Aerospace Education Workshop
University of Hawaii

June 1964

PROPULSION ~~LECTURE~~

Our first subject of discussion is "Propulsion in Space." This is that portion of modern propulsion which does not depend upon any atmosphere. Unlike our present airplane propulsion systems which use the oxygen content of the air in our atmosphere to burn the fuel they carry, these propulsion systems use propellants, fuels and oxydizers on-board both in liquid and solid form. We will not discuss today the supersonic ramjet and ramjets with air liquification.

There are some systems which use only one propellant, a so-called mono-propellant; others are called hybrids--but more about that later.

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A short excursion into the history of propulsion will introduce us to our present day technology. As early as in the 12th century, the use of "arrows of fire" was mentioned as a Chinese weapon. Earlier than that, "Hero," a Greek physicist in our sense of the term, demonstrated his whirling aelopile. I would call it the forerunner of our present lawn sprinkler which also uses the same reaction force for propulsion. Later in that same time frame, the story is told of a clever Chinese using solid rockets, fireworks of that time, for vehicle propulsion.

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His happy smile was quickly erased because of a miscalculation - or lack of calculation. His vehicle disintegrated and propelled him to heaven. You might call him the first unhappy astronaut.

Black powder, or a similar concoction, was finally re-invented in Europe by a monk named Schwartz who was employed at the royal court in Saxony as an "alchemist." Since that time, with a colorful history, black powder, guns, and rockets have been with us to stay.

Far back in the 16th and 17th centuries, rockets were used in warfare. Italian, French, German, and Polish inventors claimed many different accomplishments for their rockets.

Around 1800, Sir William Congreve started a real boom in rockets. These rockets could reach up to 2 miles with sizeable loads of almost 50 pounds. The last extensive use in that century was by the British navy in 1807. The Danish capital, Copenhagen, was set afire with about 30,000 rockets. It might well have looked like this

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The actual origin of our modern rocketry, specifically our liquid and solid approach of today, is somehow blurred. Who was first, and who heard from whom, is hard to establish precisely. Making no attempt to judge, I want to mention a few names.

A first liquid working rocket was claimed by Pedro E. Paulet, a Peruvian engineer, in 1895. K. E. Ziolkowsky, a Russian mathematician, proposed a liquid-fed rocket motor. In his first manuscripts, dated back to 1896, he proposed a hydrogen-oxygen rocket that we are using today, some 70 years later. Professor Hermann Oberth promoted the use of rockets as transportation into planetary space. His book, a classic, was published in 1923. I was personally fortunate enough to hear him lecture in 1931 at my university on the subject of space travel. At that time I certainly did not dream that my later professional life would be solely filled with rocket propulsion and space travel. This is Professor Oberth as I remember him.

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Here in the United States, Professor Robert H. Goddard began his experiments as long ago as 1915. In 1919 he published a book, "A Method of Achieving Extreme Altitudes." This was a timid title for "space propulsion." In 1920 he began tinkering on his first models which finally flew for the first time in 1926. He moved with his experiments, which his neighbors and associates considered dangerous, to Roswell, New Mexico, where his only observers were usually desert rabbits and rattlesnakes.

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Finally, in 1930 his rockets, propelled by liquid propellants, achieved altitudes of 2000 feet and velocities of up to 500 miles per hour.

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Shortly after this, spirited young amateurs formed the first "American Rocket Society" which now has several thousand members from all layers of the professional community.

Reaction Motors Incorporated was established in the midthirties and was for a long time the first industrial focal point for early space propulsion. Jet Propulsion Laboratory of the California Institute of Technology was formed officially at the beginning of World War II. From then until now, JPL has been synonymous with the early rocketry efforts and successes in the United States. These include different JATO systems, firings of the WAC Corporal series, the Corporal Weapons System, the Sargent Weapons System. Others are the Nike Anti-aircraft Systems and the Sparrow Air-to-Air Rocket. The first multiple stage firing was also attributed to JPL. As late as 1958, JPL participated with solid rockets in the firing of the first American satellite, the Explorer I.

Let us go back to Europe where Professor Oberth, a math teacher in a high school in Transylvania (also the "stomping" grounds of Dracula, if you are familiar with these stories) succeeded in developing formulas and relation of space propulsion which are valid today and form the cornerstone of modern astronautics.

Young men gathered in a Berlin precinct and began experimenting with rockets. The time was in the midthirties of this century. Young Wernher von Braun joined the group. With his unvanishing enthusiasm, he pushed the development of the first rockets, which were also liquid propelled ones. Searching for customers, the group found the postal department somewhat interested in rockets for mail delivery to inaccessible hamlets or islands. However, the transportation costs were higher than were considered economical for the postal department. Soon the military showed some interest because they recognized in the rockets a substitute for long range artillery which was outlawed at that time by the treaty of Versailles.

The government poured enough money into a new development center so that the "tinkering" could become logical scientific and engineering experimentation. This center was Peenemuende under the technical direction of Dr. Wernher von Braun --

SLIDE 7

the birthplace of our modern rocketry.

After the bloody collapse of the Third Reich, the essential scientific and engineering workforce, which had escaped the Russian grip by a wild Odyssey-like travel to the Bavarian Alps, was rounded up by the American armed forces.

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and placed in an interrogation camp. They were freed after 3 months of intensive scrutiny by U.S. Security officials and all others who wanted information. These Pennemuende specialists were stranded and mostly displaced, with their homes and their families located in all directions, some even behind the iron curtain. At this time, farsighted military men recognized the value of this group which had the knowledge and experience to analyze, engineer, build, and launch large rockets, and they knew the impact these people could have on the rocketry program of the United States.

Collectively, hundreds of years of experience were available in this group--just waiting to be utilized. Foremost in the action to bring them to the United States was the now-retired Major General Holger Toftoy who successfully unwound the Washington red tape to the extent that the War Department finally approved the "import" of 117 scientist engineers and specialists under the code name "Paperclip." I use the term "import" because officially this group was not allowed to enter the United States for another 2 to 3 years, despite their physical presence.

The group was self-contained in that it had all the talents to begin or to continue a propulsion or missile project. Now, after this historical excursion, we will return to the subject of propulsion.

In my discussion I will specifically exclude conventional airplane jets, which are air-breathers and, therefore, do not rank nor function in space as space propulsion systems. On the other hand, it is most important that rockets, liquid propelled or solid propelled, are also able to function within the atmosphere. They do not depend upon the air, as people usually think, to push themselves forward. The efficiency of rockets actually is even increased with diminishing external or atmospheric pressure.

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With the next slide I will explain the simplified fundamentals of jet propulsion. On the left side you see a sphere which is filled with high pressure air of 3000 psi, surrounded by the atmosphere we breathe of 15.4 psi. There is no reason why this sphere should move on its own in any direction. The internal pressure is contained by the wall; it exerts the same force in all directions. The external pressure surrounds the sphere. We can say mechanically that there is force-wise a state of equilibrium.

You noticed, perhaps, that this picture shows a plug screwed into the right side of the wall of the sphere.

Because it is dangerous, I expressly do not recommend that you perform this experiment, but just imagine that the plug is unscrewed and removed. Momentarily, the equilibrium is disturbed. The force which was pushing against the plug disappeared when we removed the plug. Still, all other forces acting on the inside of the sphere remain there. On the right side of the picture, all forces which are in equilibrium are shown in a light shade, except the one force depicted by a dark arrow opposite the hole which lost its partner. This force F resulting from the internal pressure p_c minus external pressure times the cross section A_c of the plug is now pushing against the wall and I can assure you that the sphere will move and the cart will start to roll. Obviously with such a hole in a pressure container we will lose the pressure fast and the force will decay along with the pressure toward zero, as shown in the diagram. This is but one portion of the inherent energy in the gas I have described at this time. In order to obtain a useful propulsion system, we must in some way sustain this force on the high level and to do this we must sustain the pressure in the sphere at the same level as at the moment we removed the plug.

How can this be done? The simplest way would be to keep the sphere connected to a pressure source. How do you obtain high pressure gas or air? You have seen compressors with huge motors--they are heavy machinery and if we expected to use this primitive system to propel us, we would have to take all the machinery along--also some air. I can assure you that it would be most uneconomical and we would not get far. We, therefore, must look for a lighter, more economical way to replenish the pressure in the sphere to sustain the reaction force we obtained.

Before I continue my explanation of the ways and means of replenishing and keeping the pressure in the sphere, let us look at the simple relationship shown in my next slide.

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This is not absolutely new.

SLIDE 10

Mass M is attracted by the gravitational forces of the earth (neglecting the gravitation force of the mass M itself) which results in a gravitational acceleration g_o. If you support the mass M in your hand, keep it from falling, then you feel the weight of the mass. With the basic equation of:

Force = Mass x accelleration or

Holding up the mass of a certain weight as described, we exert a certain force which is equal to the weight. The mass has a certain potential energy--P.E. If we now lift the mass for only one foot, we have to exert a Power F which is equal to the Weight W over a distance of one foot. We spent the work of weight x 1 ft to increase the potential energy, now possessed by that mass, by so many ft lbs. We added to the potential energy of Mass M which exerted the force of its weight on our hand, a certain amount of work in ft lb and increased the potential energy of the mass. You will notice that potential energy and work are both measured in ft lb.

If we now assume dropping the sphere or mass we have just lifted one foot into the other hand, the potential energy is converted into kinetical energy before it is caught in the other hand. During the free fall of the mass, its potential energy is reduced until it has the same level as that with which we started. The total effort we exerted in lifting the body from A to B is now converted into kinetic energy.

This energy is impacted to the hand and we counteract this impact and break the fall by exerting some force along a certain distance.

If we just dropp the mass on a piece of wood, this work would be converted into a dent in the wood.

We have just discussed two energy forms, KE and PE, both are plain mechanical energies.

Let us consider a gas. The potential energy of a gas or enthalpy is dependent upon its pressure, temperature, and composition. This type of energy is of interest to us. It is measured in BTU or calories. There is a relation of BTU or calories to mechanical energy. One BTU equals 778 ft lb.

High temperature gases, under pressure, are able to work if we allow the potential energy or enthalpy to become kinetic energy by changing its temperature and pressure into velocity. There is no linear relation between temperature pressure and enthalpy. The amount of recoverable energy depends entirely upon the properties of the gases. Hydrogen is a gas with a large amount of recoverable enthalpy. There are others not as good.

I repeat that energy is defined as the ability to work. Work is measured as force along a distance. Energy is measured in ft lbs. Work is measured in ft lbs. Power is measured in ft lbs per second. That means that work (ft lb/sec) is performed in a defined time element. One horsepower (HP) is defined to be 540 ft lb/sec.

So much for the mechanical measures

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Please disregard all formulas and explanations shown on this slide and follow my simple explanation.

Remember the sphere in one of the previous slides--the sphere with the plug and the simple hole? We established the momentary force F, a product of the pressure differential p_c minus p_a and the cross sectional area of the plug A_c.

A Swedish gentleman, Mr. DeLaval, invented a nozzle which can be used to transform one form of energy into another in gases flowing through the nozzle. Such a nozzle is nothing more than an inverted funnel--with the flow in the opposite direction from the usual application of a funnel. DeLaval limited the opening angle of such a funnel, or nozzle, to $2 \times 15^\circ$ maximum, otherwise the gas flow would not follow the contour and would detach itself. With such a simple nozzle, we can convert thermal energy into kinetic energy.

The potential energy of the gas in the sphere is a function of T_1, p_1 at a velocity v_1 equal zero. $v_1 = 0$

In the critical cross section, the throat, we have traded off T_1 and p_1, that is the temperature and pressure of gas into velocity v_c. The remaining pressure is p_c and the temperature is T_c. Remember that v_c is the maximum speed achievable in the critical cross section A_c. Using the nozzle, the gas is rushing further downstream.

To maintain flow continuity, by law the same mass has to flow through every cross sectional area of the nozzle. The gas velocity will have to increase from area to increasing area of the nozzle. Remember that we had v_c, sonic velocity, at A_c; now the velocity increases into the supersonic region. The kinetic energy increases more and more by trading off T_c, p_c, into velocity v_e. The potential energy left is determined by the values of T_e and p_e. For simplicity I omitted all losses such as friction, heat transfer, etc.

How can we influence the thrust of such a device? We can:

Increase A_e

Increase in the mass flow in a (time unit) or $\frac{\mathring{w}}{g_o}$

Increase v_e according to formula $p_e v_e = RT_e$ $\quad v_e = \frac{RT_e}{p_e}$

Increase T_e (T_c and T_1)

Decrease p_e

Increase R:

R^1 = constant and with $R = \frac{R^1}{M}$

Decrease <u>M</u>

We can tamper with all above values as we please except the M which is a value inherent to the gas itself. Only by changing the gas could we improve here.

Now I must go back to the discussion of how to maintain the pressure in the sphere to obtain a continuous flow through the hole, our critical cross section or throat of the rocket motor.

There are several ways to do this:

a. We can inject suitable propellants in liquid form into the sphere we now call "rocket chamber" and can ignite and burn them so that a high combustion pressure and temperature is generated.

b. Use the chemical decomposition process to convert liquids into high temperature gases; the high gas volume causes a high pressure.

c. We can place solid propellants into a chamber and burn them (same as a.).

d. We can use only solid fuel in a large chamber and add an oxidizing liquid necessary for the combustion (same as a.).

e. We can use high pressure gases produced by vaporizing of liquids prior to injection into the chamber and heating them by any suitable efficient process such as

(1) Heating through the heat freed by nuclear process in a solid, liquid, or gaseous reactor.

(2) Heating in an electrical discharge (continuous lightning in a chamber).

This again causes volume expansion and high pressure in the chamber. It increases the enthalpy or potential energy of the gases.

Electric and photon propulsion systems work differently and I will explain them later.

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In a simplified manner this next slide shows the different propulsion categories. This is a schematic illustration depicting the type of rocket engine we can distinguish today.

First, the chemical types:

These chemical rocket engines utilize the potential energy of the gases in the container or combustion chamber. The high potential energy is imparted to the gas by a chemical process combustion or decomposition of the propellants.

1. THE MONOPROPELLANT ROCKET ENGINES

In order to obtain the desired chamber pressure, a suitable propellant is fed under pressure over a catalyst bed into the chamber. The catalyst bed decomposes the fuel under development of heat which is imparted to the products of decomposition, for instance choosing H_2O_2 = hydrogenperoxide, we obtain $2H_2O$ water or steam plus the surplus + O_2. Achieved velocity 2 km/s. $I_{sp} \approx 200$ sec.

Here I have used for the first time the expression "specific impulse," or I_{sp}.

Simply explained, it expresses the quality of a rocket engine. Customarily I_{sp} in seconds is equal to the amount of propellant burned per second to achieve a certain thrust of the engine. However, there is a relationship between the exhaust velocity and the specific impulse.

The exhaust velocity is equal to the I_{sp} times earth gravity acceleration or $I_{sp} = \frac{v_e}{g_o}$ or,

approximated, the exhaust velocity is 10 times the specific impulse.

2. THE BI-PROPELLANT ROCKET ENGINE

By feeding into the chamber a fuel such as alcohol or kerosene and an oxydizer such as liquid oxygen or N_2O_4 (nitrogen tetroxide) and igniting the mixture, we obtain combustion gases with a sustained high pressure. The combustion products have also a high temperature. Their composition is dependent upon the chemistry of the propellant. For liquid hydrogen and liquid oxygen the combustion products are

$$H_2 + O = H_2O$$

Achieved velocities 3-4 km/s. $I_{sp} \sim 380 - 400$ seconds.

3. SOLID PROPELLANT ROCKETS

Solid propellant rockets contain a prepackaged mixture of fuel and oxydizer in one solid body in the now somewhat larger pressure vessel which serves as storage container and as combustion chamber. After ignition, the propellants burn from the surface into the body, converting by chemical process the cold low-volume solid into a hot, high-volume gas; velocity 2-3 km/s; $I_{sp} \sim 200 - 300$ seconds.

<u>Other, non-chemical types:</u>

4. NUCLEAR ROCKET ENGINES

The nuclear rocket engines of today use suitable liquid which can be vaporized and then, being fed through a solid core nuclear reactor, heated up to the highest temperatures possible. This temperature is only limited by the high temperature capacities of materials used in the construction of the reactor and the rocket engine. Velocities up to 9 km/s are achievable. $I_{sp} \sim 900$ seconds.

Using gaseous or liquid reactors, where the fissionable material is contained in a vessel without touching the wall, we can obtain higher temperatures and higher velocities: v up to 15-25 km/s; $I_{sp} \sim 1500-2500$ seconds.

5. ARC-HEATED PROPULSION ENGINE

The arc-heated propulsion engine uses the heat contained in an electric discharge to heat a suitable gas which is forced to pass through and around the arc.

The potential energy of the heated gas is converted into velocity in an adjacent nozzle.

Velocities achieved are up to 15 km/s; $I_{sp} \approx 1500$ seconds.

Let me expand slightly on the electric propulsion system. The early work of Russian Konstantin Eduardovitch Tsiolkovski contains some derivations of formulas for rockets in general. Equations, still valid, express the burnout velocity of a rocket in terms of mass ratio and exhaust velocity. Generally, it is shown that the higher the exhaust velocity and the mass ratio, which is the ratio between propellant used and launch weight, the higher is the burnout velocity which can be achieved by the rocket.

In order to appreciate the possibilities of an electric propulsion system, we must look a little longer at the basic rocket performance formulas.

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Naturally, if we want v_r as large as possible, we have to increase v_e and also the expression.

Generally, the second portion of the formula can have the maximum value if the dead mass of a rocket reaches 2 to 3 % of the total takeoff weight which is propellant plus rocket empty weight plus payload.

The expression $\ln\left(\frac{m_o}{m}\right)$ reaches a maximum value of approximately 3.5. We do not anticipate that this value can be raised in the near or distant future beyond approximately 3.8 to 3.9 (and that without payload). Therefore, the only way to increase burnout velocity is to increase the exhaust velocity v_e to such an extent that the influence of a decrease of the value $\ln \frac{m_o}{m}$ is overshadowed.

One possibility is to apply electromagnetic or electrostatic forces to the gas particles leaving the rocket engines. Here we enter the field of propulsion systems of the future.

6. THE PLASMA JET ENGINE

The plasma jet engine utilizes an arc discharge to ionize and heat a limited amount of suitable gas as propellant. The ionized gas acts as an electric conductor and in an adjacent electromagnetic field the gas sheet is accelerated in a combination of nozzle and magnetic field.

The achievable velocities reach 200 km/s with a corresponding I_{sp} 20,000 seconds.

7. THE ION ROCKET ENGINE

The Ion rocket engine utilizes propellants which require low ionization energy. With little effort, in certain gases an electron is knocked out of orbit around the nucleus of every molecule thus creating positive charged ion particles of the propellant. This is, for instance, achieved by having the gas passed through an electrically heated screen. These gas columns, consisting of positive charged particles, again are accelerated in an electrostatic field and escape the engine with high speed. Little tricks are also applied by guiding the collected "knocked out" negative electrons around the accelerator back into the gas stream, allowing them to rejoin the positive ions. Velocities up to 120 km/sec can be reached; I_{sp} = 12,000 seconds.

8. THE PHOTON ENGINE

The photon propulsion system works just as a flashlight. The light bulb containing an electrically heated metal wire emits photons which you see as a light beam. Raising the temperature of the photon emitter to temperatures as high or higher than 100,000°C, perhaps by a sustained nuclear process, can cause a complete conversion of matter into photons. Despite a low mass utilization, we obtain a very high velocity like that of the light which is close to 300,000 km/s; I_{sp} are therefore the highest with I_{sp} = 30,000,000 seconds.

9. PULSE DRIVE ENGINE

The final type of propulsion I want to mention is a pulse drive. A large heavy pusher plate is connected to the end of a rocket with some type of shock absorber. A simple mechanism releases explosive charges through a hole in the center. The charge is exploded below the pusher plate. The plate absorbs the shock pressure of the explosion and, over the damper system, imparts the energy to the vehicle. Obviously this type of propulsion needs lightweight high-efficiency explosive charges. I mention this type of propulsion only to complete my description of systems. I do not foresee any practical application in the near future.

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All values achieved are with a p_e expanded to p_o or atmospheric pressure. As you will recall from previous explanations, the total thrust formula is

$$T = A_e (p_e - p_a) + \mathring{M} v^2$$

The first portion of the equation contains the exit area A_e ; the exit pressure p_e; and the ambient pressure p_o .

This portion is maximum at a p_a pressure level of 0 psi, that is in space if the product $p_e A_e$ is an optimum with $A_e \rightarrow \infty$ $P_e \rightarrow 0$. Somewhere in between, with a fairly large A_e, we obtain a certain p_e. Engineering considerations in optimizing these two values are the determining factors. A large nozzle will be heavy and the gain by increasing it will be nullified soon by loss of performance caused by the weight of the increased nozzle size.

Another compromise has to be made. If the rocket in question is supposed to be useable only in space, then we choose a large nozzle. If the engine is used for a launch from earth, then we use a smaller nozzle. With a large nozzle we would over-expand the jet on the ground. The external pressure would creep into the nozzle and would make a certain portion of the nozzle absolutely ineffective.

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So far we have discussed

a. How we can obtain thrust.

b. Different forms of possible rocket propulsion: total of nine.

The remainder of my lecture today will cover only the liquid propellant rocket engines and description of slides. I will explain some salient features and explain the development trends. All nine types of propulsion have their particular applications, advantages, and disadvantages. For instance, solid rockets are ideal in smaller size because of their simplicity. Larger rockets can remain unattended for years and still function properly like our ICBM's. Large solid rockets are in competition with liquid rockets if you consider a mass production. Considering research and development, small production, and the request for repeated ground testing, solids have shortcomings. With liquid rockets you can ground test repeatedly to make absolutely sure that all parts function properly and that you have flushed out all the deficiencies and problems.

Nuclear, plasma, and ion engines are typical space propulsion systems and work usefully only in vacuum. It can readily be seen that in the future we will have use for many kinds of propulsion.

It is necessary for us to get into space with heavy chemical propulsion systems, then do some space traveling with the best suited space propulsion system. A manned fly-by around the planet Mars would require preferably nuclear and/or ion engines. Both are in an advanced stage of development. Today nuclear propulsion certainly has an edge on any other system for that particular mission. A very practical size engine developing approximately 200,000 pounds thrust is under active development.

The highest specific impulse, I_{sp} = thrust divided by the consumption per second, for a chemical engine is in the vicinity of 480 $\left[\frac{lb}{lb/sec}\right]$

The nuclear engine, in comparison, can develop 800-900 $\left[\frac{lb}{lb/sec}\right]$

The ion engine develops specific impulses of 3000 to 12,000 $\left[\frac{lb}{lb/sec}\right]$

Plasma engines go as high as 20,000 $\left[\frac{lb}{lb/sec}\right]$

Development on the ion and plasma engines is not quite as advanced as that of the nuclear engine.

Another problem is the relatively powerful electrical energy source needed for the ionization of the gases and the acceleration by a magnetic or static field. The electrical power source development, which could again be nuclear or thermonuclear plus solar batteries, has not reached a status of utilization.

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Simplified, we have two types of liquid propulsion systems:

a. pressure-fed system

b. pump-fed system

The main components of a propulsion system are the combustion chamber and the nozzle or injection system. In both systems you see the same basic elements.

For better comparison of the size engines used in the Saturn launch vehicle family, the next slide

SLIDE 17

shows the F-1 engine, the J-2, the H-1, the RL-10, and the C-1. The application of the C-1 will be explained with the next slide.

Once in space, the necessity of controlling the attitude and making smaller velocity and position correction demands a variety of small engines. The natural trend is to build these as simply as possible. The next slide shows the location and typical arrangement of control engines for the Apollo space ship.

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The Command Module has six quadruplets of control engines with 96 pounds thrust per engine. The module has in addition to the main engine, which is a pressure-fed system of 21,900 pounds, thrust-using storable hypergol propellant and quadruple clusters of control engines.

The Lunar Excursion Module is equipped with:

a. A descent stage engine, again storable hypergol throttleable engine of 10,500 pounds.

b. An ascent stage engine of the same type with 3500 pounds thrust. Again, the LEM has six quadruplets of control engines developing 96 pounds thrust per engine.

There are several types of engines in use with a variety of special requirement thrust, total burning time, different pulse increment, specification, etc. In some instances, available engines from the Gemini program were used in the Apollo program in order to save time and money. Today, we finally have an interchangeable engine, the C-1, which can be used in all control applications. Also, the third stage of the launch vehicle, the S-IVB stage, has auxiliary propulsion pods on both sides with a total of three to four attitude control engines which are used to control the attitude and for settling the propellants before ignition of the main engine, the J-2.

Let us discuss briefly the non-chemical propulsion systems.

First, the nuclear propulsion:

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We see here, simplified, the salient features of one type of solid core nuclear rocket engine. Describing the engine, I will start on the end where you see a cooled nozzle, then the throat (the critical cross section of our previous discussions), and the chamber. In the chamber a nuclear reactor is schematically shown.

In this case, the nuclear reactor is built to allow the flow of gaseous hydrogen through its system. The reactor is used as heat source and heat exchanger instead of the chemical combustion process used in the chemical rockets.

The gaseous hydrogen carried on board the rocket as a liquid is gasified in the process of cooling the nozzle, the chamber, and the elements of the reactor and then is heated in the reactor to an extremely high temperature as it cools the fuel elements of the reactor which are allowed to go critical in a controlled manner. Without their cooling, the reactor would melt and explode.

Taking advantage of the high temperature of the gas, the low molecular weight of the hydrogen, the efficiency of the solid core nuclear engine is roughly twice as high as that of a chemical rocket. The actual reactor fuel consumption used in the process of heating the hydrogen is very small.

When using a reactor in a launch vehicle, we have to consider the radiation problems associated with this type of propulsion. Another lecture at a later date will cover this type of propulsion in more detail.

The last picture I will show you is an ion engine which was built and has been tested by the Electro Optical Systems, Inc., of California.

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In conclusion, I would like to point out that the development of rocket engines in the last two decades took a sharp upswing. Consequently, today we have the propulsion systems necessary to explore the planetary space of the inner planets of the solar system.