of the velocity of light. This is the famous $E = mc^2$ and characterizes the hidden reserves of energy in a substance. The less mass, the less reserve of energy. When a chain reaction of disintegration of atomic nuclei of uranium or plutonium occurs, then the initial mass of nuclear fuel as a result of such reaction decreases less than one tenth of one percent; in the case of hydrogen-helium thermonuclear reaction this decrease of mass is approximately one and a half times more, but still equal to only approximately one tenth of one percent. Here is the one thousandth talked about above. Decrease of initial mass to 1/1000 signifies the same decrease of initial potential energy. Only 1/1000 is used by the photon engine in our example, but 999/1000 remains unused. Yes, this is not what is required for an interstellar ship!

However, does science know, in general, ways of completely liberating the potential energy of a substance? Yes, at least, one such way is known. Inasmuch as in this process, which scientists have repeatedly observed in experiment, all potential energy of the substance is used, the mass of the substance becomes equal to zero, and the substance vanishes or, so to speak, annihilates (from the Latin "nihil" – nothing). Therefore, the process itself is called annihilation. It is doubtful whether the name is successful if it is considered that the mass in general never vanishes – the mass of energy liberated in the process is exactly equal to the initial mass of the substance. Here as in an atomic reactor the mass of liberated atomic energy is just equal to the "defect," i.e., the shortage of mass of the parent substance; the total mass of matter and energy (after all energy is also one of the forms of existence of matter) is always the same.

What is the physical process of annihilation? The best known and simplest example of this process is collision of an electron with its "antiparticle" – a positron, i.e., a positively charged electron. With such collision both particles annihilate and generate a quantum, and that and two-three quanta of electromagnetic radiation generate a photon. The total mass of these quanta is equal to the initial mass of colliding particles, i.e., twice the mass of an electron. The only difference is that the electron and positron possess rest mass, and the quanta formed in their place do not possess such mass.

Besides electron-positron annihilation, scientists know other examples of this process of annihilation, indeed more complex ones with several consecutive transformations. One fact is important – in nature there exist and, consequently, can be used processes in which potential energy of a substance is completely converted into energy of radiation. Here is a process the result of which is flows of quanta (we assume, as was noted above that they can be focused in one general "stream"), and can serve as a basis of the photon engine starships. After all in it and only in it are there happily maximum values and exit velocities and degree of utilization of potential energy of substance. This is why future interstellar cosmonautics is so connected with hopes of creation of a photon annihilation engine.

But it seems that it should grieve the reader even more. Even if this maximum possible, ideal rocket engine, the unattainable dream of astronauts, is created all the same this will probably not solve the problem of interstellar flight. Since such a flight should last too long in this case and, mainly because reserves of annihilation "fuel" obtained on board the ship are nevertheless too large. However, science does not turn away even here from difficulties which seem in principle insurmountable because of their physical essence – for science there are no such strengths which the creative genuis of man would not dare to storm. It is true, we are here getting into a region of still more daring fantasies.

Scientists think the deficiency "of fuel" on board an interstellar ship could be compensated for by the use of interstellar space substance as such "fuel." Outer space is not empty; it is filled with particles of matter floating in it, extremely rarefied on the average. A ship flying with almost the speed of light will encounter on its way enough of such matter in spite of its rarity; for such a ship space will never be "empty." It is possible to preselect routes for the flight of a ship which cut through zones of high concentration of space matter – clouds of dust and gas. The capture and "processing" of this substance in radiation is already a matter of technology, although it is still, it is necessary to confess, not supported in this respect by science. Thus it will be possible to obtain a unique straight-flow photon annihilation engine. It is possible, of course, to try to feed the ship by energy from without, from special energy stations sent after it. Incidentally, especially interesting possibilities are opened in this respect by remarkable achievements of quantum radio physics connected with creation of quantum-mechanical generators of coherent radiation, so-called masers (for the radio frequency section of the spectrum of electromagnetic waves), lasers (visible section) and irasers (infrared rays).[1] After all these quantum-mechanical generators of electromagnetic waves can send great, quite recently seemingly fantastic, distances in space accurately directed, highly concentrated (an this seemed recently unattainable), and especially powerful (and this exceeds the boldest fantasy of recent past) rays of electromagnetic energy. With the help of these energy rivers extending hundreds of millions of kilometers it is possible to count on organizing the supplying of starships with energy in their distant trips.

No matter how complicated all these problems are, nothing is impossible in their solution. But how is it possible essentially to

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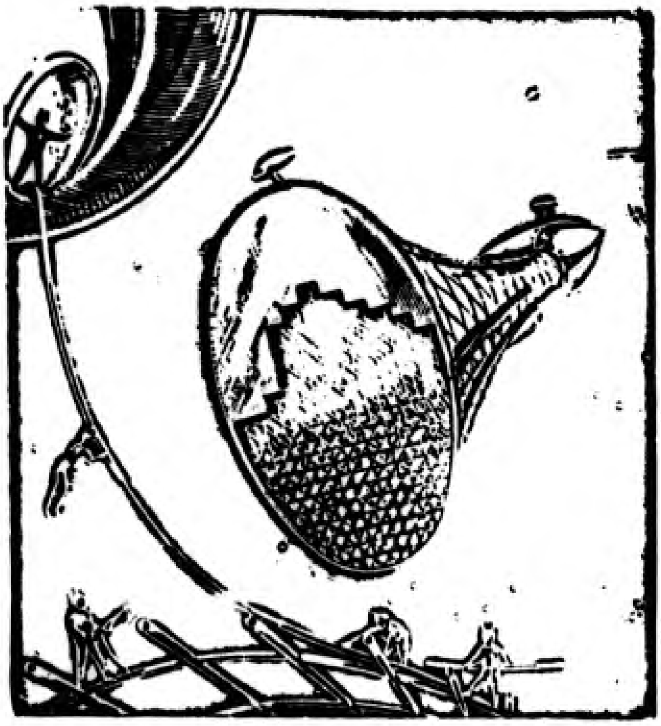
[1] As is known for development of these instruments Soviet physicists N. G. Basov and A. M. Prokhorov were honored with the Nobel prize in physics in 1964.



GRAPHIC NOT
REPRODUCIBLE

Fig. 89. Astronauts will dash to distant stars at speeds near that of light on quantum (photon) spaceship-starships.

decrease the duration of flight and can this be done in general if it is possible neither to exceed the velocity of light nor bring the destination nearer, to decrease the distance to it? After all time is distance divided by speed; everyone knows that.

And here nature itself unexpectedly turns out to be benevolent and comes to the aid of cosmonautics. If laws which seemed fixed do not organize it, it changes them. In reality, of course, the discussion is about new more exact laws of nature discovered by science and formulated by the Einstein theory of relativity. According to these laws time goes by much more slowly on the ship than on earth, the more slowly the nearer the speed of the ship is to the velocity of light. With enough proximity this "deceleration" of time on the ship and, accordingly, increase of "natural" speed of its flight (i.e., speed according to the ship clock) turn out to be so considerable that the most distant space targets turn out to be unexpectedly quite close. Thus, flight a distance even of millions of light years if desired (if one keeps in mind, of course, that we are talking only about theoretical possibility, regardless of scientific and engineering difficulties connected with it) can be accomplished in a year and even faster. It is true that astronauts returning home to earth after such a flight will find that millions of years have passed here, and they will not find even their distant relatives, but can this stop a man yearning for the unknown?

We could only slightly touch the subject of interstellar flight in connection with the photon annihilation engine which can make it real. Certainly, only one engine cannot by far solve this whole gigantic problem; it is no match for this problem and difficulties on the way to its realization.

But science, true, daring science believes in realization of even intergalactic flights, believes in encounter with thinking creatures of other worlds.

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