N85-27933

NASA TECHNICAL MEMORANDUM NASA TM-77654

DESCENT VEHICLES

Ye. I. Popov

Translation of Spuskayemyye apparaty, Novoye v zhizni, nauke, tekhnike, Seriya kosmonavtika, astronomiya, No. 4, 1985, Moscow, "Znaniye" Press, pp. 1-64

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 MAY 1985

STANDARD TITLE PAGE

1. Report No. NASA TM-77654	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESCENT VEHICLES		5. Report Date June 1985
		6. Performing Organization Code
7. Author(s) Ye. I. Popov		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address The Corporate Word, Inc. 1102 Arrott Bldg. Pittsburgh, PA 15222		11. Contract or Grant No. NASW-4006
		13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes Translation of Spuskayemyye apparaty, Novoye v zhizni, nauk tekhnike, Seriya kosmonavtika, astronomiya, No. 4, 1985, Moscow, "Znaniye" Press, pp. 1-64.

16. Abstract The creation of descent vehicles marked a new stage in the development of cosmonautics, involving the beginning of manned space flight and substantial progress in space research on the distant bodies of the Solar System. This booklet describes these vehicles and their structures, systems, and purposes. It is intended for the general public interested in modern problems of space technology.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	THIS COPYRIGHTED SOVIET WORK IS REPRODUCED AND SOLD BY NTIS UNDER LICENSE FROM VAAP, THE SOVIET COPYRIGHT AGENCY. NO FURTHER COPYING IS PERMITTED WITHOUT PERMISSION FROM VAAP.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	49	

DESCENT VEHICLES

Ye. I. Popov

INTRODUCTION

Launching the first spacecraft, initially into artificial Earth satellite orbit and then to study the Moon and planets, was the first phase in applied aeronautics. However, because manned spaceflight was ahead, the spacecraft (or part of it) had to return to Earth. In turn, space flights to study the Moon and planets required that the problem of landing on the subject heavenly body be solved. The velocity of a spacecraft relative to Earth and other bodies in the Solar System ranges from 2.4 km/sec for the Moon to 60 km/sec for Jupiter. And this is with initial zero velocity far from a planet (as specialists say, velocity at infinity). At higher initial velocities, i.e. non-zero, rendezvous velocity will be even higher. /3*

Even if the spacecraft assumes the orbit of an artificial satellite of a heavenly body, velocity relative to the given body will be only about 1.4 times lower (e.g. for the Moon 1.7 km/sec, for Jupiter, about 43 km/sec). Direct contact between a spacecraft and a heavenly body at these velocities results in complete destruction of the craft. Therefore, to land on Earth or on another planet, the spacecraft's velocity must be reduced to an acceptable level. This reduction in velocity must be smooth to ensure cosmonaut safety during return to Earth, but may be abrupt for space probes landing on other planets or for returning unmanned compartments from orbital space probes. /4

In radio transmissions and newspapers, we come across the expression, "After successful completion of work in outer space in artificial Earth satellite orbit, the cosmonauts returned safely to Earth in the descent vehicle." Why in a "descent vehicle," and not the "Soyuz" spacecraft, which the cosmonauts entered from the "Salyut?"

The concept "descent vehicle" appeared only at a certain stage in the development of aeronautics. This concept is not typical of means of transport invented previously: automobiles and railroads, seagoing and airborne. All these forms of ground transportation arrive at their destination in the same form in which they departed. We have never seen or heard that a passenger boarding a train arrived at his destination in a separate car without the train. Even an airplane delivers a

*Numbers in parentheses indicate pagination in the foreign text.

passenger to the airport's landing strip, landing as a whole in its original form.

What's going on? Why are individual parts of a spacecraft usually used for landing?

Before we answer these questions, let us consider and compare the velocities at which means of transportation familiar to us, as well as spacecraft and unmanned probes, travel. Seagoing and river ships have maximum traveling speed of 10-20 m/sec (36-72 km/hr); automobiles: 20-40 m/sec (72-144 km/hr); high-speed trains: to 60 m/sec (about 200 km/hr); passenger airplanes: 80-250 m/sec (300-900 km/hr). Spacecraft fly at velocities 2-3 times higher. To become an artificial Earth satellite, a body must assume a speed of about 8,000 m/sec; a Venera or Mars space probe, more than 11,500 m/sec. Even greater velocities are required for flight to more distant planets.

Note that an artificial Earth satellite's velocity, on the order of about 8 km/sec, is about 10 time higher than that of a bullet shot from a rifle. Only one person, Baron Munchausen, flew at about the speed of a bullet by firing himself from a cannon, and even this is legend. But typical velocities for spacecraft in artificial Earth satellite orbit are now 10-20 /5
times higher than that produced by a cannon. And cosmonauts live and work inside the spacecraft and orbital probe.

The kinetic energy of the spacecraft's travel is quite high. For example, if a bullet traveling at low velocity strikes an obstacle, it becomes seriously deformed and heats up. What happens to a spacecraft traveling at high speed when it collides with the surface of the Earth or of another body in the Solar System?

There are quite a few of these "experiments" in nature. The surfaces of the Moon and other bodies in the Solar System have many craters of varying sizes -- from meters to 200 kilometers or more. We can see them on the Moon even with a small telescope. The surfaces of other bodies in the Solar System become just as clearly visible as a spacecraft flies toward them. These craters originate from collisions with falling meteoroids and other heavenly bodies of relatively small mass. There are such craters on Earth. They include the famous Azov Crater, as well as newer, small craters from the fall of the Sikhote-Alinsk meteorite and others.

Besides suffering damage, the falling body heats up to incredible temperatures because a huge amount of kinetic energy is converted into heat. For example, an artificial Earth satellite flying at 8 km/sec has an energy of 32 MJ per kilogram of mass, while a celestial body flying relative to Jupiter at second cosmic velocity (60 km/sec) has 1,800 MJ per kilogram of mass. If, for example, we melt ice and then heat the resulting water to complete evaporation, we would require only a little more than 3 MJ per kilogram of mass. When metals are heated to melting and then boiled until complete vaporization, each kilogram of mass requires 8 MJ for iron, 6.5 MJ for copper, 7.16 MJ for magnesium, and 11.6 MJ for aluminum.

Consequently, if all kinetic energy, even that of an artificial Earth satellite, turns into heat, the body completely vaporizes, regardless what material it was made of. For comparison, note that, if all the kinetic energy of a high-speed /6 train racing at 60 m/sec (200 km/hr) were converted into heat and were used to heat the train, the train (made of aluminum-magnesium alloy) would heat up by only 1°C. This difference in heating is determined by the fact that the kinetic energy of the moving body increases nonlinearly as velocity increases, but is proportional to the square of the velocity.

All these calculations demonstrate the importance of the problem confronting spacecraft designers to ensure cosmonauts' safe return to Earth and, at the same time, they show what large amounts of energy are involved. There are two approaches: slow the spacecraft, expending little energy, or ensure adequate heat protection for the spacecraft to keep it from heating as it slows in the planet's atmosphere. The natural choice would be to reduce the amount of energy consumed in deceleration or, because of the large energy flows, to make heat shielding relatively lightweight, without, of course diminishing the safety of the cosmonaut's flight upon descent to Earth.

This problem is easily solved if we do not try to save the entire craft, but only part of it, named the descent vehicle. This separate compartment can easily hold the required equipment, as well as cosmonauts and material delivered to Earth after manned flight.

Descent vehicles are thus intended to deliver cosmonaut-researchers to Earth or scientific equipment to another planet to conduct research in its atmosphere or on its surface.

THE PURPOSE OF THE DESCENT VEHICLE

In near-Earth flight, the descent vehicle is intended to deliver cosmonauts to Earth after they have completed their research program in artificial Earth satellite orbit and to deliver the material for these studies -- photographic and movie film, results of technological experiments, etc. The descent vehicle of an unmanned space probe intended to study bodies in the Solar System delivers a set of scientific equipment /7 to the surface of a planet. This equipment is used to photograph the landing site, transmit images to Earth, and study the chemical and mechanical properties of the soil. The atmosphere's chemical composition (if there is one), the level of illumination in the atmosphere and on the surface, wind speed, the presence of aerosols, and many other factors are determined.

Descent vehicles may deliver cosmonaut-scientists to other bodies (particularly to the Moon), and then part of the descent vehicle is launched into artificial planetary satellite orbit to dock with the mother ship. The descent vehicle of the mother ship then delivers the cosmonauts to Earth. Descent vehicles without a cosmonaut, equipped with automated equipment, may also contain a return stage.

For example, the Luna 16, which landed on the Moon's surface, had a return stage. After the descent vehicle was loaded with lunar soil, the return rocket was launched from the descent vehicle's base, which was on the Moon. Launch occurred vertically, without the artificial Moon satellite leaving orbit, and, following flight trajectory, the descent vehicle returned to Earth. The return stage had a rocket module (propulsion system with fuel supply), instrument compartment, and descent vehicle intended for landing on Earth. The descent vehicle delivered samples of lunar soil to Earth which were transfered to scientific institutes for research.

Space craft descent vehicles are classified in two large groups in terms of design. These are descent vehicles for landing on planets with an atmosphere like Earth's or denser and descent vehicles intended to land on bodies in the Solar System without atmosphere. A mandatory condition for the first group is a heat-shielding covering to prevent the spacecraft from overheating during deceleration in the upper layers of the atmosphere. At the final stage of deceleration, a parachute /8
system is usually used for a soft descent vehicle landing.

The second group of descent vehicles does not require a heat-protective covering for deceleration in an atmosphere because there is no atmosphere. A parachute is also useless in a vacuum, since there is nothing to fill its canopy. The basic component of a descent vehicle for a body without atmosphere is rocket engines capable, during relatively prolonged operation, of reducing velocity from cosmic to an insignificant level on the order of 1-10 m/sec. For landing on a planet with a rarefied atmosphere (e.g. Mars), the two methods are used in succession: aerodynamic deceleration in the atmosphere with release of the parachute and final deceleration using the propulsion system.

Thus, a descent vehicle is a device intended to bring about a soft landing on Earth or on another body of the Solar System and to protect man and scientific equipment from significant g-forces and thermal currents during atmospheric deceleration.

DECELERATION IN AN ATMOSPHERE

Until now, descent vehicles for planets with an atmosphere like Earth's or denser were used to land spacecraft on Earth and on Venus. Chronologically, descent vehicles intended for landing on planets with atmospheres appeared before those for planets without atmospheres. The first landing of a descent vehicle on Earth occurred in 1960. This was an unmanned satellite spacecraft intended to perform all stages of manned flight into space. The first landing of a spacecraft on a body without atmosphere (the Moon) occurred on February 3, 1966 (Luna 9).

It is true that a spacecraft landed on the Moon in 1959, but this was without a descent vehicle and the collision with the Moon's surface resulted in the craft's complete destruction. However the special (three-dimensional) arrangement of message bags made it possible to prevent damage to some of them.

As already noted, there are two basic ways to reduce the velocity at which a spacecraft travels: use of a propulsion system similar to the one which puts a satellite into orbit, and deceleration in the planet's atmosphere. The first method requires consumption of a large amount of fuel to reduce the high velocity and is now considered uneconomical for planets with an atmosphere if chemical fuel is used. /9

Deceleration in the atmospheres of celestial bodies is a common phenomenon in nature. Because of the presence of an atmosphere, we find "celestial stones," called meteorites, which have fallen to Earth. They are stone, iron, or something in between. Having fallen to Earth, meteorites are the remains of meteoroids traveling on their own orbits which have collided with Earth. Traveling through the atmosphere at an incredible initial velocity is costly to our "heavenly guest." Most of it melts, vaporizes, and disperses in the atmosphere. Fortunately, this does not happen to all of it, otherwise we would not find meteorites.

The point is that released thermal energy is not totally used up in heating a meteoroid or spacecraft (therefore, the calculations presented earlier for converting a falling body's entire kinetic energy into heat were exaggerated). The nature of thermal energy is such that, at a certain intensity, it strives to distribute itself evenly. And during deceleration in the atmosphere, thermal energy (generally most of it) is transfered to the atmosphere.

And all velocities at which meteoroids travel toward the Earth are high -- from 11.2 to 72 km/sec. Theoretical calculations and data from observations indicate that, at approach speeds above 22 km/sec, meteoroids are completely destroyed in the Earth's atmosphere. It is interesting to note that on June 30, 1908, witnesses saw the trail of the Tungus Meteorite traveling from northwest to southeast. Consequently, it traveled at a high angle toward Earth and, possibly, perpendicular to the Earth's movement. Thus, approach velocity was more than 30 km/sec, which may be why the heavenly body was completely destroyed.

But let us return to the problem of decelerating a spacecraft. Note that even if natural deceleration in the atmosphere is used, it would still be impossible without a /10 propulsion system. Free fall from orbit because of deceleration in a rarefied atmosphere cannot be considered acceptable, since there are problems predicting the time and site of landing. The propulsion system creates a braking impulse to shift orbit so that its perigee is precisely in the dense layers of the atmosphere. The greater the braking impulse, the steeper the entry of the spacecraft into the dense layers of the atmosphere and the more rapid its deceleration.

However, deceleration rate should be limited by g-forces tolerable to crew and instruments, as well as by the spacecraft's structure. In view of these considerations, the slope of entry into the atmosphere must be smaller. Most of the kinetic energy of a descent vehicle transformed into heat energy when it decelerates in the atmosphere must be disseminated in the outside environment; only a small part of it may be absorbed by the structure's mass or the craft's heat-shielding system. If trajectories for descent into the atmosphere are flat, the level of g-forces and the heating rate are lower. However, because the amount of time required for reduction increases, the total portion of heat energy delivered to the craft's surface rises.

Atmospheric parameters such as density, pressure, temperature, molecular free path, disturbance dissemination speed (speed of sound), molecular mass, etc. affect the nature and intensity of the interaction between the descent vehicle and the air during reduction and deceleration. But even these parameters are not constant and fluctuate depending on the time of year and day, on changes in solar activity, on climatic factors, on change in wind, etc.

The high velocity at which a descent vehicle enters the atmosphere causes major disturbances in it. In front, in the direction of flight, atmospheric gas begins to compress, not gradually, but with an impact. A seal develops -- a so-called shock wave. This shock wave moves somewhat ahead of the descent vehicle at the same travel velocity. The temperature in front of the shock wave reaches several thousand kelvins. Currents of heat travel everywhere, including to the descent vehicle. /11 The flow of heat reaching the descent vehicle depends on the composition of the atmosphere and its thermodynamic characteristics.

At high entry angles, the increase and decrease in flow because of sharp deceleration occur in peaks. A powerful thermal and dynamic impact is produced, and solid material is rapidly carried off from the heat shield. At low entry angles, the curve for the increase in thermal flow is flatter, the time during which it acts is longer, and less shielding is removed, but, without exception, the entire heat-shielding system heats up considerably.

Thermal energy during spacecraft deceleration enters the atmosphere from the craft's surface in two basic ways: because of convective heat transfer in the boundary layer and because of the shock wave front irradiation. At high flight velocities, convective heat transfer is complicated by gas ionization, irregularity of the boundary layer, and, if mass is removed from the plating surface (the shielding heats, the heat shield evaporates, etc.), by mass exchange and chemical reactions in the boundary layer. Irradiation of the shock wave -- radiant heat transfer -- becomes considerable at flight velocities of 6-8 km/sec and, at higher velocities, becomes a decisive factor.

Thermal energy carried from inside to the descent vehicle's plating is partially dispersed due to radiation from the heated surface, is partially absorbed or carried away (during cooling with mass removal) by the heat shield systems, and partially accumulates due to the thermal capacity of the descent vehicle's structures, causing a temperature increase in the power components. Thorough study of thermal conditions at various points on an actual descent vehicle's plating, which requires rather detailed consideration of heat and mass exchange close to the cooled surface and study of the temperature fields in the structure, is a very complex task. Approximation ratios which make it possible to evaluate the heating rate for certain typical sections of the descent vehicle's surface are usually used. Then these calculations are made more precise on the basis of experiments. Thus, creation of descent vehicles for particular planets with /12 atmosphere is a time-consuming and very complex job, even only from the standpoint of the heat shield, but design bureaus perform it successfully.

EQUIPMENT FOR DESCENT IN AN ATMOSPHERE

Let us look at descent vehicles which exist and are already in use from the standpoint of thermal flow distribution. The kinetic energy of a descent vehicle, although high, is easy to calculate. Only a small part (1-2%) of the energy liberated when a descent vehicle decelerates in an atmosphere is used to heat it. Most of this energy heats surrounding air and disperses in the atmosphere. Basically it is for this 1-2% of the energy allocated to the descent vehicle that heat shielding must be designed.

Generally speaking, energy is wasted in aeronautics. When a spacecraft is launched, only 1-2% of the energy of the fuel burned in the propulsion system is used to increase the spacecraft's kinetic energy. The rest is lost in heating gases and releasing them into the atmosphere, in moving, and in increasing the kinetic energy of the booster rocket's first stages, etc.[1]

The angle of entry into the atmosphere determines both how long the thermal flow's effect lasts and how high head resistance is. At high entry angles, drag increases so sharply that the load factor can reach several g's. This was typical for the first generation of Venera space probes (up to and including Venera 8). Their entry angles reached 62-65°, and load factors were up to 450 g's. This means that each instrument, each component in the descent vehicle became 450 time heavier and exerted that much more pressure on the support to which it was attached than when it was installed on the descent vehicle in the assembly shop.

The Venera spacecraft was in zero gravity on interplanetary orbit from Earth to Venus for a long time, and for over 4 months the spacecraft did not experience power loads. Only upon approaching Venus was great force applied suddenly to the vehicle's hull -- the force of atmospheric drag, trying, like a high-power press, to crush the descent vehicle. It was subjected to the impact of two simultaneous forces: that of the atmopsheric drag and that of a high-power thermal energy current. /13

Something similar happens to any descent vehicle incorporated either into an interplanetary probe or into a spacecraft returning cosmonauts to Earth.

The frontal, outer layers of heat shielding sublimate, i.e. evaporate, and are removed by the air current, creating a glowing trail in the atmosphere. The high temperature in the shock wave ionizes air molecules in the atmosphere and a plasma develops. The plasma cover encompasses most of the descent vehicle and, like a screen, encloses the descent vehicle being carried in the atmosphere, at the same time preventing contact with the cosmonauts or with the unmanned vehicle's radio system during landing. Under terrestrial conditions, ionization takes place usually at altitudes of 120-15 km at maximum in intervals of 80-40 km.

---

1 Apparently, these percentages occur often in nature. As Academician I. B. Petryanov-Sokolov has shown, even the efficiency of processing minerals on Earth is about 1-2%, but this coincidence is probably a topic for another discussion.

Descent Vehicle Shapes. First, note that descent vehicles intended for planets with an atmosphere can be created either for controlled descent -- along a ballistic trajectory --or for descent with a motion control system capable of ensuring that a maneuver will be completed in the atmosphere. Naturally, even the most modern descent vehicles fitted with a control system can also perform descent in ballistic trajectory.

The first descent vehicles used for artificial Earth satellites were spherical. These were the descent vehicles of satellites, Vostok and Voskhod spacecraft, and of biological satellites. Their descent follows ballistic trajectory and is no different from that of natural "descent vehicles" -- meteorites. The sphere is the simplest and most common shape in /14 nature. This is the shape of the stars, planets, small water droplets, etc.

A sphere is not subjected to drag or any other force except gravitation. Aerodynamically speaking, a sphere has a zero lift/drag ratio, i.e. lift during flow around a sphere equals zero. For a spherical structure, g-force depends on flight velocity and angle of entry into the atmosphere. For an artificial Earth satellite whose velocity in orbit is less than 8 km/sec, entry angle must be small, on the order of about one or a few degrees, so that g-force does not exceed 10 g's, which is very important for descent from orbit of a manned descent vehicle.

What does it take to make cosmonauts descending from orbit comfortable, i.e. to cause deceleration as terrestrial gravity accelerates (i.e. about 10 m/sec^2)?

First, the deceleration route must be 3200 km long. Second, if there are no obstacles, i.e. if we disregard the atmosphere, it should take 800 sec to descend with engine running. But in terrestrial conditions, the air envelope cannot decelerate so smoothly during ballistic descent, and deceleration occurs abruptly with high g-forces.

In other words, reducing g-force requires that descent not follow ballistic trajectory, but that lift be used instead. In this case, a descent vehicle with lift/drag ratio must be used. A sphere, as we said earlier, has no lift/drag ratio, but a plate, if it is placed on an incline in the air current, shows the presence of lift. Such a plate (actually round in cross section and convex toward the current) is being used in aeronautics, but behind the crew's compartment: the result is a descent vehicle in the shape of a headlight.

This structure has a lift/drag ratio of 0.35 or, in other words, during travel with the forward wall of the headlight at a specific slope, lift develops, reaching 35% of the force of drag. Lifting force makes it possible to descend along a flatter trajectory, with lower g forces. This shape is typical for the descent vehicles of the Soyuz, Mercury, Gemini, and Apollo spacecraft. However, the Mercury spacecraft cannot take advantage of its own shape to create lift. The craft's design approach does not permit this, and the craft always descends along ballistic trajectory. /15

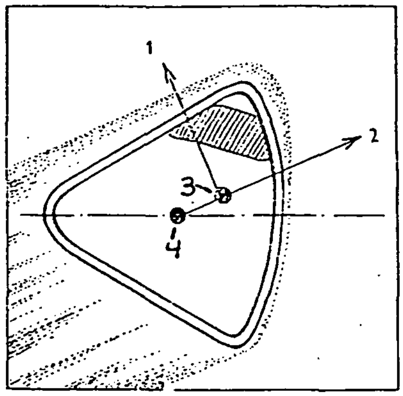


Figure 1. Shifting the center of mass of a descent vehicle.
1 - Lift;
2 - Flight direction;
3 - Center of mass;
4 - Center of pressure.
Shaded area indicates equipment with higher mass.

What does it take to make the forward wall of the headlight slope when an air current flows past it?

In principle this can be done with an orientation system. But fuel consumption would be high. Considerable controlling moments would have to be established to compensate for moments arising because of aerodynamic forces. And, from the standpoint of the expenditure of huge amounts of fuel, this approach is unacceptable.

A simpler approach is to shift the center of mass relative to the axis of symmetry. In a headlight, the main bearing surface is the forward wall -- a bottom having the shape of a segment of a sphere of relatively low curvature. The lateral surface of the descent vehicle is either conical or conical and spherical combined. The vehicle descends bottom up. Since, in terms of outer appearance, a descent vehicle is a body of rotation, its center of pressure (producing the force of aerodynamic effects) is on the axis of symmetry. Thus, the shifted center of mass lies between the bottom and the center of pressure.

This alignment ensures stable positioning of the descent vehicle in an air current (bottom up), as well as asymmetric streamlining of the descent vehicle. Thanks to the latter, lift develops perpendicular to the oncoming flow (figure 1). /16

An artificial Earth satellite can descend successfully from orbit over a wide range of initial conditions with acceptable g-forces and thermal loads both in ballistic trajectory and during descent using the descent vehicle's lift/drag ratio. A motion control system is widely used which is based on a method of controlling the descent vehicle by programmed rotation at the list angle (if the angle of attack is constant) which, during flight, ensures change in effective force -- the projection of lift on a vertical plane. This method requires rather low controlling moments, thanks to the so called static neutrality in terms of angle of list and the constancy of the air current flow pattern during control.

But even when a spacecraft returns from a flight to the Moon, when the velocity at which the vehicle enters the terrestrial atmosphere is near second cosmic velocity, the problem of descent is complicated because of increased g-force and increased thermal flow stress. Successful solution of the problem requires that the "corridor" of entry into the atmosphere, which determines the boundaries in terms of angle of entry into the atmosphere, be maintained very precisely. In case of high angles, there are high g-forces, and, in contrast, when angles are very small, the atmosphere cannot "grasp" the descent vehicle because there is little resistance to its motion.

Note that the boundaries of the entry corridor depend both on the aerodynamic characteristics of the descent vehicle and on how the lift/drag ratio of the vehicle is used at the initial stage of submersion in the atmosphere. In addition, as flight velocity increases, the width of the entry corridor decreases, and this leads to increased navigation and correction system operating accuracy in the ascending phase of the trajectory.

For a descent vehicle with a motion control system, return from the Moon can be approached by another route. At a sufficiently steep entry into the atmosphere, when the entry angle is greater than 2°, the descent vehicle's trajectory, even /17
at small constant angles of attack and at low lift/drag ratio (from 0.2 to 0.3), contains an ascending phase, i.e. the vehicle may ricochet. In this case, the vehicle may enter the atmosphere twice (cf. figure 2). When flying toward Earth at second cosmic velocity at a 3° entry angle, the descent vehicle leaves the atmosphere after first entry, enters an elliptical orbit, and then reenters the atmosphere -- 10,000 km from the point of exit.

However, it is difficult to ensure accurate landing this way, since a deviation in velocity of 0.001 (about 8 m/sec) from design leads to a 300-km deviation in the distance to the point of reentry into the atmosphere, while a 0.1° deviation in in trajectory slope results in a 180-km deviation in distance. To reduce this uncertainty, the trajectory must have as high a slope as possible at the point of exit from the atmosphere. Indeed, this angle is limited by the descent vehicle's marginal lift/drag ratio, as well as by the permissible limit for maximum g-forces (otherwise, submersion into the atmosphere

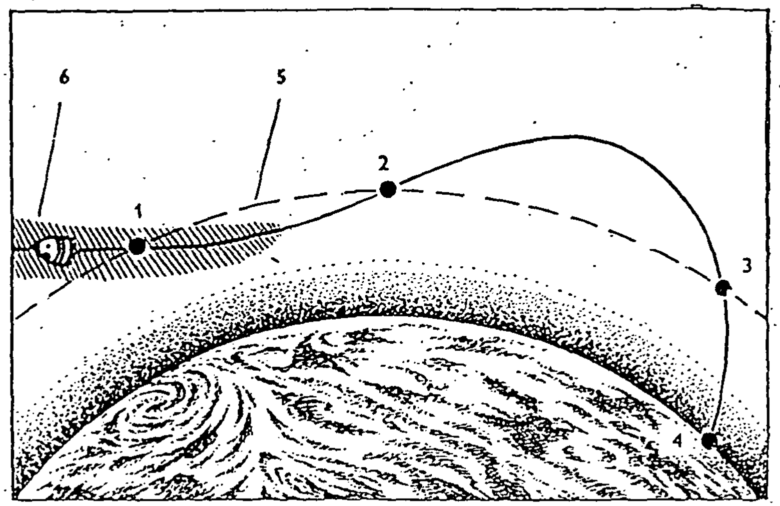


Figure 2. Double submersion into the atmosphere. 1 - First entry; 2 - Exit; 3 - Second entry; 4 - Landing; 5 - Hypothetical boundary of the atmosphere; 6 - Entry corridor.

will be deeper in the first segment). At the intermediate flight phase, the vehicle cannot be controlled, and therefore, the accumulated deviation in distance may be compensated only at the atmosphere reentry phase. /18

We must emphasize that, because of the descent vehicle's capabilities during return from orbit and from lunar trajectories, we provided programmed motion control for the vehicle. However, situations may occur during return from orbit when the descent trajectory cannot be controlled using aerodynamic forces; for example, if a descent vehicle suddenly cannot orient itself before entry into the atmosphere or perhaps while preparing the control system. In these situations, descent must be ballistic, which occurs without use of the vehicle's lift and lateral aerodynamic forces.

A trajectory is selected which ensures much less dispersed landing sites and makes it possible to avoid intolerably high g-forces. But high g-forces are possible if the descent vehicle, let's say, enters the atmosphere turned 180°, i.e. when lift does not push the vehicle upward, but forces it to enter an even denser layer of the atmosphere and descend more steeply. However, arranging the required ballistic descent is rather simple -- the vehicle only need to be made to turn relative to the axis coinciding with the direction of flight. Given this rotation, the action of transverse aerodynamic forces is minimized.

Heat-Shielding Covering. As also noted, almost all energy transmitted by the booster rocket to the spacecraft must be dispersed in the atmosphere when it decelerates. However, a certain part of this energy heats the descent vehicle when it moves in the atmosphere. Without adequate protection, its metal structure burns upon entry into the atmosphere and the vehicle ceases to exist. Heat shielding must be a good insulator against thermal energy, i.e. it must have a low capacity to transfer heat and must be fireproof. These requirements are satisfied by various types of synthetic materials -- plastics.

A descent vehicle is usually covered with a heat shield made of synthetic materials and consisting of several layers. The outer layer is usually made of relatively strong plastic with a fill of graphite, the most heat-resistant material. The next thermal insulation layer is most often plastic with a fibrous glass fill. To reduce thermal insulation mass, its individual layers usually number in the hundreds and are porous, but are sufficiently strong. /19

Heat shielding thickness depends on the type of descent vehicle and its purpose. For example, the descent vehicle of the Venera 14 lost about 30-70 mm of the thickness of its heat shield when it passed through Venus' atmosphere. Consequently, heat shielding had to be thick enough to preserve the descent vehicle's metal structure. This constitutes a large percentage of the mass permitted the descent vehicle. Thus, for the Vostok's descent vehicle, with a mass of 2,460 kg, the mass of the spherical heat shield was 800 kg.

And so, when exposed to high temperature, the heat shield heats from its surface inward and then vaporizes, at the same time removing excess thermal energy from the descent vehicle. To reduce heat shield mass, maximum thickness occurs only at points subjected to the greatest effects of thermal flow. In headlight-shaped descent vehicles, this is the bottom, while side surfaces subjected to less heating have a heat shield of negligible thickness. In individual descent vehicles which have undergone most of the deceleration and are no longer affected by thermal loads, the massive heat shield on the front side (from the bottom) is jettisoned.

<u>Parachute System.</u> After intense aerodynamic deceleration ends, the descent vehicle's motion becomes rather uniform. The rate at which velocity decreases for various structures in the atmosphere near Earth ranges from 50 to 150 m/sec. To preserve the descent vehicle and ensure crew safety, velocities upon landing must be much lower. For example, velocity for landing /20 in water must not exceed 12-15 m/sec; on earth (solid ground), 6-9 m/sec. For comparison, sport parachutists land at 5-8 m/sec. Various parachute systems are used to reduce the velocity at which the descent vehicle falls to Earth.

The mass of these systems also constitutes a specific portion of the mass of the descent vehicle and, as a rule, an increase in the vehicle's mass requires a proportional increase in that of the parachute system. Introducing a parachute system into an air current and turning the canopy are by no means simple tasks, but they are performed successfully in practical aeronautics. At relatively high flight velocities, releasing the large canopy of a main parachute leads to high loads which the parachute material cannot withstand. And high loads can also affect the vehicle's crew. Structurally, this problem is solved by using a system of parachutes.

First, a drogue parachute with a small canopy is shot off with the parachute compartment cover. This drogue parachute deploys the canopy of the decelerating parachute into the oncoming air flow. As a result, the descent vehicle's velocity drops by almost half, and, then, using the deceleration parachute, the main parachute is released. Only part of the canopy of the main parachute is released, not the entire canopy. When the descent vehicle's velocity drops further, the rope used to gather the main canopy is cut, and then main parachute canopy is completely unfurled.

The main parachute canopy has a large working area, which makes it possible to reduce the rate of descent to levels safe for the crew and the descent vehicle itself. However, in principle, it is impossible to completely decelerate a descent vehicle with only one such parachute. Therefore, depending on descent vehicle mass, the main parachute may have one or several canopies. Sometimes, instead of deceleration and main parachutes in stages, a gathered main parachute is used, but, as descent velocity decreases, the gathering in one or both /21
stages is eliminated.

Final deceleration is conveniently accomplished using solid fuel engines. These engines are started directly before touching the Earth's surface, and they reduce descent velocity to 2-4 m/sec. Note that the descent vehicles of the American Mercury, Gemini, and Apollo spacecraft were equipped only with a parachute system, and soft-landing solid fuel engines were not used, since these descent vehicles land in the ocean -- in water.

THE DESCENT VEHICLE FOR VOSTOK AND VOSKHOD SPACE CRAFT

One of the first descent vehicles successfully returned to Earth was that of a Soviet spacecraft/satellite, in the shape of a sphere. This craft/satellite was intended to carry out all elements and stages of manned flight in space. Its descent vehicle was virtually the same as that of the Vostok. The latter consisted structurally of two main compartments: the descent vehicle and the instrument compartment. The descent vehicle included the cosmonaut's cabin.

Upon descent from orbit after executing the deceleration impulse, the descent vehicle separated from the instrument compartment and landed on Earth, while the instrument compartment entered the dense layers of the atmosphere and ceased to exist. The mass of the descent vehicle was about 2,460 kg; its hull was a sphere with a 2.3-m diameter and was made of aluminum alloy. Externally the entire hull, including portholes, was covered by a heat shield, on top of which was applied a layer of thermal insulation required for normal functioning of the craft during orbital flight.

The cosmonaut's cabin had an armchair and craft control instruments. Ensuring the cosmonaut's normal state of health and maintaining normal working capacity in the cabin required two basic systems: life-support and heat adjustment. They maintained normal air composition in the cabin, absorbing CO_2 /22
exhaled by the cosmonauts and ensuring a constant oxygen content in the air, as well as removing excess moisture and creating normal temperature conditions from 20 to 25°C. Pressure in the cabin was held at 755-775 mm Hg.

A fan was installed to uniformly mix the atmosphere in the cabin, which did not have convective currents in zero gravity. The heat adjustment system, common to both compartments, was liquid-based. There was a battery to ensure normal operation of equipment in the descent vehicle. The cosmonaut's console had a craft orientation control lever with three stages of play, as well as an optical device for the orientation system.

Before separation, the spacecraft was oriented in a strictly preset direction and, at a specific time, the propulsion system was activated, transmitting the deceleration impulse to the spacecraft. The engine developed a thrust of 17.5 kN and velocity decreased by 150-200 m/sec. Orbit became elliptical with a perigee less than 100 km above the Earth's surface. As a result, the descent vehicle entered the dense layers of the atmosphere and decelerated.

At an altitude of about 7 km, the cosmonaut could be catapulted through a special opening hatch and, along with his chair, was jettisoned along special guides. After a certain time, a decelerating parachute opened above the chair and, a few tenths of a second later, at an altitude of 4 km when the cosmonaut was separated from the chair, the main cosmonaut parachute opened. The cosmonaut landed at a velocity of 5-6 m/sec. The vehicle descended on its own parachute. Landing was possible without leaving the cabin -- in the descent vehicle, which descended at about 10 m/sec.

Descent vehicles used up to now in Soviet artificial Earth satellites for biological experiments differ little from those of the Vostok, and we will therefore not dwell on them individually. Note only that they go through all stages of descent, including catapulting, since there is no cosmonaut /23
chair. Within the descent vehicle are various representatives

of the animal and vegetable kingdoms, as well as equipment to feed animals and water plants.

The Voskhod, in contrast to the Vostok, had multiple seats. Accommodating several cosmonauts simultaneously required rearranging the cabin. It held three customized chairs, i.e. they were designed to fit the body contours of each cosmonaut. Since landing could take place only with cosmonauts inside the descent vehicle cabin, the non-catapulting chairs were fitted with extra shock absorbers. The main stages of descent from orbit were similar to those for the Vostok. But for greater reliability, this ship had redundancy: In addition to the liquid fuel jet propulsion system, above it was installed a solid fuel decelerating engine.

To reduce impact with the Earth's surface, descent during the parachuting phase occurred with two parachutes, which are attached by separation charges, not directly to the descent vehicle, but to the soft landing engine hull. After landing, the separation charges activated and parachute suspension lines were released from the descent vehicle, so that in high wind the parachute could not drag the vehicle and cosmonauts behind it along the ground.

The solid fuel soft landing engine was activated by a tubular rod lowered 3 m below the descent vehicle. The rod was formed by unwinding spring strip from a coil and winding it into a tube. When the rod touched the Earth's surface, contact was complete and the propulsion system was engaged, having reduced descent velocity by half to 2-4 m/sec.

DESCENT VEHICLES FOR RETURNING LUNAR "GEOLOGISTS"

Descent vehicles for the Luna 16, 20, and 24 unmanned space craft, intended to land on Earth after collecting lunar soil, were 0.5-m diameter spheres. This shape did not require /24
development of the special orientation system needed by a descent vehicle with a lift/drag ratio. Descent in the atmosphere took place along a ballistic trajectory. Critical here was the requirement that the descent vehicle's mass be limited. The absence of a cosmonaut also eliminated obstacles imposed by high g-forces.

The landing stage of these unmanned Luna probes, a descent vehicle for landing on the Moon, served also as the launching device for the Luna-Earth space rocket. This rocket had a liquid fuel rocket engine with spherical tanks for fuel components, as well as an instrument compartment with four antenna spikes and a descent vehicle attached to the instrument compartment by tension tape. The instrument compartment served as the installation site for instruments in the control system, the radio set, the battery, and outside automation.

The rocket's flight path to Earth followed ballistic trajectory, which did not require nor stipulate correction (flight to Earth took about 3 days). Three hours before entry into the Earth's atmosphere, the descent vehicle, using explosive charges, separated from the rocket. Entry into the terrestrial atmosphere was completed at more than 11 km/sec.

At the aerodynamic deceleration stage, the descent vehicle, acted on by the oncoming air current, turned front side to the direction of travel, and the damping device reliably held it in this position. Later the landing process was execute with outside automation devices. As a consequence of the high atmosphere entry angle, the descent vehicle experienced g-forces of 350 g's, and its heat shield was exposed to a temperature of more than 10,000 K. When an altitude of 14.5 km was reached, /25
the descent vehicle's velocity decreased to 300 m/sec.

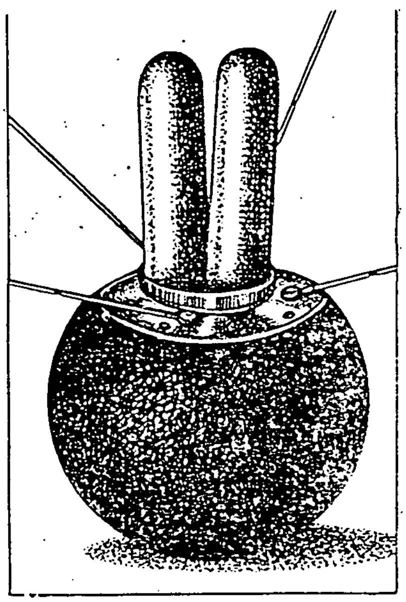


Figure 3. Descent vehicle for the Luna 16 on Earth.

At this point, upon command from the g-force sensor, the parachute compartment hatch was jettisoned and the deceleration parachute was released into the air current. At an altitude of 11 km, on a signal from a barometric sensor, the deceleration parachute detached, and the main parachute was released. Landing took place on solid ground, although the descent vehicle could also have descended into water. To increase buoyancy at the top of the descent vehicle, after the parachute hatch was jettisoned, two flexible balloons were inflated with compressed air.

The descent vehicle of this lunar probe (figure 3) was a hermetically sealed metal sphere whose outer surface had a heat-shielding covering to preserve the vehicle during aerodynamic deceleration upon entry into the Earth's atmosphere. The heat-shielding covering varied in thickness:

greatest at the front (to 35 mm), and only a few millimeters on the opposite end.

Structurally, the descent vehicle consisted of three compartments: instrument, parachute, and a cylinder container for lunar soil samples. The instrument compartment holds radio direction-finder transmitters, batteries, automated components, and a programmer. The parachute compartment contains the parachute (gathered), four direction-finder transmitter antennas, and two elastic balloons used after landing and after inflation to fix the position of the descent vehicle, as well /26
as to create buoyancy if it lands in water.

This descent vehicle was relatively small, and the landing sites in the designated area were spread over hundreds of square kilometers. Therefore, finding the vehicle after touchdown was a problem. For this reason, direction-finder transmitters installed on the vehicle continuously sent signals on a strictly regulated frequency, which made it possible to easily find direction and determine the landing site. A damper which made it possible to reduce vehicle vibrations when it passed through this phase of aerodynamic deceleration was installed inside the bottom of the hull at the front of the descent vehicle.

DESCENT VEHICLE FOR THE SOYUZ SPACE CRAFT

This vehicle became the first Soviet descent vehicle which executed a controlled descent in the atmosphere. The floor and ceiling of the descent vehicle are spherical segments; its side walls, truncated cones. Cosmonauts were placed in chairs with shock absorbers, mounted so that the direction of g-force action during approach to orbit and during descent would be optimized from the standpoint of tolerability.

Sometimes it is worthwhile assigning some of the descent control functions to the crew. It must be kept in mind that g-forces reduce human capabilities. Enduring g-forces was most difficult when they were directed from toe to head, and easiest when they acted at angles from 10 to 15° toward the chest/back and thus there was a small constituent from head to toe. But even in these circumstances, with three or four g's, the scope of movement of hand joints is significantly reduced, and at 8 g's or more, only movement in radiocarpal joints remains free.

This is taken into account during design of control organs. For best g-force endurance, the cosmonaut had to maintain muscle coherence during descent, and handles are best for this purpose. In front of the cosmonauts were a control console and optical view finder used to orient approach /27
control. Behind the chairs are containers with the parachute systems. Instruments and equipment, remotely controlled, are located at the bottom of the compartment beneath the chairs.

Portholes are placed to the right and left of the cosmonauts on side walls.

The heat shield is mounted outside the descent vehicle's hull. This part, which is on the bottom, is a separate panel. During parachute descent, the panel is released. Below the panel to be jettisoned are four soft landing thrust sections which are engaged by a signal from a gamma-ray altimeter.

A board with electrical connection sockets is mounted on the inside surface of the descent vehicle. These connections lead to the other compartments. Before the craft separates, the sockets automatically disconnect.

After aerodynamic deceleration in the descent phase, barometric sensors measure pressure outside the descent vehicle. At an atmospheric pressure corresponding to 9.6 km, a preset timer starts up which formulates the command to jettison the main parachute system container hatch and to activate the drogue parachute. After 16.5 seconds, a command is issued to release the main parachute. At 5.5 km altitude, the main parachute, provided it opens normally, must ensure predefined descent of the vehicle.

To check proper working order of the parachute, actual descent velocity is monitored for 50 seconds. If velocity exceeds the permissible limit, a command is formulated to jettison the main parachute and activate the backup parachute system.

After 75 seconds have passed and an altitude of 5.5 km has been reached, the preset timer sends a signal to detach the front heat shield, and triggering the separation sensor removes the interlock for starting the soft landing engines. In addition, the preset timer issues a command to reconnect the parachute to a symmetric hanger, activate the gamma-ray altimeter, and reset the chair shock absorber system. A signal from the altimeter at about 1 m from the Earth's surface /28
activates the soft landing engines. Special impact sensors, which record the vehicle's landing, remove the interlock to jettison the parachute suspension line.

Let us take as an example the flight of the descent vehicle of the Soyuz T-12. Before the landing operation was executed, the spacecraft was oriented for deceleration. The 4-kN propulsion system was activated above the Southern Atlantic. Having run for 800 seconds, the engine reduced orbital velocity by 115 m/sec -- the orbit became elliptical. Above the Mediterranean Sea at 130 km the spacecraft was set in initial position for separation.

This position is selected so that, by the time separation occurs, the craft's longitudinal axis will have deviated from flight direction by an angle close to 90°. In this case, after separation, aerodynamic forces cannot cause the compartments to approach again and collide. After separation, only the descent vehicle, protected by the heat shield, withstands and overcomes high temperatures and atmospheric resistance. The other compartments are not designed for such extreme conditions and, therefore, burn up in the atmosphere. Controlled descent began over eastern Turkey.

During flight with controllable descent, cosmonauts note that flight resembles travel on a cobblestone pavement because of the vibrations and fluttering which occur. Each of us probably experiences these phenomena during flight on high-speed passenger airplanes. Vibration occurs when the airplane descends to land, especially when it passes through dense cloud cover in which turbulent updrafts exist. In addition, in the upper layers of the atmosphere there are always upward/downward flows, winds blowing, and separate low- and high-pressure areas. During flight in a glider at low velocity, these irregularities roll smoothly and slowly and the glider rises and falls smoothly. If velocity significantly increases, these irregularities occur and alternate more often, one might say, flicker and shake the flying vehicle with small impacts.

DESCENT VEHICLE FOR THE ZOND /29

The descent vehicle for this craft differs little from that of the Soyuz. It enters the atmosphere at second cosmic velocity. Therefore, its heat shield is thicker, and the vehicle is designed for flight to the Moon and back.

Note only that, after flying around the Moon, the descent vehicle for the Zond-5 executed a landing in the Earth's atmosphere along a ballistic trajectory near the Indian Ocean, and the descent vehicle of the Zond-6 landed on Soviet territory using a controllable descent system. First submersion in the atmosphere was about 10,000 km from the landing site. At first submersion, the descent vehicle's velocity was reduced to 8 km/sec; at the second, to 220 m/sec. All subsequent landing stages were similar to those of the descent vehicle for the Soyuz spacecraft.

DESCENT VEHICLES OF AMERICAN SPACE CRAFT

Mercury Descent Vehicle. Although American specialists used spherical shapes which execute descent along ballistic trajectory in unmanned space vehicles, the descent vehicles for all types of manned craft were not spherical. For the Mercury spacecraft a descent vehicle was developed in the shape of a truncated cone joined to the cylindrical part of the hull at the small base. The other side of the cone, the bottom, was in the form of a spherical segment.

Virtually the entire Mercury craft consisted of the descent vehicle, from which a truss with emergency rescue engines was jettisoned after entry into orbit; it separated during deceleration after the propulsion system had stopped running. The deceleration propulsion system was attached to the bottom of the descent vehicle, which could execute a descent only along ballistic trajectory bottom up. The vehicle's bottom also experienced greater heating from the shock wave front during /30
descent. Conical and cylindrical side surfaces experienced less heating.

The Mercury's parachute system had two stages, consisting of main and deceleration parachutes (the latter also acted as the drogue parachute). A relatively thick heat shield, which separated and was suspended on shock absorbers after release of the main parachute, was mounted on its bottom. Upon impact with a water surface, the shock absorbers absorbed g-forces experienced by the descent vehicle. Note that all American descent vehicles with astronauts land in water (except multipurpose, multi-use cargo craft).

There is one unique feature which distinguishes American descent vehicles. Although our manned craft provide cosmonauts with a cabin atmosphere in which the physical and chemical parameters of the air resemble those of the Earth's air, the Mercury, Gemini, and Apollo craft have pure oxygen at a pressure one-third of normal (at sea level).

Gemini Descent Vehicles. The Gemini Program was intended to study problems of prolonged space flights, rendezvous and docking in orbit, entry into outer space, reentry of the descent vehicle into the atmosphere, descent to Earth using lift, etc. The results of work done under the Gemini Program were used in the Apollo Program.

Gemini became the first American spacecraft produced with a descent control system for the descent vehicle (crew compartment). The descent vehicle was shaped like a headlight. Reentry into the Earth's atmosphere took place bottom up, and, because the center of mass shifted relative to the longitudinal axis, flight in the atmosphere took place at a constant angle of incidence. Controlled flight was carried out through rotation of the descent vehicle at list angle. The Gemini descent vehicle accommodated two, which made it possible to enter outer space. The entire astronaut cabin atmosphere, consisting of oxygen, was jettisoned into space and was /31
restored by reserve oxygen from tanks after the hatch cover was replaced.

Apollo Descent Vehicle. This vehicle, which American specialists called the crew compartment, was incorporated into the primary module, which consisted of the descent vehicle and propulsion compartment. The Apollo craft consisted of a primary module and a lunar module. Here we will discuss only the descent vehicle, which was intended to carry three cosmonauts into selenocentric orbit and return them to Earth.

The mass of the Apollo descent vehicle was 5.56 tons. It was shaped like a cone with a rounded apex and had a base diameter of 3.85 m, height of 3.4 m, and taper of 66°. The topmost conical part served as a parachute hatch cover which separated before the parachutes unfolded. The descent vehicle's hull was steel, assembled from layered panels with stainless steel honeycomb and enclosed between two steel plates. The bottom of the vehicle was a spherical segment.

The interior of the descent vehicle held the crew cabin, made of aluminum alloy, with the same layered structure and honeycomb fill. The honeycomb had varying density (from 0.07 to 0.114 g/cm^3) to make sure that the entire descent vehicle's center of gravity was located as assigned. The cabin had three astronaut chairs suspended on special shock absorbers. The seats of the chairs could be set at various angles for the back. The cabin also contained the control console, navigation system equipment, and scientific equipment.

All descent vehicle equipment was arranged so that the center of gravity of this compartment was located a certain distance from the longitudinal axis. As a result, when the descent vehicle entered the atmosphere, a certain angle of attack was set and lift developed. List angle and, consequently, lift during flight in the atmosphere could be adjusted through the orientation system engine, which made it possible to carry out a controlled descent.

According to program, the descent vehicle landed in water. /32
However, measures were taken in case it should land on solid ground. On the one hand, the compartments had four special projections (covered by thin screens along the contour of the cone) which, upon impact with the surface, were supposed to be demolished and thus dampen impact loads. To ensure that the compartment fell on the projections, parachute lines were attached asymmetrically to the descent vehicle.

The entire surface of the descent vehicle was protected by heat shields 8-44 mm thick at the conical part and 63 mm thick at the bottom. The heat shields were made of glass reinforced plastic with honeycomb fill. The filler was an ablation material: phenolic epoxy resin, to which hollow glass spheres were added.

When aerodynamic deceleration in the atmosphere was completed, the parachute system, which included two deceleration, three drogue, and three main parachutes, triggered. The deceleration parachutes, 5 m in diameter, were released into the air current at an altitude of 7.6 km. They reduced velocity from 120 to 60 m/sec. Drogue parachutes, 3 m in diameter, were released at 4.5 km; after several seconds, at 4-4.2 km, the gathered main parachutes, each of which had a canopy 26.8 m in diameter, were released.

Main parachutes were unfurled in three stages. They were gathered upon release into the air flow; partially unfurled 5 seconds later, open more 3 seconds after that, and finally, a few seconds later, completely unfurled. Upon touchdown in the water, velocity was 8 m/sec; 10.5 m/sec if there was one failure, i.e. if one parachute did not unfurl, (which occurred during one Apollo flight).

Reusable Space Craft. With the exception of the Space Shuttle, modern aeronuatics uses single-use spacecraft in orbiting artificial Earth satellites. A typical feature of these spacecraft is usually that they do not return to Earth in one piece after they have completed their space flight. Normal descent conditions are ensured for only one compartment, the descent vehicle. Design studies have shown that these craft have several advantages over those which return in one /33
piece. Their engineering approach is simpler and their development and implementation require less material.

The fact is that saving the entire craft involves many additional problems. First, to ensure controllable descent into the atmosphere with acceptable temperature conditions, the craft must be streamlined with predefined aerodynamic characteristics. This means that the craft must either have no projecting members, or they must be retracted into the interior space before descent. Second, to prevent overheating of the structural components and the atmosphere in the living compartments, the entire outer surface of the craft must be covered by a heat shield. This significantly increases total mass.

On the Space Shuttle, heat shielding accounts for about 9 tons of the total 111 tons of the craft's mass. The landing system is more complex and heavier. Controlling descent requires more fuel. On the whole, the entire craft becomes more complex and expensive, and sending it into orbit requires a more powerful booster rocket.

Note that, in single-use craft, all equipment used to control descent and landing and to support the crew from landing to evacuation is placed in the descent vehicle. Devices for manual control of the craft in orbit and devices to control lateral systems are placed here for the crew's working convenience during preparation for descent. There are also places for materials with experiment results and equipment returned to Earth.

probe mass of 1,106 kg, Venera 7 and Venera 8 had a descent vehicle with a mass of 500 kg out of a probe mass of 1,200 kg.

At an atmosphere entry velocity of about 11 km/sec, g-forces reached 450 g's, and the temperature of the gas at the front of the shock wave reached 11,000 K. At these high temperatures, the descent vehicle's surface did not even burn, but simply vaporized.

Descent vehicles for Venera 4 through Venera 8 were sphere-like and had about a 1-m diameter. The outer surface of the sphere, especially the lower front area, was fitted with a thick heat-shielding envelope. This also deflected heat inflow from the sphere's surface into a hermetically sealed container when the descent vehicle moved through Venus' atmosphere.

Descent vehicles separated from the unmanned space probe when they were still 20-40,000 km from Venus. This maneuver was an attempt to save the descent vehicle from damage during entry into the atmosphere. In these circumstances there will be no collisions between probe compartments and, as a result, no damage to the descent vehicle. The orbital compartment has its own function -- it carries the descent vehicle to the planet and now can be demolished as it falls through Venus' atmosphere,
since it does not have corresponding heat protection.

However, throughout the entire 4-month flight from Earth to Venus, the orbital compartment provided temperature conditions for its own needs and for those of the descent vehicle. Before separation, the heat adjustment system in the orbital compartment took care of the descent vehicle, as was necessary to prolong its capacity for work in the hot conditions of the Venusian atmosphere. The orbital compartment also provided electricity for operation of various systems, taking it from the Sun by means of solar batteries. This compartment was used to determine the position of the probe in space and to carry out the required flight correction to direct the descent vehicle into the preset area in the region of the planet where /36
it was to fall.

But, despite these important functions, the orbital compartment was actually only a means to carry the descent vehicle to Venus in good working order.

Structurally, the descent vehicle consists of two isolated compartments: bottom for instruments and top for the parachute. The parachute compartment, under a cover which is jettisoned after aerodynamic deceleration, holds sensors for scientific instruments, radio antennas, and altimeter, as well as a two-stage parachute system (deceleration and main parachute). The parachute fabric maintains required strength at temperatures to 500°C. Here also were located removable antennas for the radio set of the last two probes in this series.

After rapid aerodynamic deceleration, when a velocity of about 200-250 m/sec was reached, barometric sensors (at 0.6 atm) formulated a command to jettison the parachute compartment cover and release the 2.2-m^2 deceleration parachute into the air current. During subsequent reduction in velocity, the preset timer issued a command to detach the deceleration parachute and release the main parachute.

The area of Venera 4's main parachute was 55 m^2, but after its flight, during which the descent vehicle descended through an entirely "inhospitable" atmosphere for almost 1.5 hr, it was necessary to review the main parachute's characteristics. After its release at about 70 km, the descent vehicle stopped working at an altitude of about 30-40 km if atmospheric pressure was above 20 atm. Too long a descent time caused the equipment to heat rapidly in the hot atmosphere.

To accelerate descent, the area of the main parachute for the Venera 5 and Venera 6 descent vehicles was reduced to 12 m^2. As a result, descent velocity increased and descent itself lasted 51-53 minutes. These descent vehicle fell to altitudes with pressures of 27-28 atm, and descent on parachutes took place until 36 and 38 atm. Venera 7 and Venera 8 descent vehicles reached the planet's surface with equipment working. /37

The lower instrument compartment of first-generation Venera descent vehicles (figure 4) contained outside radio transmitters, preset timers, unmanned modules, telemetry systems, radio-altimeter, battery, heat adjustment system, and scientific equipment. The lower part of the descent vehicle had a special mechanical damper which increased the vehicle's motion stability in Venus' atmosphere and reduced its oscillation amplitude. The lower the amplitude, the lower the lateral g-forces which, when added to axial g-force, diminish /38 the effect on the descent vehicle.

After data on the actual characteristics of the Venusian atmosphere was obtained, designers were able to design and build a new generation of descent vehicles for comprehensive research on the physical and chemical properties of the atmosphere and surface of this planet. Second-generation descent vehicles were desgiend to perform many scientific tasks, including "inspecting" the planet's surface. Therefore the descent vehicles were equipped with phototelevision equipment. A soil collector was developed and installed on the descent vehicle to conduct chemical analysis, and inside the vehicle was a complex system for chemical analysis of collected soil. Rods held antennas and sensors to determine wind velocity, illumination, etc.

Most scientific equipment had to be placed outside the descent vehicle. However, if it were forced to decelerate in the atmosphere in this condition, all projecting parts of the

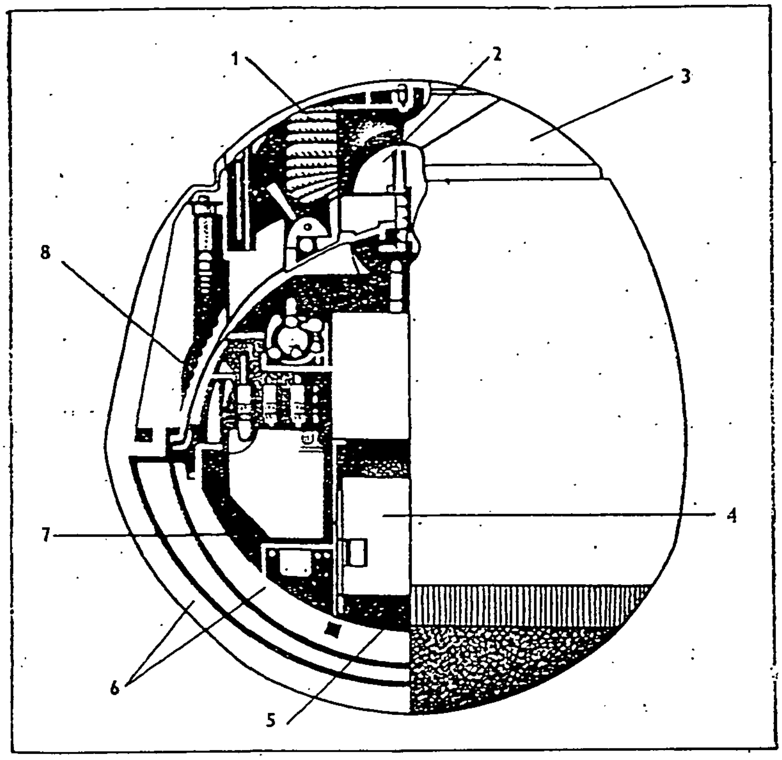


Figure 4. Venera 8 descent vehicle.
1 - parachute; 2 - transmitting antenna; 3 - parachute compartment cover; 4 - radio transmitter; 5 - damper; 6 - heat shield; 7 - hull; 8 - heat exchanger.

scientific equipment would have been destroyed in a firy death during aerodynamic deceleration. Therefore, the original descent vehicle was called a landing vehicle, and on top of it was set a sphere with a heat shield. As a result, a new descent vehicle was produced, but it was already much larger. The sphere's diameter was 2.4 m; it consisted of 2 hemispheres separated by the explosion of pyrotechnic devices (figure 5).

The Venera probes themselves were also altered. An unmanned interplanetary probe was launched by a more powerful booster rocket. Therefore, the probe's mass reached 4.5-5 tons. It thus became possible to save the orbital compartment, i.e. the Venera itself, after separation and to use it to relay radio signals from the descent vehicle.

This requires shifting it from a trajectory falling toward the planet to fly-over trajectory. Consequently, before flight toward the planet, the descent vehicle had to be separated and precooled to increase viability in the hot atmosphere; then the propulsion system shifted the probe to fly-over trajectory. /39
As a rule, the descent vehicle and probe were separated two days before approach.

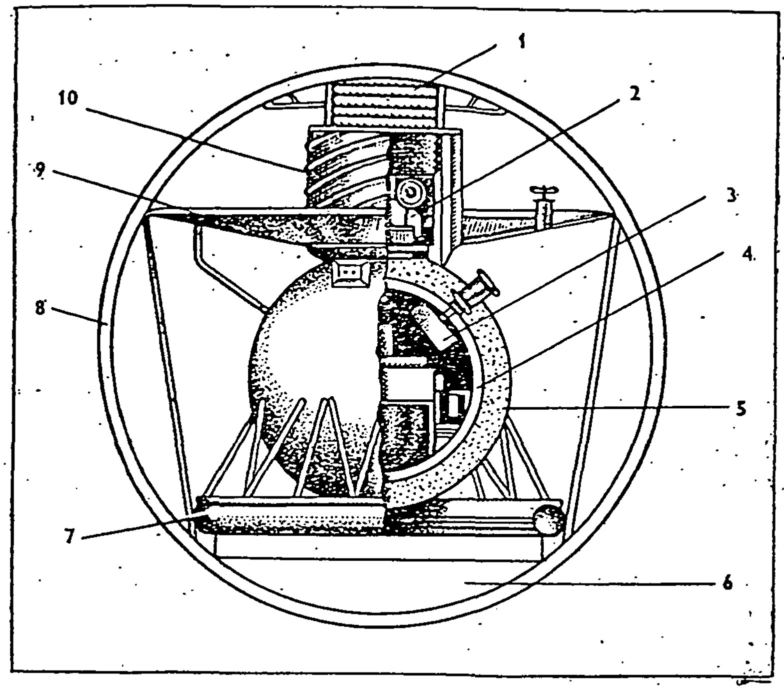


Figure 5. Venera 10 descent vehicle.
1 - Parachute; 2 - Scientific equipment, operating in the atmosphere; 3 - Telephotometer; 4 - Pressure hull; 5 - Heat shield; 6 - Damper; 7 - Landing gear; 8 - Heat-protective hull; 9 - Deceleration panel; 10 - Antenna.

Why two days, not 1 or 9, why not 27 or 59 hours?

For the descent vehicle, the later the separation the better, since it uses the probe's heat regulation system and its equipment is checked for proper functioning by the probe's systems. But the probe requires early separation to create a less powerful impulse for reliable shift from falling trajectory to fly-over trajectory. A compromise approach resulted in a separation time at 48 hours (two days) before approach to the /40
planet. After separation and until the parachute system was activated, the descent vehicle traveled in silence; the Earth could not monitor it. Exactly two days are needed so that separation can take place when ground radio tracking equipment located in the USSR is facing Venus. And landing the descent vehicle on the planet (which was set beforehand) also had to occur when the Soviet Union was within radio range. Naturally, these periods of radio contact repeat every 24 hours -- the period of the Earth's diurnal rotation.

After separation, the Venera can be shifted to the orbit of an artificial satellite around Venus (as was the case with Venera 9 and Venera 10) or to fly-over trajectory with subsequent flight around the Sun along an orbit between those of Earth and Venus. The ability to use the probe as a relay permitted a significant reduction in the descent vehicle's strength characteristics, since stringent conditions for descent to the center of face of the planet facing Earth were eliminated.

Thus, it became possible to significantly reduce the angle of entry into the atmosphere. Permissible deviations from design trajectory made it impossible to use the smallest possible angle of entry, since, in this case, the atmosphere might not even grasp the vehicle. Angles of entry of 20-23° were set as nominal for second-generation Venera probes. Maximum g-force for these angles reached only 170 g's.

The descent vehicle could land at virtually any point on the planet, even on the far side invisible to Earth. Now radio signals from the descent vehicle were received by the spacecraft flying past the planet. Signals were received and recorded through an antenna precisely aimed toward Earth, but they could also be recorded aboard the probe, then reproduced as often as necessary and transmitted to Earth.

PIONEER-VENUS DESCENT VEHICLES /41

To conduct research in Venus' atmosphere, American specialists launched the 885-kg Pioneer-Venus 2, which had four descent vehicles, in 1978. One, with greatest mass, was 1.5 meters in diameter; the rest had a mass of 96 kg and a diameter of 71 cm. The small vehicles were intended for descent into the atmosphere on the day and night sides of the planet, as well as near Venus' north pole.

The descent vehicles were spheres made of titanium, able to withstand pressures of 100 atm. The outside of the sphere was protected by a heat shield whose front side had a phenolic-carbon coating. Its bottom was coated with foamed elastomer.

Twenty-four hours before arrival at the planet, about 12 million km away, the large descent vehicle separated from the craft, followed 5 hours later by the small vehicles every few minutes. The descent vehicles entered the planet's atmosphere at a velocity somewhat higher than 11 km/sec. Deceleration was aerodynamic.

This entry and rapid deceleration phase lasted about 20 seconds. Then the heat shield was jettisoned from the large vehicle, and it descended for 17 minutes by parachute (the small descent vehicles had none). At the end of this period, the parachute was jettisoned to speed travel through the atmosphere right down to the surface. Communication with the descent vehicle continued for 1 hour, 19 minutes until impact with the surface.

After their heat shields were jettisoned, the small descent vehicles also continued radio transmission until impact with Venus' surface. The "daytime" descent vehicle (one of the three small ones) even continued to send radio signals for 68 minutes after impact with the surface. The Pioneer-Venus 2 probe itself, like Venera 4, burned up in the planet's atmosphere.

Actually, these descent vehicles, which were not intended for soft landing on the planet, acted only as probes to collect data on the atmosphere as they fell. Only the small vehicle which continued to function after impact on the surface can actually be called a descent vehicle. /42

Its survival can be attributed to Venus' dense atmosphere, which can reduce the rate of falling and, consequently, the magnitude of g-forces at impact with the surface.

Why, then, were descent vehicles intended to land on Venus only spherical and why, therefore, did they descend only in a ballistic trajectory?

First, it was not a man landing on Venus, but only scientific instruments which can withstand g-forces of 100 g's or more. Second, the sphere is simpler and does not require a special descent control system. If a headlight-shaped descent vehicle with a lift/drag ratio is used, it is necessary to use a complex orientation system to determine entry into the atmosphere and lifting force direction, as well as to permit control of lifting force when the vehicle rotates in list. In any event, the simplicity and relatively low development costs of such a vehicle undoubtedly played a decisive role is selecting the shape of the descent vehicle for landing on Venus.

DESCENT WITHOUT AN ATMOSPHERE

Given the state of the art of aeronautics, a soft landing without an atmosphere can be accomplished virtually only on the Moon. But, in principle, such descent vehicles can be sent to Mercury, Mars' satellites, atmosphere-free satellites of other planets, and asteroids. Note that, the lower the mass of the Solar System body, the less fuel is used to land on its surface.

Descent vehicles intended for soft landing in the absence of an atmosphere are not covered with a heat-shielding layer, but are usually outfitted only in a "fur" of vacuum-shield thermal insulation to protect them from the Sun's radiant energy and to keep the back end of the vehicle from cooling too much in space. This type of decent vehicle also does not use a parachute, since the canopy cannot be filled in a vacuum. Therefore, to prevent collision with the planet's surface, the only device used is a rocket engine, which can reduce high velocity to insignificant levels of several meters per second. /43

In this case, the landing of the spacecraft resembles a rocket launch, except in reverse. The engines, expelling flames from nozzles, do not increase travel speed, but reduce it. To do this, the engine nozzle is turned toward the direction of travel. Operation of the propulsion system not only ensures reduced vehicle velocity, but also compensates for the force of gravity of the Solar System body.

The deceleration engine must reduce vehicle velocity to several meters per second, and the conclusion of deceleration must coincide with the moment when it approaches the planet's surface. Otherwise, the descent vehicle will again develop high velocity as a result of free fall. Analysis of various deceleration patterns showed that the most reliable deceleration alternative in the first experiments was for the probe to drop vertically, which made it possible to simplify the landing system.

Theoretically, this problem is easy to solve: existing data on the planet's gravitational force, the engine's thrust, and the spacecraft's traveling velocity before deceleration are used to calculate the distance from the planet's surface at which the spacecraft must activate the propulsion system. But in practice it is not easy to calculate when to activate the propulsion system for deceleration. There is no one to ask how many kilometers to the planet. There are no mileposts in space. The spacecraft must be equipped with an altimeter or, to put it simply, radar, which can be used to determine the distance from the planet's surface.

According to the program developed beforehand and stored in the spacecraft's memory, the altimeter issues a command to activate the propulsion system at the required altitude above the surface. However, until the thrust section starts up, the engine must be turned nozzle down. "Up" and "down" have no /44
meaning in space. Usually, for large heavenly bodies such as stars or planets, "up" is related to their center, but for small bodies such as asteroids, "down" and "up" are determined only from the direction toward the center of gravity.

Therefore, to land on a body without an atmosphere, the propulsion system's nozzle must be turned at a point such that velocity will be close to zero upon contact with the surface. The spacecraft can be turned toward the direction of gravitational force only if the craft's position relative to the target and the direction of its travel have been defined. Only then is the required impulse to correct for proper execution of the descent trajectory determined. Using the laws of celestial mechanics and executing the required correction make it possible to direct the spacecraft toward the center of the visible face of the body or toward any other assigned landing site.

The descent vehicle can be turned in the direction required for deceleration using the orientation system. This system's optical sensors define the direction of the Sun or of a reference star. To solve the trigonometric problem, the direction to the center of the planet is found relative to the direction of the Sun and the direction of the star. And, finally, the control system turns the vehicle to the required position.

The period from engine start until landing is calculated beforehand during spacecraft design, and the distance to the planet is determined using the radio altimeter. Depending on vehicle mass, engine thrust, and the altitutde at which it should be started, only part of the spacecraft is saved. At the moment when the thrust section starts, the superfluous compartments, i.e. those already unnecessary for landing, are jettisoned. These are the astro-orientation system modules, required only to fly from Earth to the subject body, as well as chemical power sources, etc. For example, note that, for Luna 9, the mass of the jettisoned compartments was commensurate /45 with the mass of the unmanned lunar probe which descended to the Moon.

All this is done to reduce the amount of fuel required to decelerate the spacecraft. But monitoring the spacecraft's movement requires that its velocity be regularly calculated. Velocity cannot be measured in terms of inertia. However, when the spacecraft's propulsion system is activated, acceleration occurs. In this case, a gyroscopic integrator can be used to measure travel velocity by integrating linear acceleration. This does not provide actual spacecraft velocity, but only the magnitude of change in velocity resulting from thrust section operation.

This problem is solved with a computer which checks the altimeter for data on altitude and receives from the integrator the velocity increase at the times corresponding to the distance to the surface of the planet as defined by the altimeter. Then the electronic brain follows a stored program to develop recommendations to choke or boost the propulsion system if actual velocity differs from the calculated value stored in the computer's memory.

The descent vehicle lands on the surface after the thrust section has completed its task by dropping a short distance under the effect of the planet's gravitational force. The collision with the surface is usually moderated to reduce g-forces on all descent vehicles using three or four pads with individual shock absorbers.

Only the first lunar craft, Luna 9 and Luna 13, landed descent vehicles differently.

LUNA 9 and LUNA 13 DESCENT VEHICLES

Until a descent vehicle completed its landing on the lunar surface, information was most contradictory. According to some data, the lunar surface was a mountainous, rocky desert; according to other data, the seas and continents of the Moon were considered to be covered with a thin layer of dust in which any spacecraft bold enough to descend to its surface could sink. /46

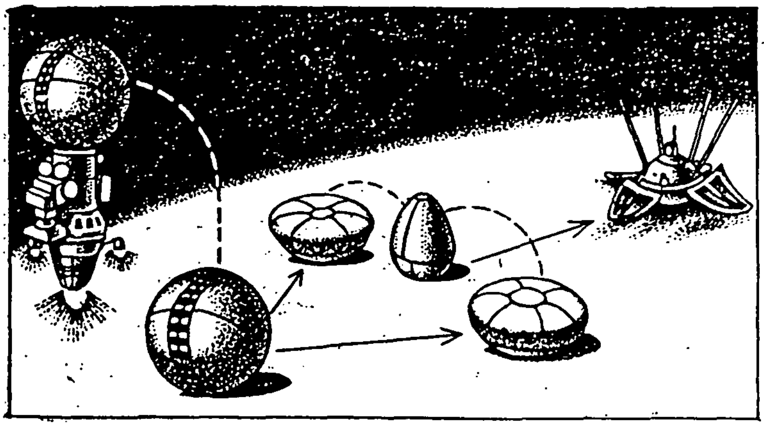


Figure 6. Diagram of the soft landing of the Luna 9.

The original approach to execute a soft landing on the Moon was proposed by S. P. Korolev. At first, the flight of the lunar probe had to be slowed by the thrust section to a velocity of several meters per section. Then the unmanned lunar probe could be jettisoned with the thrust section and the descent vehicle would end up on the Moon, packed in a soft, elastic balloon inflated with compressed gas (figure 6). Given the insignificant mass (about 100 kg) and relatively large support surface of the balloons (about 1.5 m^2), specific pressure on the ground was negligible. The landing system was developed so that the probe could land reliably on any soil (solid rock or loose dispersed soil).

The descent vehicle for the Luna 9 is actually an unmanned lunar probe with a mass of about 100 kg. Everything else was destroyed or damaged upon contact with the surface. The descent vehicle's hull is a sphere about 50 cm in diameter which, with lobes closed, looks like an egg. The astro-orientation system turned and locked the probe in a specific direction so that the thrust section nozzle would be turned toward the lunar surface. /47

Forty-eight seconds before approach, when the moon was still 75 km away, the self-contained altimeter sent a signal from the probe to separate the two already superfluous equipment compartments and to activate the deceleration propulsion system.[2] The propulsion system's operation is monitored according to a program stored in the probe's memory. The engine can adjust thrust over a relatively wide range.

From the moment the propulsion system began to work, the two elastic ballons which hold the automated lunar probe started to inflate. The balloons, holding the descent vehicle, were firmly connected to each other, forming a large elastic ball. Near the lunar surface, the engines shut off, and the nozzle's shear was turned to form a tubular probe of flat spring strip. Touching the surface, the probe gave a signal to jettison the descent vehicle with balloons. Communications with the probe were virtually destroyed, and separation occurred through the elastic force of the balloons, initially attached to the probe's support.

The surface to which the balloons were attached was somewhat tapered so that the automated lunar probe detached not along the vertical, but laterally. The ball with the probe bounced several times and stopped. On a signal from the preset timer, connections between the balloons were cut and, they, like two balls, bounced off the probe. The descent vehicle softly descended from a low altitude to the surface.

Thanks to its oval shape and low center of mass, the vehicle was able to assume the predefined position. Four minutes after landing the programmed timer issued a command to open the separation charge and the antenna lobes unfolded, freeing the antenna spike at the same time. The lobed antennas during flight acted as receiver-transmitter antennas, and after /48
opening, began to function as transmitting antennas, while the spike antenna acted as receiver.

Inside the descent vehicle's hull was a rigid frame with radio equipment, electronic preset timers, automated instruments, and telemetric and scientific equipment. A telephotometer, which made it possible to see the surrounding panorama and transmit it to Earth, was located at the top. Temperature conditions required for continuous operation of equipment under lunar conditions were maintained. This was accomplished through an exterior thermal-insulation hull, as well as by operation of the heat adjustment system. This system included a water tank, explosive valve, evaporative valve, fan, and piping system.

---

2 It would be more correct to call it a correcting-deceleration propulsion system, since in flight from Earth to the Moon, it was used to correct the trajectory of the flight to the Moon.

After landing on the Moon, the separation charge detonated, the water evaporation system turned on, and the fan which provided heat transfer from instruments to gas began to operate. The evaporative valve was the system's sensing element, water supply regulator, and evaporator. Water entered it from the tank under pressure -- more rapidly the higher the valve temperature. In the valve it evaporated and removed heat from the gas blown through the valve.

The Luna 13 unmanned space probe was similar in design and mass to Luna 9, but it contained additional scientific equipment, as well as instruments for direct study of the lunar soil. These were mechanical soil gauge/penetrometers, which made it possible to determine the mechanical properties of the upper layer of lunar matter, and a radiation densitometer to determine the density of the upper layer of lunar soil. Instruments were mounted on mechanisms which extended the instruments attached to the probe's outer hull. The extension mechanisms made it possible to set these instruments on the Moon's surface 1.5 m from the unmanned lunar probe.

The flights of Luna 9 and Luna 13 provided fundamental data on the properties of the lunar soil. From this point it was no longer necessary to design descent vehicles capable of landing both on rocky soil and on a surface covered with a thin layer of dust. All subsequent descent vehicles intended for /49
lunar landing already used other means to accomplish soft landing. As a rule, they began to use landing gear with supports in the form of feet. This landing gear could withstand and absorb the impact of the probe with the soil at vertical velocities of 6-8 m/sec and at a horizontal velocity component to 3-4 m/sec and could ensure stability when landing on an incline with a 15-20° slope.

DESCENT VEHICLES FOR LUNA 16 PROBES

The descent vehicle for the new generation of Soviet lunar craft was developed as a landing stage in the form of an independent, multi-purpose rocket module. This module had a liquid-fuel rocket engine, a system of tanks with fuel components, instrument compartments, and shock-absorbing supports for landing on the Moon's surface. The landing stage also had an outside radio system antenna and orientation system actuators.

The instrument compartment contained a control and stabilization system computer and gyroscopic instruments; electronic orientation instruments; radio receivers; outside transmitters for the radio measurement system; a preset timer which automatically controlled the operation of all systems and assemblies; chemical batteries and current converters; heat adjustment system components; self-contained devices to measure altitude and horizontal and vertical velocity components during landing; and other equipment, including scientific devices.

The propulsion system of the landing stage was used not only for deceleration during landing, but also for correcting orbit during flight from Earth to the Moon. The propulsion system also included two low-thrust engines, which turned on during the final landing stage. The main landing stage engine could be relaunched.

In contrast to the first descents to the lunar surface, there was no landing directly from flight trajectory. The /50 spacecraft went into artificial Moon orbit beforehand. By maneuvers executed using the propulsion system, a pre-landing orbit required to create optimum conditions for precise landing in the assigned area of the lunar surface was established.

The unique feature of this orbit is the high altitude of orbit at the pericenter above the Moon's surface -- about 15 km. The pericenter in this case is set above the assigned landing area. Note that this altitude is necessitated by the Moon's mountains, up to 9 km high. The remaining 5-6 km allow a permissible degree of error in formulating the orbit.

Before the propulsion system started up, operations to orient and carry out the programmed turn were executed to ensure that the probe would travel with engine nozzle forward. With engine running, flight distance from the point of departure from orbit to the landing point was about 250 km. Throughout the entire descent, the probe's position was strictly stabilized. Altitude and vertical descent velocity were continuously monitored by outside Doppler velocity gauges and altimeters. All operations during descent were executed by unmanned probe devices without interference from Earth.

Once the predetermined altitude above the lunar surface and vertical velocity components were attained, the engine switched off and then on again, and, at 20 m, the low-thrust engine started up in its place. Before the deceleration engine started up, two compartments with empty fuel tanks (the fuel was used for correction and deceleration near the Moon to create the artificial Moon satellite orbit) and astro-navigation equipment and other instruments not involved in landing were jettisoned, and the lightened landing stage with payload descended to the Moon (figure 7). In Luna 16, Luna 20 and Luna 24, the Moon-Earth return rocket was used for this purpose; in Luna 17 and Luna 21 -- a self-propelled Lunokhod vehicle.

After the propulsion system was shut off, the landing stage descended to the surface. Impact with the ground was /51 softened by four supports with shock absorbers. The energy of impact was consumed by tension in metal rods located in support struts and by crumpling dish-shaped supports made with honeycomb fill.

SURVEYOR'S DESCENT VEHICLE

The Surveyor program was intended to study characteristics of lunar soil and conditions on the lunar surface to ensure successful execution of the Apollo program. Structurally, Surveyor consists of a shell made of aluminum tube to which are attached three landing gear supports and a mast for a solar battery and pencil beam antenna. The shell has two hermetically sealed containers with electronic equipment, propulsion system, television camera, and navigation and scientific equipment.

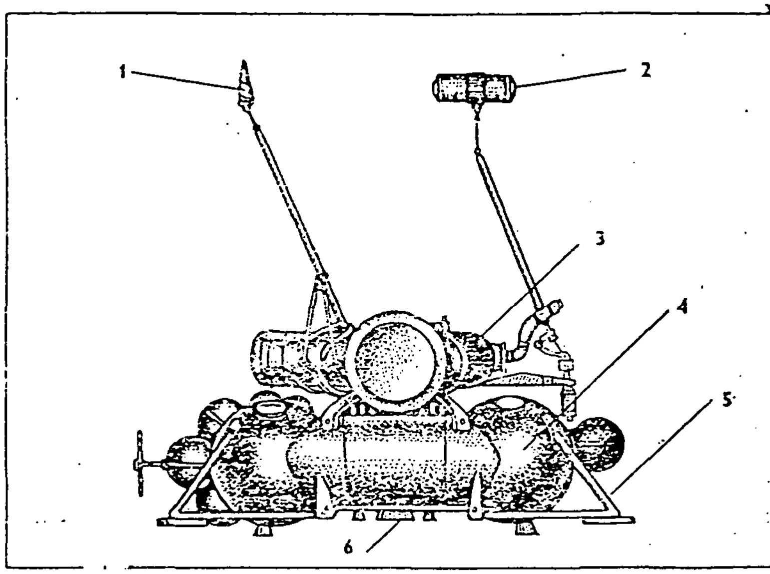


Figure 7. Luna 16 descent vehicle.
1 - Antenna; 2 - Soil collector; 3 - Control system compartment; 4 - Fuel tank; 5 - Support; 6 - Engine

Surveyor's starting mass was about 1 ton, but the descent vehicle which landed on the Moon had a mass of about 280 kg after fuel was used up and the equipment not needed during landing was jettisoned. /52

The main spherical deceleration engine ran on solid fuel. Low-thrust engines installed on the vehicle ran on liquid fuel. The vehicle included a solar sensor and a sensor for the reference star Canopus, as well as several radar units to determine descent velocity and distance to the lunar surface. A radio altimeter gave a signal to shut off the deceleration engine. Another altimeter, with an onboard computer, controlled the low-thrust engines.

At launch, the vehicle's landing gear was collapsed, unfolding only after the vehicle had entered trajectory for flight to the Moon. Supports had struts with airplane-type shock absorbers. Dish-shaped shock absorbers of aluminum honeycomb were hinged to the bottom of the supports. Shock absorbing modules of aluminum honeycomb, intended to soften impact with the ground when the main supports bent, were attached to the bottom of the shell.

THE APOLLO DESCENT VEHICLE

American specialists called the descent vehicle of this craft a "lunar module." It was intended to carry two astronauts from selenocentric orbit to the Moon's surface and to ensure their landing on and return from the surface to selenocentric orbit. The lunar module consisted of a landing stage and take-off stage. At take-off from the Moon, the landing stage remained there. The lunar module was a complex engineered structure which contained a life-support system, guidance and navigation system, power plant, communications equipment, onboard engines and scientific equipment.

After the lunar module separated from the Apollo and was 18 m from it, the module was rotated for inspection to find possible damage. Then the main landing module engine, which carried the descent vehicle into elliptical orbit with a /53
pericenter 15 km above the lunar surface, ran for 32 seconds. The lunar module descended to the Moon's surface in three stages: deceleration, entry into the landing area, and landing.

Upon reaching the pericenter, the lunar module's landing stage engine switched on. During operation on full thrust, it provided 8 minutes of deceleration. During this time, the module traveled about 400 km and descended about 15 km. Then entry into the landing area began. For this phase, the lunar module was rotated so that the astronauts could see the region selected. At this time, the landing stage engine operated at 60% of full thrust and, in less than 1.5 minutes, reduced module velocity from 130 to 15 m/sec.

At the end of this phase, altitude above the surface was 150 m, and distance from the landing site was about 360 m. In the final landing phase, astronauts were in full control of flight. The lunar module was oriented, engine thrust decreased gradually, and the module descended vertically from an altitude of 30 m. Minimum landing time was 75 seconds. However, it took longer in practice, since time was needed to inspect the landing area and select the most appropriate place to touch down.

The landing stage was equipped with a special chassis to ensure soft landing. At takeoff it was collapsed, and its telescoping struts were held tight to the landing stage hull. The chassis was rotated only after the astronauts had moved to the lunar module. Dish-shaped supports made of aluminum honeycomb were hinged to the chassis struts. Removable honeycomb filler made of aluminum alloy and contained in the collapsible landing chassis struts was used to absorb the shock of impact loads. A strut could be telescoped to 0.8 m.

It was stipulated that, at about 1 m altitude, the astronauts would shut off the landing stage engine to keep the bottom of the descent vehicle from overheating from the exhaust jet reflected from the ground. There was also a hazard of engine explosion if it were to touch the ground while running. /54 However, in practice, during the first landing astronaut N. Armstrong forgot to shut off the engine. At the moment it touched the ground, the lunar module was at virtually zero velocity. The engine was shut off by a probe located on a chassis strut.

The astronauts returned from the Moon with the take-off stage. Take-off was similar to launching a rocket on Earth, except that the landing stage was used instead of launching gear. The take-off stage entered artificial Moon satellite orbit and then docked with the main Apollo module. After the astronauts left the lunar module, taking with them the necessary equipment, it was detached from the main module. Later, the take-off stage was either left in selenocentric orbit or returned to the Moon's surface.

DESCENT IN A RAREFIED ATMOSPHERE

In aeronautical flight practice, these descent vehicles have been used only for flight to Mars. The atmosphere of this planet is highly rarefied. The atmospheric pressure on the surface there is from 1/160 to 1/100 that of normal atmospheric pressure on Earth. But, despite this thinness, entry into the atmosphere at cosmic velocities is associated with phenomena similar to those in the Earth's atmosphere. There is enough aerodynamic force for deceleration and reduction of velocity from space velocity of several kilometers per second to about 200-300 m/sec, even in the Martian atmosphere.

The entire problem of descent in Mars' atmosphere is that a velocity of 200-250 m/sec can be attained only near the surface or before impact with it. There is virtually no time left to release the parachute system, and the descent vehicle can be destroyed upon impact with the surface before effective deceleration can be achieved with the parachute. Therefore, the parachute must be released not at flight velocities of 200-250 m/sec, but much sooner -- even at hypersonic velocities on the order of Mach 2 (about 650 m/sec).

There then arises the problem of releasing parachutes into /55 a hypersonic flow. A high-strength material which can withstand high loads developed when the parachute is open must be used to make parachutes. To reduce loads on the parachute, several stages of parachutes with larger and larger canopy areas must be released one after another. In this case, loads increase slowly. Another way to reduce g-forces is to release a collapsed parachute system with the main parachute gradually unfolding in several stages.

In Martian conditions, the parachute system efficiently reduces flight speed only to several tens of meters per second (about 100 m/sec). A parachute system of dimensions suitable for Mars' atmosphere cannot decrease velocity to acceptable levels, about 10 m/sec. Therefore it is necessary to use a combined system: the propulsion system along with the parachute system. The entire deceleration stage in this case first proceeds like that for planets with an atmosphere, first relying on aerodynamic deceleration and then using the parachute system. However, in the final stage, as for planets without atmosphere, the propulsion system is used. Equipment which has completed such a landing on Mars includes the Soviet Mars probes and the American Viking probes.

MARS DESCENT VEHICLES

When it was being decided which system to select either the propulsion system, or the parachute system after aerodynamic deceleration and the propulsion system only in the final stage for soft landing on the surface, the second alternative was chosen. This choice was made due to better mass characteristics for the descent vehicle. In fact, in the first system, the deceleration system's mass, as calculations show, would have accounted for 70% of the descent vehicle's mass; in the second system, only 50%. Thus, using a parachute system as one of the components in the entire process of descent vehicle deceleration provides advantages in the mass of the scientific /5
and other equipment used.

Since the Martian atmosphere is highly rarefied, and the potential for aerodynamic deceleration improves the larger the midship section of the descent vehicle if mass is unchanged, the descent vehicle was equipped with an aerodynamic deceleration cone 3.4 m in diameter. When the descent vehicle was designed, it was stipulated that entry into the atmosphere should take place with zero lift/drag ratio and, consequently, travel during descent would occur along a ballistic trajectory. Consequently, it was not necessary to install a descent control system on the descent vehicle.

During the flights of the second and third unmanned Mars probes, the descent vehicle was to carry out a soft landing on the planet's surface and transmit signals to the probe orbiting the planet. Creating an artificial Martian satellite required that the probe enter a region of Mars such that it would travel not along a falling trajectory, but on a fly-over trajectory -- at a relatively low altitude above the surface.

But such a trajectory is unacceptable for the descent vehicle. Its flight trajectory should end with a fall, if not to the planet itself, then at least to the atmosphere. However, due to the thinness of the atmosphere and, consequently, to increase the vehicle's path of travel in it for most efficient aerodynamic deceleration, the descent vehicle should fly almost tangent to the planet's surface. Because of the notion of reliability of performing an assignment, it was accepted that the entry angle be no less then 10°. At smaller angles, the atmosphere might not seize the descent vehicle, since there would be no effective deceleration, and the descent vehicle, already oriented, would move directly away from the planet.

The solution to all these problems was to plan the Mars probe's flight along a fly-over trajectory, but to detach the descent vehicle from the probe at a distance of about 40,000 km from the planet and then travel along a new trajectory in the planet's atmosphere. To ensure that flight trajectory /57
could be changed, the descent vehicle was equipped with a deflection system consisting of a truss with a propulsion system running on solid fuel and a control system.

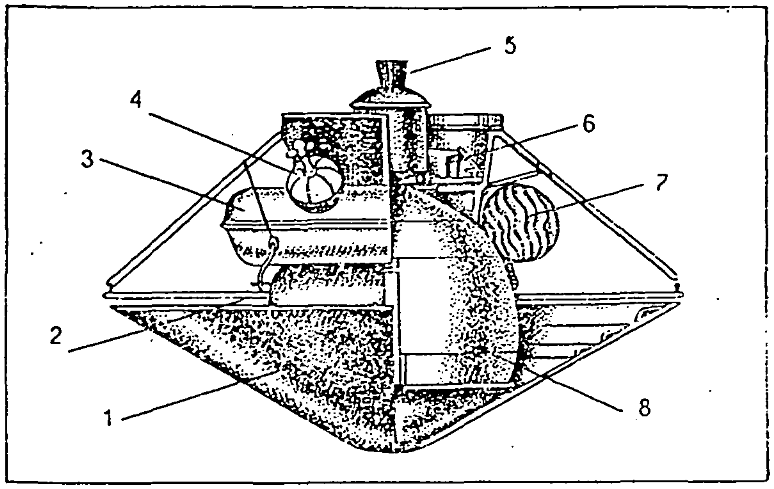
Before the probe and descent vehicle separated, the Mars probe was oriented specifically so that the descent vehicle was directed properly at the moment of separation. Fifteen minutes after separation, the solid fuel deflection engine switched on. Having gained extra speed, equal to 120 m/sec, the descent vehicle was directed to the designated point of entry into the atmosphere. Then the control system located on the truss turned the descent vehicle with the aerodynamic deceleration cone toward the front in the direction of travel, to ensure properly oriented entry into the planet's atmosphere.

Gyroscopic stabilization is carried out to maintain the descent vehicle in this orientation while it is flying toward the planet, about 4 hours. The vehicle was spun on its longitudinal axis by two small solid-fuel engines installed on the periphery of the aerodynamic deceleration cone. The truss with the control system and deflection engine, now superfluous, was separated from the descent vehicle.

Before entry into Mars' atmosphere, a command from the preset timer turned on the other two solid-fuel engines, also located on the periphery of the deceleration cone, after which the descent vehicle stopped spinning. Note that the following circumstance has been taken into account in this case. After the escape system is jettisoned, the moment of inertia and mass of the descent vehicle decrease. Therefore, the engines intended to stop the spin created less impulse than the gyroscopic stabilization engine.

Spin was also stopped primarily so that suspension lines would not tangle during parachute system release.

The descent vehicle's entry into the atmosphere occurred at 5600 m/sec, but it was protected from thermal effect by the aerodynamic deceleration cone, whose outer surface was covered



/58

Figure 8. Mars 2 descent vehicle.
1 - Aerodynamic cone; 2 - Radio altimeter antenna; 3 - Parachute container; 4 - Drogue parachute release motor; 5 - Descent vehicle escape engine; 6 - Control system instruments and equipment; 7 - Main parachute; 8 - Unmanned Martian probe.

with a heat-resistant envelope (figure 8). Deceleration by the atmosphere continued while velocity slowed to Mach 2. Releasing the parachute system at these velocities requires large forces. When the descent vehicle travels in the atmosphere at high velocity, a vacuum forms behind it, into which the parachute, still not entirely open, may be sucked (especially during slack release). The solid-fuel engine located on the cover of the drogue parachute compartment was used for forced release of the parachute.

At the end of the aerodynamic deceleration period, a command from the g-force sensor released the drogue parachute even at supersonic flight velocities by means of the solid-fuel engine. One and a half seconds later, the parachute compartment was detached using an elongated propellent grain, and the top of the compartment (cover) was carried away from the descent vehicle by the drogue parachute. The cover in turn released the main parachute with gathered canopy. The main parachute suspension lines were fastened behind the binding of the propulsion systems which was already attached directly to the descent vehicle.

Then the vehicle slowed to near-sonic velocity, and the preset timer signaled for unfurling -- full opening of the main parachute canopy. A second or two later, the aerodynamic cone was jettisoned and the soft landing system radio altimeter antenna opened. During descent on the parachute, velocity descreased to about 60 m/sec in several minutes. /59

At an altitude of 20-30 m, a command from the altimeter turned on the solid-fuel soft landing deceleration engine and disconnected the upper solid-fuel deflection engine along with the main parachute. This engine moved the parachute to the side so that the descent vehicle would not be covered by the canopy. After a certain point, the soft landing engine shut off, and the descent vehicle, separated from the parachute container, descended to the surface. The parachute container with the soft landing engine was moved to the side by a low-thrust engine. Upon landing, a special shock-absorbing covering reliably protected the descent vehicle from possible damage.

It was during this space experiment that an original communications system was used for the first time. A signal from the descent vehicle on the planet's surface traveled to the artificial Martian satellite -- Mars 3, which, after separation from the descent vehicle and startup of the engine, entered orbit around Mars. The satellite stored the signals transmitted from Mars. Then, after a certain time, these signals were sent to Earth.

THE VIKING DESCENT VEHICLE

The unmanned Viking space probes were intended to conduct research on Mars, both from artificial satellite orbit and using a descent vehicle sent to the planet's surface. Each of the two probes had a mass of 3,620 kg, of which the descent vehicle accounted for 1,120 kg. After the flight to Mars, Viking went into artificial satellite orbit using the propulsion system to study the planet and select a landing site for the descent vehicle.

After the descent vehicle's landing site was determined from Earth, the vehicle's biological envelope was jettisoned. The vehicle was kept in this envelope after sterilization to prepare for launch, even in winter conditions. These measures were taken to prevent carrying terrestrial microorgniams to Mars. An hour and a half after the biological envelope was jettisoned, the descent vehicle detached from the probe.

The descent vehicle was oriented and, 30 minutes later, eight liquid-fuel rocket engines started up for deceleration. The vehicle's orbit became elliptical, descending at pericenter to the depths of the planet's atmosphere. The velocity at which it entered the atmosphere was 4.6 km/sec at an entry angle of 16.5°. A front screen protecting the descent vehicle from high temperatures was built and attached to the vehicle to create a lift/drag ratio of 0.18.

After aerodynamic deceleration, at an altitude of 6 km and a velocity of Mach 1.9 (somewhat higher than 600 m/sec) the parachute system was released. Its release, like that on the

Soviet Mars probes, occurred with the help of the solid-fuel engine. After 15 seconds, the front screen was jettisoned at about 4.4 km. At an altitude of 1.2 km and a velocity of about 113 m/sec, the parachute separated. This marked the end of the deceleration phase using the atmosphere and the beginning of deceleration using the propulsion system.

The propulsion system, with a thrust of 270 kg/sec, activated for 25-40 seconds, and at an altitude of 15 m thrust was throttled (reduced). At this altitude, the propulsion system shut off and the descent vehicle fell freely to Mars' surface. Impact velocity was 1.5-3.3 m/sec. Of the 1,120 kg of mass separated from the probe, the vehicle, with a mass of 577 kg, fell to the surface. Final reduction in velocity took place using supports similar to those used for vehicles landing on the lunar surface.

RESEARCH WITH HARD LANDINGS

These spacecraft are, naturally, intended for soft landing on the target planet and study the planet from a short distance /61 during flight toward it. In the early stages of aeronautics, when descent vehicles were just being developed or were being first used on spacecraft intended to return to Earth, study of other bodies in the Solar System could already be conducted during approach. The first such craft were Luna 1 and Luna 2.

Luna 3 and Zond 3 were use to photograph the Moon from close up. Later, Luna 12 and several craft in the Zone series were used for this purpose.

The American program to study the Moon from approach trajectory used Ranger spacecraft, which made it possible to photograph the lunar surface at altitudes from 1,800 km to 480 m, 0.12 seconds before impact and destruction of the craft. The photographs were transferred by six television cameras and two transmitters.

CONCLUSION

In the early phase of conquering space, relatively simple descent vehicles were developed in which the atmosphere was used for deceleration and reducing velocity without using lift, i.e. descent was not controllable. These descent vehicles were either spherical or of some other shape with a center of mass on the longitudinal axis. Experience gained made it possible to refine the descent vehicles both structurally and from the standpoint of equipping them with descent control systems.

At present, under terrestrial conditions, more refined descent vehicles, which rely on lift to control descent, are used to ensure that humans land after returning from a space flight. For space research on remaining planets with an atmosphere, which still have not been visited by man, unmanned probes with descent vehicles which carry out descent along ballistic trajectory have been used up to now (with a few exceptions).

This uncontrollable descent is used to reduce costs to develop descent vehicles. This is also done because these descent vehicles are more reliable to operate than those with controllable descent, on which additional control systems and components must be installed. However, we still have to contend with g-forces, which reach 100 g's or more. /62

In the future, as aeronautics develops, manned flight to other planets will require development of descent vehicles with controllable descent. Even if man is only flying past these planets and returning to Earth, it will be necessary to create new descent vehicles. At atmosphere entry velocities of more than 17 km/sec, it is virtually impossible to exert control only in terms of list angle with a constant angle of attack with approach corridors about 12-16 km wide to ensure acceptable g-forces.

The width of the atmosphere entry corridor substantially decreases as approach velocity increases, which, in addition to everything else, requires increased orientation and navigation system operating accuracy, as well as high accuracy in executing corrections during the approach phase. For example, along certain calculated trajectories for flight with return from the planet Mars (or from its environs), Earth approach velocity increases to about 20 km/sec. In this case, existing types of descent vehicles cannot ensure crew safety during descent in the atmosphere.

Solving to this problem requires other landing methods. First, Earth approach velocity must be reduced, i.e. deceleration must take place before the atmospheric phase by means of the propulsion system. Velocity must be reduced to about 11 km/sec -- second cosmic velocity. At present this approach is unacceptable because of high fuel consumption. Only with the creation and application of new, non-chemical fuels will this method become attainable in reality.

Second, the descent vehicle's lift/drag ratio range must be enlarged to increase the entry corridor. However, increasing the ratio above 1.0-1.2 to expand the entry corridor is not effective and leads to a substantial increase in the mass of the heat-shielding covering. /63

Third, development of descent vehicle motion control systems should make efficient use of aerodynamic characteristics. Control only in terms of list angle with angle of attack unchanged is insufficient in this case. Control must be exerted both in terms of angle of attack and in terms of list angle. The angle of attack should be adjusted by adjusting the descent vehicle's center of mass. Finally, if, when adjusting for angle of attack, it turns out that the vector of full aerodynamic force varies widely with respect to the descent vehicle's axes, then it is necessary to provide a crew chair orientation system to ensure optimum g-force effects.

Descent according to two angles of list and attack must be regulated according to programs stored in the control system. The descent vehicles of the Soyuz and Apollo craft were ineffective for regulating aerodynamic deceleration in terms of two angles. More acceptable in this case are descent vehicles in the form of semi-cones with a flat top. When such a descent vehicle is used, landing on Earth can be linear, with approach trajectory or with double submersion into the atmosphere.

In the latter case, after first submersion, the descent vehicle leaves the atmosphere for a transitional elliptical orbit. A descent vehicle travel trajectory during the first submersion phase must also be formulated, and g-force limitations of the crew, flight altitude, and thermal loads taken into account, so that velocity on leaving the atmosphere does not exceed second cosmic velocity.

Descent vehicles for atmosphere-free planets will not undergo much change in the near future. Descent to the Moon has recently been accomplished using artificial Moon satellite orbit for getting to the area marked for landing with high accuracy. But this is only from the standpoint of the landing pattern. The comfort and convenience of the astronauts will continue to increase and new, more refined orientation and control system instruments will continue to be used.

CHRONICLE OF MANNED FLIGHTS[1]

No.	Date	Astronauts (craft commander first)[2]	Space craft[3]	Flight duration		
				Days	Hours	Minutes
103[2]	1/24	T. Mattingly(3) L. Shriver (b. 1944) E. Onizuka (b. 1946) J. Butchley (b. 1945) K. Payton (b. 1948)[5] (All USA)	D	3	01	33

1 Continuation. For previous entries, see 1984 pamphlets 3, 7, 11 and 12.

2 Astronauts launched into space for the first time are in bold face (for the rest, the number in parentheses indicates the number of previous flights).

3 Full name of spacecraft: Discovery.

4 Secret flight in a Pentagon program.

5 U.S. Defense Department astronaut.