nothing in the record so far to guarantee that man is capable of transcending in space the conflicts, which have kept his earthly home in turmoil and peril. All we can do is hope that the ever-accelerating thrust into this new realm will in turn push social invention to the point where it has a chance of catching up in the race of history.

Whether at home, in formulating our national space policies, or in seeking to construct a better design for managing men's affairs in the world at large, the task lies ready at hand. Reinhold Niebuhr, with his customary wisdom, supplied the relevant perspective when he wrote:

> It is man's ineluctable fate to work on tasks which he cannot complete in his brief span of years, to accept responsibilities the true ends of which he cannot fulfill, and to build communities which cannot realize the perfection of his visions.

1.

The technical prospects

◆ H. Guyford Stever

A serious prognosis of the technical prospects of space flight requires more than a mercurial judgment about the quick attainment of some of the projects now being discussed. It requires an appreciation of the history of technology, of how new technologies unfold. There is a striking parallel between the history of the airplane and the history of space flight to date. A review of this parallel can show the kinds of indicators to be looked for in estimating the prospects for the future of space flight. (No attempt is made here to detail the history of the airplane. For those interested, reference is made to *The Airplane,* a superb historical survey by Charles H. Gibbs-Smith.)

THE ANALOGY OF THE AIRPLANE

Man's early dreams of flight in the atmosphere like a bird were intermingled with his

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dreams of space flight to other planets throughout the solar system. Confusion existed because natural philosophers did not have an accurate picture of the extent of the atmosphere. The early myths of manned atmospheric and space flight include that of Daedalus, builder of the Minoan Labyrinth, and his son Icarus, that of King Bladud, tenth legendary King of England and father of King Lear, and a host of other tales, some of which may well be based on early, probably tragic, experiments in flying with bird-like wing constructions. As science began to develop in the Middle Ages, more practical dreamers, if we may use such a term, such as the Franciscan monk, Roger Bacon, and later Leonardo da Vinci, had ideas which might have led to practical embodiment had the technology been sufficiently advanced. For over two hundred years before flight was achieved, physical experiment and attempts to fly increased steadily, and more and more men began to get the concept of powered flight.

The engineering basis of flight was laid in the early nineteenth century, long before the Wright Brothers first flew, by Sir George Cayley, a British minor nobleman, who was a brilliant engineer in many different fields. His accomplishments in aeronautics, though not widely appreciated, were astounding. He was the first to realize that the airplane would attain the lift needed to counteract its weight by a thrusting device including a propeller and an engine which would overcome the drag of the air. Among his many other aeronautical accomplishments he designed and built the first model of a practical airplane. But, more important, he had a very clear vision of the future and in 1809, almost a century before manned controllable powered flight was achieved, he wrote:

> I may be expediting the attainment of an object that will in time be found of great importance to mankind, so much so that a new era in society will commence from the moment that aerial navigation is familiarly realized—I feel perfectly confident, however, that this noble art will soon be brought home to man's convenience and that we shall be able to transport ourselves and our families and their goods and chattles more securely by air than by water and with velocities of from 20 to 100 m.p.h.

Though his numbers fell short of the mark, he had the spirit of the modern development of air transportation. These were the words of an imaginative but still practical engineer.

On the other hand, few basic research scientists had anything to do with the attainment of flight, nor were they sanguine about its use. They generally ignored the field or discounted it. For example, Lord Kelvin, one of the world's great research physicists, said in 1896, only seven years before the attainment of controllable manned powered flight, "I have not the smallest molecule of faith in aerial navigation other than ballooning."

Even after the achievement of controllable powered-manned flight and after many people had followed the Wright Brothers' lead, it was still difficult to foresee the future. In 1908 the Wright Brothers, who were still leading in the development of airplanes all over the world, delivered to the United States Army an airplane to fulfill a contract which called for a flight speed of about 32 m.p.h. It was constructed of airplane cloth and a hickory wood frame; it had two small 9-foot propellers geared by belt drives to a single motor of which the power output was about 25 horsepower, lower than that of practically any modern automobile. You recall the pictures of the Wright Brothers' Flyer, with its fixed horizontal tails in the front, vertical rudders to the rear. It did not even have wheels—just skids. It was normally launched with a catapult mechanism, though occasionally Wilbur Wright was skillful enough to take it off on wet grass. A standard stunt in those days was for a man or two to push on the rear of the wings to help the airplane get started.

Still the concept of flight was exciting to enough people so that in its infancy many predictions were made of the technical prospects of the airplane and of its use to mankind. Not all were imaginative. In 1910, for example, the British Secretary of State for War said, "We do not consider that airplanes will be of any possible use for war purposes."

The first uses of the airplane which spurred its development were military. It was an improved means of performing certain limited military tasks such as observing the enemy. To most minds its function was to replace the cavalry as the eyes of the army and the balloon as the spotter for the artillery.

It was very difficult for a practical man in 1909, when the first Wright planes were being adopted for military use, to conceive of commercial air transportation. Although calculations of the air-transportation economics of those days vary quite considerably, they point up some basic facts. In 1909 a plane could travel at 42½ m.p.h. with a pilot and a single passenger. The plane had a useful life of only a small number of hours—possibly 30—and it cost $30,000. The cost per passenger mile might then turn out to be something like $25 per passenger mile or, in 1960 dollars, $80 per passenger mile. Today the operating cost of a jet airplane which flies more than ten times as fast and has a useful range of almost

100 times as great with 100 times as many passengers is only a few cents per passenger mile.

No one accurately foresaw the shape of things to come for the airplane. Those who had faith that technology has a future came closest to predicting the future. There is a story, possibly aprocryphal, that the head of the Astor business enterprises said that important men would conduct their business by traveling in airplanes in 50 years. He did not worry about the limits to the load-carrying capacity of wood and fabric airplanes. He did not worry that there were limits in the power available. He did not worry that flying an airplane at that stage was dangerous. He did not even stop to consider the tremendous development cost.

Astor went right to a useful purpose that the knowledge of the day promised, and his faith in technology proved right. The structures changed from cloth and wood to metal. Steel and the light aluminum and magnesium alloys were developed, and the technique of stressing the skin instead of using a bracing framework brought aeronautics to its modern era. The engines developed from a few tens to many thousands of horsepower; internal combustion gasoline engines with propellers were replaced by turbojet engines. The vast technological improvements in every field of engineering associated with the airplane have made commercial flight commonplace.

The parallel between the story of the airplane and that of the applications of our space technology is obvious. In the military context, the first space concepts were observation satellites. The achievement of a bombardment capability from space and space combat is now being given serious thought and development. Eventually military operations may well be conducted simply for control of space as in the past they have been conducted for control of the air. In the context of peaceful applications, there has been some slower development.

Only after major emphasis on military uses do we now appear to have within our reach world-wide communications by satellite relay stations, a world-wide weather observation and prediction service using satellites, and a world-wide navigation system for ships using navigation satellites.

THE BASIS FOR PREDICTIONS

The lessons in prognosticating the technical possibilities of space flight that can be learned from this brief consideration of another great technology are numerous. For example, most people, over the long run, fall short of the mark in their predictions. Developments follow the lines of practical use. Military developments lead the way to nonmilitary applications.

I have history in mind, then, as I attempt here to look ahead to the technical prospects for outer space. Moreover, I have in mind certain very present factors which bear on any forecast.

In the latter half of the nineteenth century, when classical science was flourishing, J. Henri Poincaré wrote in *La Science et l'Hypothèse*: "For a superficial observer, scientific truth is beyond the reaches of doubt; scientific logic is infallible and, if scientists sometimes err, it is because they have misunderstood the rules." [1] If the task of presenting the technical prospects for outer space depended only upon understanding scientific truths, the future could be plotted with reasonable simplicity and confidence for some time ahead. But progress in space will not be essentially or solely scientific. It will involve engineering, in which the laws of science play an important but only partial role. Thus progress in space, like that in all engineering projects, will be critically affected by economic and social factors.

For decades space progress can be made by practicing in new and generally more expensive embodiments the arts we already know. It will depend upon engineers who must improve the design of existing equipment, design similar equipment in larger sizes, and develop new devices in fields of engineering where the principles are well known. We can already identify some of the areas in which those developments will be made. Steady but not overwhelming gains can be made in liquid and solid propellant rocketry. Nuclear rocketry and electrical particle rocketry are being developed with the promise of vast improvement in space capability. Some of the most important but least publicized gains in the recent past and expected gains in the near future are in the fields of structural design and materials. Auxiliary power is a key field of future development. Communications, radio and inertial guidance and other space navigation developments will be needed before useful space accomplishments can unfold in large number. The engineering of life-support equipment for human flight is a relatively new field which offers great promise of improvement.

It is clear also that space progress will depend upon the financial support given to the development organizations of which we already have many more in this country than we are using efficiently. Moreover, it will depend upon the size of the continuing military effort.

However, any prediction based solely on our current technology, with reasonable estimates of government interest and financial support, would most certainly lead to an underestimate of the technical prospects for outer space. As any student is aware, future progress in engineering will depend upon developments not known in today's art; and the talented young men and women who are now going through training in engineering and science, much better equipped than earlier generations both in background and in their approach to education, will march to the future of technology more rapidly than we now estimate. One can be sure that there will be major new developments which are not foreseen today, and that some of them will move the space program forward faster and farther than we can predict.

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[1] Translated from the French.

At the outset of this chapter, then, I want to declare that I am an enthusiast for the long-term potential of space flight. I can best describe my attitude by telling an anecdote about a foreign visitor who took a taxi tour of our national capital. When shown the Archives building, on which there is inscribed a quotation from Shakespeare's "The Tempest" which reads "What is past is prologue," the foreign visitor was a little puzzled, for he did not have a good command of the English language. He asked his taxi driver if he knew what the saying meant. The taxi driver answered, "Sure, bud, that means you ain't seen nuthin' yet."

I believe that we have only scratched the surface of the technology of space flight. I believe that we have the trained engineers in the aerospace field with enthusiasm and vision who can achieve their promises.

Space Flight Velocity Requirements

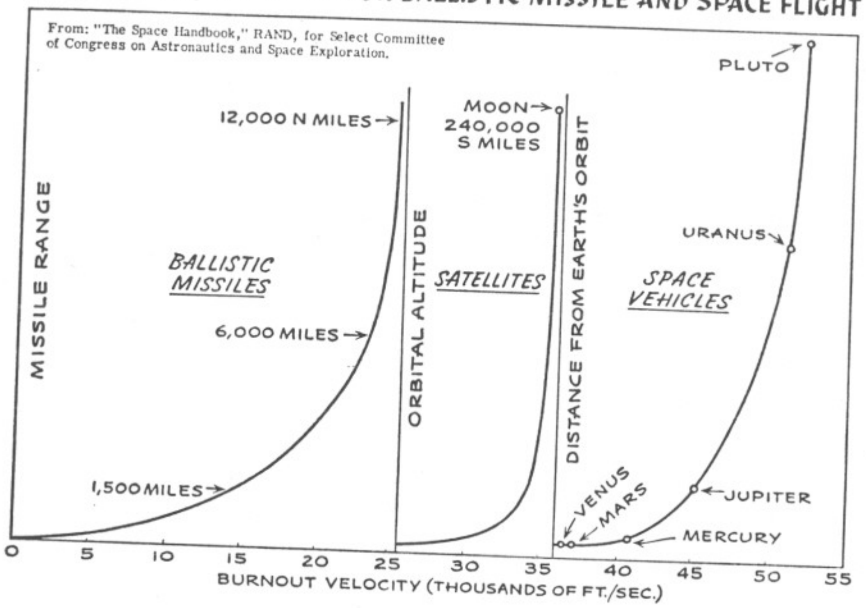
The velocity requirements for various space missions have nothing to do with the past, present, or future state of technology. They come out of a very old branch of science, celestial mechanics, which began with the ancients as they studied the motion of the stars, was given a big boost by Copernicus and mathematical foundation by Kepler and Newton, and grew to its peak many decades ago as astronomers made the system accurate. In fact, it was a science which was almost in mothballs until the new-found rocket technology returned it to prominence.

THE PROBLEM OF PROPULSION

The key technology in space flight is propulsion. Rocket boosters are now capable of accelerating useful payloads to the very high velocities which are required to orbit the Earth, to escape the Earth and go to the Moon and the other planets, and to orbit the Sun. Most alert readers of the newspapers in recent years have amassed a few characteristic numbers which describe the high velocities required for space flight. For the purposes of this chapter, in describing the speeds it is worth introducing an illustration (see graph: *Velocity Requirements,* etc.). Incidentally, this graph could have been prepared by Sir Isaac Newton using his newly enunciated Law of Universal Gravitation and the mathematical tools available to him.

The graph shows the velocity required for a body to move on an elliptical orbit starting and terminating on the surface of the Earth as the ballistic missile does, in a circular satellite orbit around the Earth as a Sputnik, a typical Earth satellite, or as the Moon does, and in an elliptical orbit changing from the Earth's orbit around the Sun to one of the planet's orbits around the Sun. Though Sir Isaac would have been capable of plotting such a graph, he certainly would have objected to the entire proceeding as

VELOCITY REQUIREMENTS FOR BALLISTIC MISSILE AND SPACE FLIGHT


From: "The Space Handbook," RAND, for Select Committee of Congress on Astronautics and Space Exploration.

not being scientific since only a dreamer would think that man could ever have the capability of attaining such velocities in any useful vehicle.

Velocities are given in feet-per-second. Many readers are more familiar with velocities given in miles-per-hour. It is easy to convert approximately from feet-per-second to miles-per-hour by taking two-thirds of the number. For example, 15,000 ft/sec is roughly 10,000 m.p.h.

First, consider the speeds required for ballistic missiles. The very high speed of 5,000 ft/sec, about one mile/sec or 3,600 m.p.h., enables a ballistic missile to achieve a range somewhere between 200 and 250 miles. An increase in speed to 15,000 ft/sec, on the other hand, enables the vehicle to attain a 1500-mile range. A speed of less than double that—between 23- and 24,000 ft/sec—permits a factor of four increase in range from 1500 to 6000 miles. An increase in speed from about 23,500 to 25,000 ft/sec increases the range from 6000 to 12,000 miles; and a very slight increase of velocity over the 25,000 ft/sec puts a satellite into orbit at low altitude.

Further increases in velocity capability from 26,000 feet to about 36,000 ft/sec permit the satellite orbit to be established at increasingly high altitudes to a point where at something over 36,000 ft/sec the gravitational pull of the Earth can be entirely escaped so that the vehicle would then be in orbit around the Sun just as the Earth is. With a few thousand ft/sec more in speed, a space vehicle can get to the regions of Mars and Venus, say at 41,000 ft/sec, to Mercury with 45,000 ft/sec, Jupiter with 51,000 ft/sec, and so on.

These speed requirements are well known to space engineers; in fact all of them have these numbers at the tip of their fingers at all times and, in this era of advertising publicity and public speeches, they are not only at the tip of the space engineer's fingers but also at the tip of his tongue.

The speeds given on the chart are minimum to achieve the objectives. If the mission requires some special maneuvering such as landing on a planet, the speeds are somewhat higher. For example, if one is considering a round-trip lunar flight in which the vehicle takes off from the Earth, uses a rocket to brake its speed as it decelerates to land safely on the Moon, takes off from the Moon, and comes back to the Earth using atmospheric braking here on the Earth, the speed capability of the rocket should not be just 36,000 ft/sec, but something like 60,000 ft/sec. Likewise, if a spaceship is required to go from Earth to Mars on the minimum velocity of about 37,000 ft/sec, the spaceship can do this only when Mars is in the optimum position and it could not use any rocket braking or other maneuvers around Mars. On the other hand, with a capability of 100,000 ft/sec change due to rocket thrust, instead of just the minimum 37,000 ft/sec speed capability, it could propel itself there in 15 or 20 days; if it had 300,000 ft/sec it could make the trip in 10 days. So the figures given on the graph are misleading with respect to space missions of an advanced nature. In reality one would like to be able to design very high speed increments into the rocket boosters which enable the space vehicle to perform its mission.

SOME COMPARISONS

One might digress here in order to put these very large velocities into context with other high velocity devices that are well known. The long history of ballistics and firearms has led to developments in which small-arms can now have velocities from 1000 ft/sec to between 2- and 3,000 ft/sec. Certain very high performance guns can go to higher velocities, and in the laboratories for special research purposes there are gun-type devices which go to 10,000 ft/sec and more. Jules Verne in describing his imaginary trip to the Moon employed a very long gun barrel with a very special new explosive to propel his ship to the Moon. Even if one could use some kind of gun-like projector for a ship for space flight, it would have several drawbacks. The first of these is that, since the highest velocity is attained right at the end of the gun barrel, which presumably would be within the atmosphere, all the difficulties of high-velocity frictional heating would plague the vehicle during takeoff. Moreover, the velocity loss in the atmosphere due to drag would be very large. In addition, there would be immense problems of high acceleration loading (high "G's") on the vehicle because the full acceleration would take place in the very short gun barrel. For these reasons the rocket principle is used.

Rockets have the tremendous advantage that the accelerations are least in the beginning and stay relatively small, small enough to be withstood by humans and by delicate instruments. The very high velocities can be reached because the accelerations occur over long periods. Furthermore, the extreme velocities are not reached until the denser portions of the atmosphere are cleared by the vehicle.

Boosters

ROCKET BOOSTER TECHNOLOGY

The concept of using rockets to attain the very high velocities for space flight is rather old. In fact, it would be difficult to pinpoint accurately the first man to conceive this. In the nineteenth century a Russian, Tsiolkowsky, a minor schoolteacher, discussed rocket power as the means by which the high velocities required for space flight could be reached. A German named Ganschwindt independently did the same.

Robert Goddard, an American physicist who started thinking along these lines during World War I, also discussed and placed on a much more scientific basis the calculations for rocket propulsion needed for space flights. He spent his whole professional career in efforts which initiated modern liquid propellant rocket technology and designed vehicles which were the forerunners of today's space vehicles, reaching in 1926 the point at which his first propellant rocket vehicle was fired.

Most of the achievements in space flight have been made using the liquid propellant rockets which were pioneered by Dr. Goddard, developed to a reasonably high state of the art by Germans in their research and development leading to the V-2 and other rocket weapons used in World War II, and developed further in both Russia and the United States mostly for ballistic missiles and only lately for spacecraft. The modern interest in rocketry revived a much more ancient type, solid propellant rocketry, started by the Chinese in the twelfth century and used sporadically but relatively ineffectively in warfare from that time until World War II, when a large number of rockets using solid propellants, such as anti-tank air-to-ground rockets, anti-submarine rockets, and bazooka rockets for infantry against tanks, became quite effective weapons. In the period following World War II solid propellant rockets also have been developed to a point where they are now figuring in current and future space plans. Though their performance is not yet quite up to that of the liquid propellant rockets, this is partially compensated for by their higher reliability and greater simplicity in operation.

Where do we stand with respect to the speed increment that can be given to a vehicle as it is shot off into space? Not only can we fire ballistic missiles more than a quarter of the way around the world; we have established circular satellites around the Earth and sent vehicles toward the Moon. Beyond the Moon, vehicles have escaped the gravitational pull of the Earth to pass near Venus, be captured in the gravitational pull of the Sun, and remain permanent satellites of the Sun. According to the chart this means that we have attained velocities in the region of 40,000 ft/sec. This represents quite an advance in speed capability when we recall that in World War II, when the V-2 was put into operation, the best speed was a little more than 5,000 ft/sec and that, only 34 years ago, Goddard's rocket got only to 184 feet in altitude.

Too often, in considering the advances made in space boosters over the recent decades, exaggerated emphasis is laid on the rocket engine. The improvement of the performance of the rocket engine is only part of the story. An important part has to do with the improvement in vehicle design in which the relative weight of the vehicle components has constantly been reduced; and there is also the final element of design to obtain the very high velocities desired, that is, multi-staging. All very high-velocity space vehicles and even ballistic missiles—the longer-range ones—are boosted by multiple stage rockets. The principle of this staging is very simple: if a single stage rocket can, say, boost a payload to half of the velocity required for a given mission, then the full velocity can be achieved by adding a larger booster stage. This booster stands in weight ratio in the same relationship to the original rocket plus payload as does the original rocket—which now becomes the second stage—in relation to the payload. This staging device has the advantage of enabling the high speeds required for the mission to be obtained; it has the tremendous disadvantage that the multiplying factor mentioned goes up very rapidly.

Suppose, for example, a mission of 25,000 ft/sec is considered. If a rocket can be designed to push a payload of 1,000 pounds to 12,500 ft/sec with the total rocket weight being ten times the weight of the payload, or 10,000 pounds, then the full velocity for the mission—the 25,000 ft/sec—can be achieved by taking the 10,000 pounds of the first rocket, and with the same ratio of ten times for a larger booster stage, or 100,000 pounds, the 100-pound payload can be boosted to 25,000 ft/sec. Carrying this same reasoning a little farther, if the mission calls for 37,500 ft/sec which would permit it to escape the gravitational pull of the Earth, the 100,000 pound total vehicle would again have to have a still larger booster stage added which was ten times its weight—or a million pounds. So the staging principle allows one tenth by weight of the first stage rocket to be boosted to 12,500 ft/sec or one one-hundredth by weight of a two-stage rocket to twice that speed or 25,000 ft/sec, or one one-thousandth by weight of a three-stage rocket to a speed of 37,500 ft/sec. One can carry on the arithmetic from there and see that it gets both expensive and discouraging to increase the stages far beyond three or four.

Since the days of the V-2, when the single-stage velocity was of the order of 5,000 ft/sec, improvements in rocket efficiency and in structural efficiency have made it possible for a single stage to reach 15 to 20,000 ft/sec. No single-stage rocket has yet reached the 25,000 ft/sec required for orbiting the Earth, though vehicles which are almost single-stage vehicles—like the Atlas, which instead of dropping off the stage only drops off some excess rocket engines, and is therefore called a one-and-one-half stage vehicle—have reached this velocity of orbiting. With today's technology one thinks of one or two stages for long-range ballistic missiles, two or three stages for orbiting vehicles, and three, four, five, or six for vehicles to go to the Moon and to escape the Earth's gravitational pull—to go to Venus or Mars or just to become ordinary satellites of the Sun. Research vehicles have been used with as many as seven stages.

One may ask the question: Can there be a radical increase in the speed increment which is obtainable from a single stage of a booster? As indicated before, such an increase must come from improving the efficiency of the engine itself or from the improvement in the structural efficiency.

Let us first look at the efficiency of the rocket itself. Over the past period of development the rocket motor design has been given a tremendous amount of attention, but for a given rocket propellant such as liquid oxygen and kerosene the expected improvement in rocket motor design cannot be very great. A given engine may be made somewhat more efficient with long and expensive development programs on the turbine fuel pumps, on the inlet design, on the jacket cooling, on the materials used, and so on. But only small gains can be made. Larger gains can be made by changing rocket propellants completely, and steps have been taken along this line. The standard rocket propellants were liquid oxygen and kerosene for the very long range ballistic missiles and spacecraft of the recent past. More recently liquid oxygen-liquid hydrogen engines have been developed with higher performance figures. There are other possible improvements using liquid hydrogen-liquid fluorine and so on. In the solid propellant field there are also possible new propellant combinations that can be made, and such tricks as making a combined liquid and solid propellant rocket are under development. One can expect some improvements then, in the propellant efficiency, but they will come in small increments and only following long-term and very expensive projects.

Considering the possibility of improving the velocity increment obtainable by a single stage by increased structural efficiency, one should point out that from the days of the German V-2 only about 70 per cent of the booster was rocket fuel. Today engineers have been achieving almost 90 per cent. Any small increment at this high percentage is valuable, but even a small increment is extremely difficult to obtain. Thus one can expect some improvements along this line, but nothing radical, barring of course one of those unforeseen inventions that cannot be taken into account in this prognosis.

COSTS OF BOOSTERS

The cost of boosting a payload to the high speed required for its mission—including the development of boosters, establishment of complex launching bases and operating them, and the manufacture of the hardware and the fuel—represents a major share of the total cost of the space program. In the first place, the development costs are huge; the boosters are complicated technological devices which require large design, development, and test teams to get them into any reasonable state of operational readiness. In the long run, however, development costs become less important than operational costs.

One of the major operational costs of space boosters is the fuel. Every vehicle, be it a long-range ballistic missile or an orbiting vehicle, takes off loaded as high as 90 per cent of its total weight with fuel which is burned in the mission. When one considers that these vehicles range up to 200,000 pounds now, and will range to millions of pounds in the future, one realizes that the fuel cost alone will be considerable. Rocket booster engineers know this full well; and in their search for high-performance fuel combustion for their liquid and solid propellant rockets they also keep an eye on the production cost figures of the propellants.

However, one should not be too discouraged by the fact that such a large percentage of the take-off weight is fuel. We already have experience with operations in which very large amounts of fuel are used but which have become economically feasible—for example, one of the standard jet aircraft used today by commercial airlines. With a take-off weight of about 280,000 pounds, the fuel weight of such a plane is 122,000 pounds, or between 40 and 45 per cent of the take-off weight. For a payload of the order of 36,000 pounds between a third and a quarter of the fuel weight is expended in a flight. If one considers not the typical passenger jet airliner but the long-range bombers designed for a maximum fuel capacity in order to achieve a maximum range, one finds that instead of between 40 and 45 per cent of fuel in the take-off weight, it runs to 50 to 60 per cent. So a mission which involves expending most of the initial weight of the vehicle in fuel consumption is not necessarily something that cannot be made economically feasible and even profitable.

In current space operations one of the greatest expenses arises from the fact that the booster vehicle is used for only one flight. R. C. Truax, Director of Advanced Development at Aerojet General's Liquid Rocket Plant, told a panel of space writers in New York that "if an airliner today were to be used only once on a cross-country trip and then thrown away, the fare per passenger just to pay for the airplane would be around $30,000." Clearly the practice of using a rocket booster for a space mission only once must be changed, an objective on which efforts are now under way.

Before describing some of the techniques of recovering the booster vehicles for space missions, it is of interest to establish in the reader's mind a cost figure for space operations to be used as a standard. It is a difficult figure to calculate accurately because a typical space mission involves not only the cost of the hardware and the fuel as purchased from the manufacturers but also the cost of the launching team and the team that tracks the vehicle in its flight, and so on. Since the organizations which carry out these functions are complex, it is somewhat difficult for a cost analyst to track through government organization and make a fair assessment to each of the many organizations involved for the cost of their share of the operation. Even recognizing this difficulty, engineers today use as a standard the cost of putting a single pound of payload into a circular orbit about the Earth at an altitude of about 300 miles. Rough cost estimates for various booster systems and various kinds of projects show that the costs run from $1,000 to several thousand dollars per pound of payload in orbit.

The long-range objective of booster engineers and designers is to cut this cost per payload pound in orbit by a factor of at least one-tenth and possibly by one-hundredth. It is not easy to achieve, at least by using the techniques at hand, but there are some hopes. A reduction in cost by the order of one-tenth might almost be achieved by making completely recoverable booster systems; there are many such proposals now under consideration. One generic type employs as the first-stage booster a kind of flying vehicle which, after taking off vertically and boosting the upper stages to some reasonable velocity, possibly a few thousand feet-per-second up to 10,000 or 12,000 ft/sec, converts itself into a flying vehicle which is flown manned or unmanned and landed as a conventional high-speed aircraft. Some designers would prefer to see the engines of this first-stage booster of the same type as current high-speed airplanes—namely, turbojet engines—reasoning that such engines give added convenience, reliability, and low fuel consumption. There are other proposals to use recoverable schemes involving parachutes and recovery systems such as snatching the returning launching vehicle in the air by a large helicopter. Though at first these sound complex and unreliable, more detailed examination indicates that they have some reasonable degree of feasibility.

Whatever the recovery system that is developed, one can be sure of two things: that such a system is entirely feasible, but that the actual development costs will be very large. It is the kind of complex development that requires few new basic scientific principles—only the application of a large amount of engineering design and effort. In the mind of the author, the development of such a system of the recovery of the early first stages in boosters is inevitable.

The cost per launch varies widely since different missions have different payloads. A few of the scientific missions of the past have used very small vehicles. For example, our first Explorer weighed only about 30 pounds, and our first Vanguard only 3 or 4 pounds. The first Mercury manned orbital capsule will weigh 2,000 to 3,000 pounds. Eventually tens of thousands of pounds of space vehicles will be sent into orbit.

For the small number of launch types of scientific and exploration missions the simple expendable booster systems will pay off best because their development costs are much less than those of recoverable systems. The many-sectioned solid propellant boosters will be somewhat lower in cost per launch than the liquid propellant systems, though as the number of launches increases, the liquid propellant systems approach the solids in cost. Also, as the number of launches go up, the cost of expendable systems goes down, but rather slowly. For missions where the number of launches begin to grow it soon becomes desirable to consider recoverable systems as discussed above—either those fully or even partially recoverable. The development cost for fully recoverable systems will be large, but not substantially more than for partially recoverable systems. With many launches, such as one might expect over the decades for a commercial satellite system or a manned military orbiting system, the fully recoverable systems would probably justify their initial development cost. In such high-performance recoverable systems which for a large number of launches will give the lowest cost per launch, one finds, as mentioned above, high-speed air breathing engines using the turbojets and ramjets and high performance liquid rockets; one also notes the entrance of the nuclear rocket into the discussion.

It is important that everything be done that is possible to reduce the high costs of space programs. The United States government alone is spending an amount approaching 10 billion dollars on its space research, development, testing, and operations programs—programs which of course are broadly based. The United States program as a whole includes medium- and long-range ballistic missiles, military and commercial satellites, scientific, research, and exploration missions penetrating deeply into the solar system, and scientific measurements of the characteristics of the Earth and the space around the Earth.

New boosters for space missions will cost hundreds of millions of dollars before they can be considered operational vehicles. After they are developed, the operative cost will still remain large until the devices themselves are made recoverable. But the present situation on development and operation is not radically different from that which existed in the development stage of large commercial jet transports. Those also cost hundreds of millions of dollars to develop, but large-scale operational use of jet transports has shown that the effects of the initial cost upon direct operating cost is almost negligible. It follows that it is important in space operation to be able to spread initial development costs over many operations if space is to become an important component of man's everyday life.

TESTING: THE BOOSTER EXPERIENCE

As developments in the component fields go forward in a technology as complicated as space flight, there is no substitute for actual space testing, the value of which has been demonstrated by the statistics which come out of the reliability studies on large space boosters.

Thus far in the development of space boosters the percentage of successes in the first ten firings ranges between two out of ten and six out of ten, with the average about four out of ten. From this rough average of forty per cent reliability for the first ten shots, reliability goes up into the eighty and ninety per cent region as the number of shots increases to a hundred. From there on, increased reliability in boosting gets more and more difficult and seems to be obtainable only with greatly increased numbers of firings.

Another indicator of the improvement that arises from experience is the *Box Score of United States Spacecraft Launches*. A similar box score for Russian launchings over the years is given. Here it is noted that the score is 100 per cent for all five years of the space age. This may be explained on the basis of somewhat different rules of scoring.

To back up the engineering developments listed above which are required to improve our space capability, some discoveries in the fundamental sciences of physics, chemistry, mathematics, and biology will be of help. In fact, in the forefront of research in the engineering fields the boundaries between these basic sciences and the engineering fields are fuzzy, and in the modern technological world they tend almost to disappear. This is not true, however, in the design, development, testing, and using of the large, complex space vehicles. Such activities are purely engineering. Here the engineer with purposefulness, vision, and sound technical training will lead the way.

The Nuclear Rocket

As one of the most interesting and widely discussed space developments, the proposed manned Moon exploration is usually publicized in the context of cost. The author has seen estimates of successfully landing a man on the Moon and returning him to Earth ranging from about one billion to one hundred billion dollars, with time estimates from 3 to 20 years. More responsible estimates range from fifteen to forty billion dollars, and from

BOX SCORE OF UNITED STATES SPACECRAFT LAUNCHES

Vanguard TV3	
Failures: 1	Successes: 0
1957 TOTAL: 1	

Explorer II Explorer V Vanguard TV3 (sic) Vanguard TV5 Vanguard SLV1 Vanguard SLV2 Vanguard SLV3 Project Able I Pioneer I Pioneer II Pioneer III Beacon I	Explorer I Explorer III Explorer IV Vanguard I Project Score
Failures: 12	Successes*: 5
1958 TOTAL: 17	

Vanguard SLV5 Vanguard SLV6 Discoverer III Discoverer IV Explorer Project Beacon II Transit IA Atlas Able IV	Vanguard II Vanguard III Discoverer I Discoverer II Discoverer V Discoverer VI Discoverer VII Discoverer VIII Pioneer IV Explorer VI Explorer VII
Failures: 8	Successes*: 11
1959 TOTAL: 19	

Samos I Midas I Courier IA Discoverer IX Discoverer X Discoverer XII Discoverer XVI Project Echo Explorer Radiation Satellite Atlas Able 5-A Atlas Able 5-B Transit IIIA/GREB II Scout-3	Echo I Pioneer V Tiros I Tiros II Courier IB Discoverer XI Discoverer XIII Discoverer XIV Discoverer XV Discoverer XVII Discoverer XVIII Discoverer XIX Midas II Transit IB/GREB I Transit IIA/GREB II Explorer VIII
Failures: 13	Successes*: 16
1960 TOTAL: 29	

Explorer S-45 I Discoverer XXII Mercury Atlas III Explorer S-45 II Discoverer XXIV Explorer S-55 Discoverer XXVII Discoverer XXVIII Samos III Discoverer XXXIII	Samos II Explorer IX Discoverer XX Discoverer XXI Transit III B/Lofti Explorer X Discoverer XXIII Explorer XI Discoverer XXV Transit IV A/Injun/GREB III Discoverer XXVI Tiros III Midas III Explorer XII Ranger I Explorer XIII	Discoverer XXIX Discoverer XXX Mercury-Atlas IV Discoverer XXXI Discoverer XXXII Midas IV
Failures: 10	Successes: 22	
1961 TOTAL: 32 (to October 24, 1961)		

* Payload successfully injected into orbit.

BOX SCORE OF USSR SPACECRAFT LAUNCHES

	Sputnik I Sputnik II
Failures: ?	Successes: 2
1957 TOTAL: 2	

	Sputnik III
Failures: ?	Successes: 1
1958 TOTAL: 1	

	Lunik I (Mechta) Lunik II Lunik III
Failures: ?	Successes: 3
1959 TOTAL: 3	

	Sputnik IV Sputnik V Sputnik VI
Failures: ?	Successes: 3
1960 TOTAL: 3	

	Sputnik VII Venus Probe/Sputnik VIII Sputnik IX Sputnik X Vostok I Vostok II
Failures: ?	Successes: 6
1961 TOTAL: 6 (to October 24, 1961)	

From: "Space Log," Space Technology Laboratories, Inc.

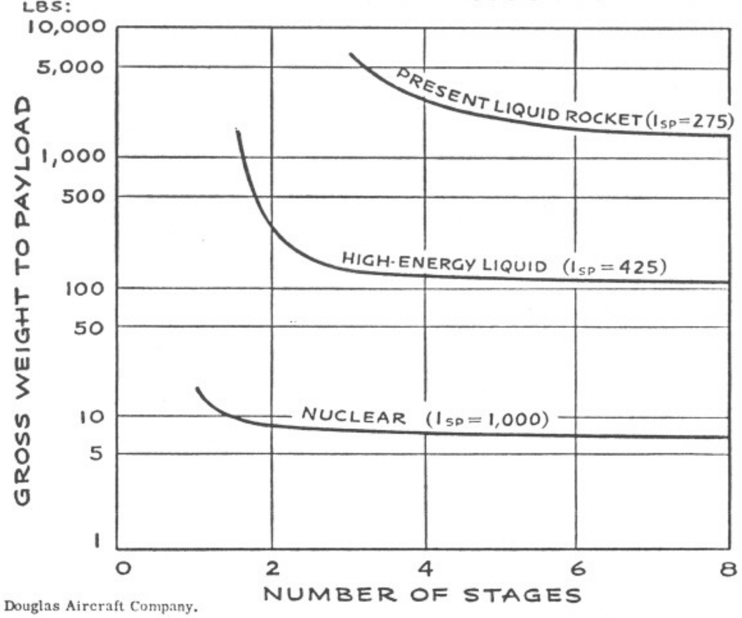
seven to ten years. Granting the importance of cost, in the technical perspective the Moon program is of special interest because it points up the importance of the development of the safe nuclear rocket. Most of the Moon planning programs have been based upon the use of high-performance liquid-propellant rockets; and the cost and time estimates of all the development and the testing and the actual missions themselves have been based upon such rockets. But the liquid-propellant rocket has been selected only because its principal competitor, the nuclear rocket, is not considered to be in a sufficiently advanced state. If the Moon program objective were moved back to a 15- or 20-year objective instead of something less than 10 years, then clearly the nuclear rocket would compete.

Just where, then, does the nuclear rocket stand with respect to its promise for the future and its current development? There has been considerable publicity given to the nuclear rocket development; and in fact a joint National Aeronautics and Space Agency-Atomic Energy Commission development project with industry has already been started. This action follows a long period of experimentation on a test-bed nuclear rocket by the Atomic Energy Commission, aided by certain industries. The new developments are aimed at a flight test engine within a period of 5 to 7 years.

Just how important is the nuclear engine? One answer to this question is suggested by a comparison of liquid, solid, and nuclear propulsion systems in terms of specific impulse, which, measured in seconds, is a merit factor for the efficiency of the use of the propellant.[1] Liquid propulsion systems now are considerably better than solid propulsion systems, and they offer room for further improvement; but the specific impulse promised by nuclear rockets is far above anything that is promised by the liquid or solid rocket propellant systems. It appears that, while the best performance for a liquid propulsion system might be about 500 seconds, and the best for a solid propulsion system about 325 seconds, the best performance of a nuclear propulsion system might be a specific impulse of 1,200 seconds.

ROUND TRIP LUNAR FLIGHT WITH ATMOSPHERIC BRAKING

IMPULSE VELOCITY: 60,000 FPS



From: Douglas Aircraft Company.

Actually, increases in specific impulse multiply over and over in the final performance of specific booster systems. That can best be shown from a graph (*Round Trip Lunar Flight,* etc.). In this graph the ratio of the gross weight at take-off to the weight of the payload is plotted against the number of stages for different kinds of rockets. If one designs a lunar rocket system requiring an impulsive velocity of 60,000 ft/sec, which is quite reasonable, and bases it upon the present liquid rocket specific impulse of 275, a six-stage vehicle would require about 2,000 pounds gross weight at take-off for every pound of payload. If the payload for a manned landing system were 16,000 pounds, the take-off gross weight would be about 32,000,000 pounds. By the time the lunar vehicle was developed, one could count on using high-energy liquid propellant systems with specific impulses possibly as high as 425. The graph shows that gross weight would be something over 100 times the weight of payload. With 150 pounds of payload the number of stages could be reduced possibly to three or four. The same graph shows that the use of a nuclear rocket with a specific impuse of 1,000 seconds would permit the use of about 8 pounds of gross weight per payload pound with only two stages.

The reader can get a good idea of the size scale of nuclear and liquid-propellant rocket space vehicles by the comparison shown in the accompanying figure (*Size Comparison*).

Clearly the nuclear rocket offers tremendous promise as a booster system for deep space operations. It is the author's estimate that the development of a satisfactory nuclear rocket booster system is the *sine qua non* for more distant future space operations. It is also interesting to note that the nuclear rocket does not require new scientific principles. The development

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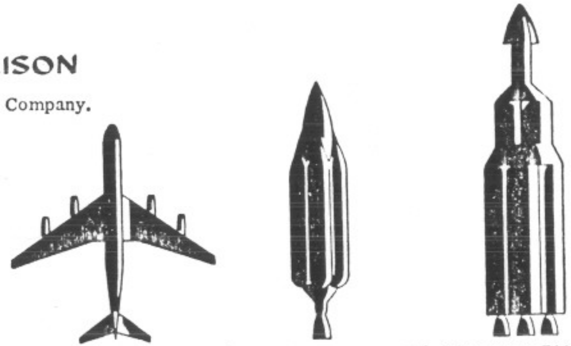
[1] Based on a graph, "Propellant Performance," taken from the testimony of Mr. S. K. Hoffman, Vice President of North America Aviation, Inc. and President of their Rocketdyne Division, and a leading developer of rocket engines, to the Committee on Science and Astronautics of the United States House of Representatives.

SIZE COMPARISON

From: Douglas Aircraft Company.



	DC-8	NUCLEAR ROCKET	LARGE CHEMICAL ROCKET
VELOCITY	830 FPS	60,000 FPS	60,000 FPS
GROSS WEIGHT	280,000 LBS	270,000 LBS	6,000,000 LBS
FUEL	122,000 LBS	213,000 LBS	5,500,000 LBS
PAYLOAD	36,000 LBS	17,000 LBS	16,000 LBS

of the nuclear rocket will be a long, complicated, expensive engineering project. If, as will almost surely be done someday, the nuclear rocket stage is developed in a form which is recoverable, it will open the door to a reasonable capability for operating in the solar system on rather elaborate missions to distant planets and returning without incurring overwhelmingly exorbitant costs. Such developments will take a long time. The author would not attempt to put a date on the achievement of these final potentialities except to say that it is clearly more than a decade away.

Some Major Problems

CONTROL, GUIDANCE, AND COMMUNICATIONS

One whole new field of development consists in the guidance and control equipment for space operations. Ballistic missiles can be guided by two basically different systems: the one employing so-called inertial navigation in which pre-set devices involving gyroscopes and accelerometers and computers guide the vehicle entirely throughout its flight; the other involving radio direction finding and radar distance measuring to perform continuous tracking and guidance of the ballistic missile. For very long-range space missions inertial guidance can be used in part, but there must be corrections to it made by optical or radio sighting devices to reference

points such as the Earth, the Sun, and the other planets and stars. A wide range of devices which contribute to this lore has been worked on over the recent decades, and the problem seems to be one not of discovering new principles but of making the technical advances necessary to develop new equipment.

RELIABILITY

In the types of devices needed for communications, guidance, and control there are many electronic, mechanical, and thermal parts which add up to very complex systems. Furthermore, there are restrictions concerning weight and size and power consumption of these parts. Experience with such complicated systems has shown that long-term reliability is always a problem.

Long-term reliability can be obtained for very simple devices. For example, the much maligned Vanguard program, which was hopefully our first but turned out to be later in the series of satellites, and the first of which consisted of only a three-and-a-quarter pound, 6-inch diameter sphere with a shell of aluminum containing two very simple radio transmitters, has been operating in space since March 17, 1958. Since the orbit it attained is sufficiently high so that the drag of the Earth's atmosphere does not tend to slow it down, the vehicle is expected to orbit the Earth for a long time, possibly centuries. One of its two transmitters was still broadcasting its position after 3 years—but it must be understood that this radio transmitter is the simplest of devices. The problem lies in the fact that reliability tends downward rapidly with increased complexity, and that thus far the process of making reliable the complex guidance, control, communication and other complicated equipment for spacecraft is difficult.

Some indications of the problems of reliability of communications equipment are shown by the tracking of the Sun satellites which have been established by both the Soviet Union and the United States. For example, the Pioneer V had the record interplanetary distance radio communication of something over 22,000,000 miles, before its communications equipment failed. The late Soviet Venus probe failed to transmit after going only a fraction of that distance.

There is one school of thought which believes that the best way of handling the complicated devices for space flight to ensure reliability is to have trained men aboard the spacecraft to repair them. This argument is advanced as one of the most important reasons for putting men into space. In the author's estimate, reliability of space equipment cannot be attained by repair and maintenance operations. One of the biggest problems yet to be conquered in space, it can be solved only by the slow process of improvement of design.

THE SPACE ENVIRONMENT

Whenever man has contemplated going into a new environment—sailing far from his native shores, first going up in balloons and airplanes—he has been challenged by the difficulties, real and imagined, of the new world he is entering. And so with space. For the space environment differs from our environment here on the surface of the Earth. There is no atmosphere to shield humans and equipment from the physical bodies, space particles and electromagnetic radiations in space; there is no atmosphere to supply life-giving oxygen.

Some of the harmful radiations such as the ultraviolet radiation from the Sun which would burn skin and eyes seriously can be easily shielded with only a small amount of material, such as the structural skin which any spacecraft requires. There are, however, other radiations from the Sun which are much more dangerous and occur mainly in solar flares. For example, there is an extremely high-energy flare from the Sun that might occur, say, once every four years, in which the energy of the particles range in the 370,000,000 electron volt range which is extremely dangerous to humans and from which they would definitely have to be shielded unless one wanted to take the chance that no human would be exposed when such a flare occurred. There are other solar flares which occur once a month or so and give out heavy radiation, concentrated around 46,000,000 electron volts. These are not as intense but still have to be taken into account. Around the Earth there is a belt of charged particles called the Van Allen Belt. The energies of the particles concentrate around 144,000,000 electron volts and also are of sufficient number that they must be taken into account in shielding. From outside the solar system, from galactic sources, there are cosmic rays with extremely high individual particle energies—around 4,000,000,000 electron volts—but which come in smaller numbers than the others. Finally, if the spacecraft employs a nuclear rocket, there must obviously be shielding for the direct and scattered neutrons and direct and scattered gamma rays from the nuclear reactor.

Throughout the solar system there are very fine particles of dust called micrometeorites, and, scattered in much smaller number, particles larger than dust. The distribution of these particles indicates that there will be some problem due to the slow weathering of outer surfaces of space vehicles by the impingement of this dust, which has a sand-blasting effect. Collision of a spacecraft with larger particles would create a hole, but self-sealing techniques and design of multiple-layer skins can minimize this hazard. Possibly the best way to describe the engineering problems raised by the foreign environment of space would be to list the various weights required in a typical vehicle design for a three-man spacecraft intended to travel extensively throughout the solar system and having a total weight of 52,000 pounds. (This vehicle has not yet been developed, but reasonably complete engineering studies have been made of the system.) The following figures, taken from Douglas Aircraft Company reports, are in pounds:

Pressurization and Oxygen System, 630
Thermal Conditioning, 720
Atmospheric Control, 340
Space Suits, 270
Three Men, 600
Interior Equipment, 560
Earth Survival Pack, 234
Food and Water, 348
Structure, 2,000
Shielding, 10,000
Electronic Equipment, 1,022
Power Supplies, 1,320
Last Stage, 20,000
Cargo, 14,000

One can see from this summary that the items required to provide the proper thermal and atmospheric control for men are relatively small; even the food and water become small items. The big items are shielding, any cargo or equipment necessary for the men to take on a trip through the solar system, and last-stage propulsion devices. But such a total can be handled by the very large liquid propellant rocket systems and the nuclear rocket systems under development.

Prospects

All that has been said here is quite independent of the special features of national technology, or of the Soviet-United States competition in space. It is clear that Soviet technology has been able to accomplish space missions with boosters larger than those used so far by the United States. However, long-term progress for the Soviets no less than the West will depend on the same considerations spelled out in this chapter.

It is this author's conclusion that, although the problems are many, the currently contemplated space missions are technically possible, and even the hazardous new environment of outer space presents no conditions which are impossible to counter by modern technology. True, the development of all the equipment for providing safe flight for humans in space will be an expensive development program, but on the other hand it seems to be a reasonably straightforward one.

In the end, achievement of the capability to use space profitably for mankind will depend upon the slow, expensive accumulation of engineering experience, not on spectacular break-throughs in the realm of scientific principles.

2.

Prospects for Human Welfare:

Peaceful uses

Introduction

◆ Donald N. Michael

Ever since Sputnik I there has been a plethora of free and easy predictions about the social impact of space activities and about the various ways in which space will substitute for, replace, or extend man's present earth activities. It seems worthwhile therefore to begin this discussion with some comments about what kinds of predictions will and will not be attempted herein and how these will differ in spirit and range from those which have been so easily made by so many for so many different reasons.

In the first place, we shall look at most no more than about 20 years ahead. But even 20 years may be too far to stretch the imagination if our speculations are to be more than sheer fantasy. For the pace of social, political, and

Outer Space

PROSPECTS FOR MAN & SOCIETY

◆ The American Assembly
Columbia University

Englewood Cliffs, N. J.
PRENTICE-HALL, INC., *1962*