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ABSTRACT

This curriculum guide is prepared for the Aerospace Education III series publication entitled "Space Technology: Propulsion, Control and Guidance of Space Vehicles." It provides guidelines for each chapter. The guide includes objectives, behavioral objectives, suggested outline, orientation, suggested key points, suggestions for teaching, instructional aids, projects, and further readings. Page references corresponding to the textbook are given where appropriate. (PS)

SEPTEMBER 1972

INSTRUCTIONAL UNIT II

SPACE TECHNOLOGY: PROPULSION, CONTROL AND GUIDANCE OF SPACE VEHICLES

INSTRUCTIONAL UNIT OBJECTIVES: Each student should —

a. Know the characteristics of engines which use the principle of oxidation in their operation.

b. Understand the differences between thrust requirements for launching a vehicle from the earth and for movement in space.

c. Be familiar with other types of propulsion systems.

d. Know the methods and problems of producing electric power for use in space vehicles.

e. Understand the principles involved in control, guidance, and navigation of spacecraft.

f. Understand the interrelationship of celestial mechanics and man-made means of maneuvering spacecraft in various types of space flights.

PHASES IN INSTRUCTIONAL UNIT II:

PHASE I - INTRODUCTION—VEHICLES IN AEROSPACE

This phase reviews and builds upon background students have acquired in previous units of the Aerospace Education curriculum. It establishes the basis of space flight in Newton's law of gravitation, Kepler's three laws of planetary motion, and Newton's three laws of motion. Then it compares the conditions of aeronautical flight with those of space flight, touching on various aspects of propulsion, control, and guidance that will be treated more fully in later phases.

1. PHASE 1 OBJECTIVES: Each student should --

   a. Know Kepler's laws of planetary motion, Newton's law of gravitation and three laws of motion, and the differences between physical conditions prevailing in air and space.

   b. Know the meanings of the terms mass, inertia, momentum, friction and acceleration.

   c. Understand the ways in which these phenomena (listed in b) affect or do not affect the motion of vehicles in air or space.

   d. Be familiar with the behavior of vehicles in air or space as affected by natural and man-made forces.

2. BEHAVIORAL OBJECTIVES: Each student should be able to --

   a. State Kepler's three laws of planetary motion.

   b. State Newton's three laws of motion and apply them to any example of motion on the ground, in air, or in space.

   c. Discuss the principles of reaction motors, whether of aircraft or spacecraft.

   d. Compare the conditions of motion in atmosphere and in space with regard to vehicle control, friction, airfoils and streamlining, and propulsion needs for launch and flight.

3. SUGGESTED OUTLINE:

   a. Principles discovered in the seventeenth century.

      (1) Gravity and gravitation.

      (2) Kepler's laws of planetary motion.

      (3) Newton's laws of motion.

(4) Terms associated with these laws: mass, inertia, momentum, friction, and acceleration.

b. Vehicles in air.

(1) Propulsion.

(2) Aircraft control.

(3) Missiles and spacecraft in air

(a) Escape from atmosphere.

(b) Reentry into atmosphere.

c. Vehicles in space.

(1) Propulsion.

(2) Control and guidance.

4. ORIENTATION:

a. This phase is one of review and introduction, with limited advancement of knowledge over that which might be assumed to be part of the student's background. The average high school student growing up in the space age has acquired quite a bit of its lore, but in a somewhat disorganized fashion. Some of it comes from a typical exposure to elementary and junior high level general science courses, some from the unfolding drama of space exploits in the press and television. Specific high school courses in physics, chemistry, or mathematics are not assumed to be to be part of the student's background. On the other hand, certain specifics of this phase have been touched upon in previous units of the Aerospace Education curriculum.

b. The main object of this introductory phase is to consider and compare the different conditions of aerodynamic and space flight before building a more thorough understanding of the latter. With this object in mind, the student should recall what he knows of aerodynamics and aircraft propulsion through study of Theory of Aircraft Flight and Propulsion Systems for Aircraft, in the previous year's curriculum (AE II). His memory may need some prodding in regard to aspects of the space environment and the rudiments of space-vehicle motion as dealt with in Space and the Universe and Spacecraft and Launch Vehicles, or the revisions of these, Aerospace Environment and Spacecraft and Their Boosters (AE I). Nevertheless, he probably knows (and considers banal) the facts that air has substance, space is essentially a vacuum, and that weightlessness is a peculiar condition experienced in space flight. He has probably not thought out what these facts imply in regard to the art of maneuvering a body through space.

c. As far as new knowledge is concerned, this phase probably presents more explicit statements of Kepler's laws of planetary motion and Newton's law of gravitation and laws of motion than the student has previously encountered. It offers only a foretaste of knowledge about space vehicle propulsion and maneuver to be covered in following phases of the unit.

5. SUGGESTED KEY POINTS:

(J-9111) pp 2-8
(J-9132) pp 100-125
(J-9146) pp 14-15

a. All vehicles, including space vehicles, move in accordance with physical laws discovered in the Seventeenth Century by Kepler, Galileo, and Newton. Only in the modern space age has man <u>experienced</u> many of these laws in action.

(J-9033) pp 44-47

(1) <u>Gravitation</u> is defined by Newton as the attraction of bodies in space with a force proportional to the product of their masses and to the inverse squares of the distances between them. Gravity is the same thing, but is usually defined as gravitation as we experience it on earth--the overwhelming attraction of the earth upon infinitely smaller objects very near to it, with a force that includes a vector for the earth's rotation.

(2) To better understand Newton's law of gravitation as it affects celestial mechanics, it is necessary to go back to Johannes Kepler, who set down the laws of planetary motion:

(a) Planets follow elliptical paths around the sun.

(J-9033) pp 60-66
(J-9132) pp 100-112
(J-9158) pp 22-32

(b) A planet's radius vector sweeps out equal areas in equal time (textbook, Fig. 2). Putting this fact more simply, the planet travels faster while closer to the sun.

(c) The <u>square</u> of the time it takes each planet to orbit the sun is proportional to the <u>cube</u> of its mean distance from the sun. Putting it more simply, inner planets travel at higher velocity than outer planets; they complete their orbits faster for <u>two</u> reasons: the shorter distance traveled and their higher velocity.

(3) Newton's law of gravitation and three laws of motion explain not only the Keplerian behavior of planets and other orbiting bodies but also any motion on earth or in space. The three laws of motion are:

(a) A body will either remain stationary or continue prior motion without change of direction or velocity unless acted upon by an outside force.

(J-9132)pp 100-125

(b) A change in a body's motion indicates the presence of a force and is proportional to and in the direction of that force.

(c) For every action there is an equal and opposite reaction.

(4) Mass, inertia, momentum, and acceleration are the terms that describe the behavior of bodies according to Newton's law in <u>any</u> environment. Another term, friction, is important to know for understanding the limits on vehicle motion on earth and in the air.

b. Vehicles in air must be adapted to an environment that resists, applies pressure, and produces friction.

(J-9023H)pp 11-21

(1) For a body to move through air, propulsion must be constantly applied to overcome resistance even if a constant speed is to be maintained without acceleration. The very limitations of this medium, however, are advantages in terms of control and maneuverability.

(2) Aircraft and rockets in air can both be maneuvered by the use of airfoils. A vehicle in air can also regulate its velocity by variations in propulsive power output <u>without</u> changing course (unlike a vehicle in space).

(J-9023H)pp 158-161

(3) If a vehicle travels at extremely high velocity through air, the heat of atmospheric friction will burn it up like a meteor. This is the "reentry problem" basic to the return of all vehicles from space. The blunt forward surface coated with an "ablative heat shield" is currently the favored solution to the problem. The gliding or "lifting body" principle is under research and development. (Note: This key point deserves special emphasis because, unlike the others, it is not treated in greater detail elsewhere in the unit.)

c. Vehicles in space move in more direct or apparent obedience to Newton's laws. Airfoils have no effect on their movement. Neither, in itself, does attitude. In space, propulsion is hard to differentiate from control, for control is achieved by use of thrust only. Not only can thrust be deflected or vector controlled for aiming a space vehicle, but change of velocity applied in a straight line results in a change of direction of travel.

d. The most difficult and costliest problem in space propulsion is that of launch. Overcoming gravity and atmospheric friction to achieve orbital velocity requires generation of tremendous thrust forces and the wasteful jettisoning of costly stages to lighten the burden as the vehicle rises into orbit.

6. SUGGESTIONS FOR TEACHING:

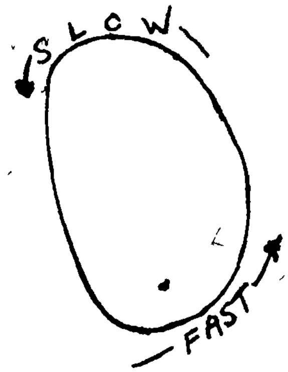
a. Suggested time:

Number of Academic Periods per Week	Recommended Number of Periods for Each Phase					
	1	2	3	4	5	6
2		X				
3		X				
4			X			

b. This is an introductory phase into a subject some students may find forbiddingly technical. Therefore, be reassuring rather than demanding. No written quizzes or challenging special projects should be assigned at this point. Ask discussion questions designed to encourage students to tell what they know out of their background (see Orientation). Welcome questions from students that show evidence of aroused curiosity; subdue hostile reactions to questions that may seem silly or impertinent; they may be asked in good faith. There is no need to feel embarrassment over questions you cannot answer; try to look up the answers before the next session. Remember we are only in an introductory phase and do not penetrate too deeply into subjects that will be taken up in forthcoming phases.

c. The text, Figure 2, already provides an illustration of Kepler's second law of planetary motion. Instead of dealing with its mathematics, try to convey a much simpler idea -- the sense of an orbiting body moving faster at perigee than at apogee -- "the closer the faster." Have a student draw on the chalkboard a simple ellipse, in vertical position, within which is a single focal point below center. This would be similar to Figure 2, but vertical and without vector lines. Repeatedly move your hand around this ellipse, moving it with exaggerated speed at perigee (underside) and exaggerated slowness at apogee (topside).

The fast motion seems to build up momentum for the "climb" to apogee.



d. Kepler's third law, on the other hand, invites mathematical exercise, and figures are available for working a simple problem (extracting a cube root) and checking results. Let a student volunteer work the problem and put his results on the chalkboard. Here is the problem:

If the mean distance from Sun to Earth (93 million miles) is one astronomical unit, the orbital period of Earth one year, and the orbital period of Mars 1.9 Earth years (actually 1.88, but it is better to simplify for classroom purposes), what is the mean distance (in astronomical units to the nearest hundredth) between the Sun and Mars?

Letting x stand for the mean distance --

$1.9^2 = x^3$ or $3.61 = x^3$ or $x = \sqrt[3]{3.61}$

Solution, $x = 1.53$

To get the answer in miles, the students can now refer to their own textbooks, Figure 61. According to data in that table, 1 astronomical unit = 93 mission miles; 93 X 1.53 = 142.29 million miles. In the same table, this mean distance is given as 141.5 million miles. Since problem was simplified by use of rough rather than exact amounts, 142.29 and 141.5 can be considered close enough to each other to corroborate Kepler. (Note: the proportion sign ($\propto$) should have been used instead of (=) but in this introductory phase, the teacher might sidestep unfamiliar mathematical signs and concepts that could throw a mental block against some students. On the other hand, if a student is able to point out this error, reassure him that he is right.

e. Display to the class pictures of various kinds of satellites (including figures 23 and 62 in the textbook) to illustrate the fact that aerodynamics or streamlining has no relation to their design.

f. Some demonstration of the basic principle of reaction motors, even if students should be familiar with it, might be valuable to reinforce the concept. Inflating a balloon and releasing it to fly across the classroom is simple, yet effective. Emphasize the fact (not apparent) that there is no "pushing" effect of released gas against outside air.

7. INSTRUCTIONAL AIDS:

a. Balloon demonstration and chalkboard illustration of Kepler's laws are mentioned above. Overhead transparency series indicated is on elementary level and most suitable for introductory phase.

b. Air Force films.

SFP 697. Down to Earth (reentry problem) 13 min. Color. 1959.

TF 5622. Space in Perspective. 27 min. Color. 1965.

c. NASA films.

HQ 205 (NASA). Space in the 70's - Aeronautics 1971. 28 min.

d. Transparencies:

T 26 through T 32, or 8013.

8. PROJECTS:

None recommended for introductory phase. It is better to assign these in connection with later phases, which go into more detail on topics introduced in Phase I.

9. FURTHER READING:

Van Deventer, C. N. An Introduction to General Aeronautics. American Technical Society, 1965.

Bernardo, James V. Aviation in the Modern World. New York: E. P. Dutton and Co., 1966.

PHASE II - CHEMICAL PROPULSION AND THE BASICS OF THRUST

This phase begins with a review of basic chemistry to provide an understanding of oxidation, the essence of chemical propulsion, which is today still the dominant means of space travel. Oxidation, because it energizes molecules into rapid motion, creates the mass flow which is the basis of thrust. From this point on, the consideration is more within the realm of physics than of chemistry as we consider combustion chamber and nozzle design, specific impulse, mass ratio, and other factors related to the heaviest task of propulsion -- boosting a vehicle off the surface of the earth to orbital velocity.

1. PHASE II OBJECTIVES: Each student should --

   a. Know that chemical propulsion of a rocket is achieved by a reaction called oxidation, and know the definition of oxidation.

   b. Understand oxidation in terms of molecular behavior, more specifically, the behavior of a hot gas in a combustion chamber and escaping through a nozzle.

   c. Understand why rocket nozzles are generally conical in shape and know the meaning of "expansion ratio."

   d. Be familiar with such terms as thrust (in pounds), specific impulse, thrust-to-weight ratio, mass ratio, gross-weight-to-payload ratio, and velocity gain (ΔV), and their application to the problem of launching a space vehicle.

2. BEHAVIORAL OBJECTIVES: Each student should be able to:

   a. Explain in molecular terms what happens in slow and fast oxidations.

   b. Compare combustion in an air-breathing engine with that in a rocket engine.

   c. Describe a molecule's path from combustion chamber to nozzle exit plane of a rocket motor.

   d. Describe the process by which a payload is boosted from the earth's surface into orbit.

3. SUGGESTED OUTLINE:

   a. Oxidation or combustion (reaction of oxidizer with reducer).

      (1) Oxidizers: oxygen most common, also fluorine and chlorine, or compounds containing these elements.

(2) Reducers or fuels: numerous elements, infinite number of compounds.

(3) Rocket propellant combinations.

(a) Bi-propellants.

(b) Solid mixtures and compounds.

(c) Liquid monopropellant mixtures.

(4) Nature and effects of oxidation.

(a) Recombination of molecules without loss of mass.

(b) Stirring of molecules into vibration and/or motion.

(c) Energy effects: heat, light, and physical force.

b. Combustion for propulsion.

(1) Qualities of a good rocket propellant.

(a) Contains fuel in solid or liquid form.

(b) Contains oxidizer in solid or liquid form (not free air).

(c) Ignites reliably.

(d) Has strong mechanical force output.

(e) Has controllable force output (not a high explosive).

(2) Pressure and mass flow.

(a) Pressure exerted in all directions.

(b) Flow permitted in one direction.

c. Basic rocket motor design.

(1) Bottleneck for retaining pressure.

(2) Flaring nozzle for accelerating flow after bottleneck.

(a) Advantages of high expansion ratio.

(b) Advantages of low expansion ratio.

(c) Compromises and problems.

d. Some basics of thrust.

(1) What is meant by thrust in pounds.

(2) Components (meaning of symbols F, w, g, C).

(3) Specific impulse.

(a) Value in rocketry.

(b) Theoretical I_{sp} of different propulsion methods (chemical, nuclear, electric).

(c) I_{sp} and molecular weight.

e. Launch propulsion.

(1) Thrust-to-weight ratio — the liftoff problem.

(a) Apparent low value of 1.17 to 1 (first stage Saturn V).

(b) How orbital velocity is built on this apparent low value (constant thrust, acceleration, weight loss, decrease of atmospheric pressure, decrease of gravity).

(2) Mass ratio (application to problem of dead weight).

(3) Gross-weight-to-payload ratio.

(a) General improvement (decrease) since 1958.

(b) Advantage of mammoth size of Saturn V.

(4) Velocity gain (ΔV) by stages.

4. ORIENTATION:

This is the first of three phases on the subject of propulsion. The approach (which, frankly, some students not of scientific bent may not welcome) is fundamental and theoretical. Thrust is the result of oxidation, and the latter subject demands a brief plunge into the fundamentals of chemistry. Once the process is envisioned as a flow of molecules, equally fundamental approaches to certain areas of physics follow. The instructor, in some cases, may feel he is getting out of his depth too. Both instructor and student will have to ~~apply~~ imagination where mathematical and scientific background is lacking -- to construct mental images of what is going on in the invisible world of molecules. The differences between kinds <u>of</u> propulsion systems -- solid, liquid, and nonchemical are <u>not</u> discussed in this phase. These topics are reserved for phases three and four.

5. SUGGESTED KEY POINTS:

a. The nuclear rocket is not yet a reality. To understand how man can reach the moon, one must understand the power of a chemical reaction called oxidation or combustion (rapid oxidation). This is the reaction of an oxidizer with a reducer (more commonly, a fuel).

(J-9023K)pp 71-76
(J-9033)pp 83-91
(J-9010)pp 57-60
(J-9132)pp 426-427

(1) The most common oxidizer is the element oxygen, occurring in free air as the molecule O_2. In its pure form, oxygen must be chilled to -297o F. to liquefy for usefulness in a rocket. Other oxidizer elements are chlorine and fluorine. The only way to provide a concentrated oxidizer at normal temperatures is to use a compound which includes an oxidizer element.

(2) Numerous chemical compounds and elements can serve as reducers or fuels. Compounds of carbon and hydrogen (hydrocarbons) are the basic fuels of transportation and industry, also much used in space. Nitrogen also figures importantly in high-energy compounds. Pure hydrogen, which liquefies at -423o F., is a high-energy rocket fuel.

(3) There are certain basic ways in which propellant chemicals are stored in a rocket and brought together into a chamber for combustion. The three most common are considered here:

(a) Liquid bipropellant -- liquid oxidizer and liquid fuel stored in separate tanks and brought together into a chamber for combustion. This is the most common type of liquid engine.

(b) Solid -- oxidizer and fuel mixture form one solid mass, which is ignited and burns in its storage chamber, which is also its combustion chamber.

(c) Liquid monopropellant -- liquid oxidizer and fuel stored together as a mixture in one tank and ignited after passage into combustion chamber.

(4) There is a difference between a mixture and a self-reacting compound. In the latter, the individual molecules contain both fuel and oxidizer elements and can, upon ignition, break down or "react with themselves."

(5) In a chemical reaction, molecules break apart, and atoms and molecules also recombine to form new molecules. This

molecular reshuffling is a physical activity, which can be slow, but in the case of rocket combustion, extremely vigorous, causing the molecules to vibrate (emitting heat and light) and move at great speed (exerting physical force). Molecules can also be stimulated into vibration or vigorous movement by nearby combustion, without undergoing chemical change themselves; sometimes unburned molecules can add to rocket thrust.

(J-9023K)pp 88-93
(J-9033)pp 98-100
(3.48-3.52)

(a) The phenomenon of a reaction vigorous enough to produce palpable heat, visible light (flow or flame), and expansion of a liquid or solid into a gas (creating force and pressure) is what we experience as combustion or fire.

(b) Fires, however, vary widely in vigor and in their proportions of energy outputs. For example -- maximum light with minimum force (photo flashbulb), maximum force in sudden release (high explosive), or maximum force in sustained release (rocket propellant).

b. With the above basics of combustion in mind, we can consider more specifically how combustion is applied to rocket propulsion. The propellant chemicals must have certain properties, and when they do, their reaction in a rocket combustion chamber follows a certain basic pattern.

(1) A propellant combination should have these properties:

(a) A high-energy concentrated fuel.

(b) A concentrated oxidizer, so that the engine need not breathe air. Such a propellant can burn in a confining or semi-confining chamber. (For this reason, explosives and gun munitions also must have concentrated oxidizers). It can also burn in a space as well as an atmospheric environment.

(c) A reliable means of ignition. Varied means are possible, such as heat, spark, shock, or hypergolic mixture (substances that ignite on contact with each other) -- as long as the reaction is sure and can be subject to feasible safety precautions.

(J-9132)pp 438-439

(d) An energy output that is strong in mechanical force (in molecular terms, high velocity of movement regardless of vibration effects). Lightweight molecules move faster than heavier molecules and thus tend to increase specific impulse. A fuel-rich hydrogen-oxygen propellant, for instance, may have higher specific impulse because of very light unburned hydrogen molecules in the exhaust.

(e) A force output, however, that is controllable, providing steady rather than sudden impulse, not a "high explosive" but rather a "low explosive."

(2) A hot exhaust-gas molecule in a rocket combustion chamber follows a very erratic course out of the chamber, zigzagging in all directions as it collides with other molecules and the chamber walls. Nevertheless, this course becomes increasingly direct and more rapid in the direction of exit. This accelerated flow of molecules is the essence of thrust.

c. The basic rocket motor is a chamber with a narrow opening to which is attached a flaring nozzle.

(1) The chamber must retain pressure and withstand heat of more than 5,000° F. The exit is a constricting bottleneck.

(J-9033)pp 100-106
(J-9083)pp 17-30

(2) After the hot gas passes the bottleneck, it flows out the flaring nozzle, which reduces its pressure as it increases its speed. The whole design follows the "convergent-divergent" principle of the motor with the de Lavale nozzle.

(a) The ratio of the difference in cross section between the throat and the nozzle exit plane is called the "expansion ratio." The same expansion ratio can exist with a long nozzle and narrow angle of flare or a short nozzle with wide angle of flare.

(b) Advantage of a high expansion ratio is that of maximum speed of gas flow. This is achieved in space, where there is no ambient pressure.

(c) Advantage of low expansion ratio is maximum resistance to ambient pressure, desirable at low altitude during lift-off. Therefore, a launch vehicle should have successively higher expansion ratios in nozzles of successively higher stages.

(d) These and other complications call for compromises in engine and nozzle design. Too wide a flare can mean inefficient aiming of thrust. Too long a nozzle (to achieve the same expansion ratio with a narrower angle) adds deadweight and takes up structural space. Some experimental designs try to achieve efficient thrust, high expansion ratio, and short length at the same time. Variable-expansion nozzles would compensate for constantly-changing ambient pressures within the range of operation of one stage.

d. The subject of basic motor and nozzle design leads to certain other basic considerations of thrust.

(1) Thrust is stated in pounds measuring the level of force maintained by a rocket motor, not a total output divided by a period of time. For example, the first stage of Scout achieves 88,000 pounds at sea level. That of Saturn V (the Apollo booster), 7,500,000 pounds at sea level. Thrust of upper stages is given as of vacuum conditions.

(2) Specific impulse (I_{sp}) is a measure of rocket propellant energy as affected by engine design and efficiency. It is the number of pounds of force one pound of propellant can deliver in one second, or the number of seconds during which one pound of propellant can continue to deliver a pound of thrust. It is thus a measure of either speed or economy.

(a) Current chemical rockets vary in specific impulse from about 200 to 400. Nuclear and electric rockets can achieve much higher specific impulse ratings, but this discussion is reserved for Phase IV.

(b) The formula $I_{sp} \propto \frac{T_c}{M}$ (specific impulse is proportional to the square root of the combustion temperature divided by the molecular weight of the exhaust gases) indicates the advantages (for high specific impulse) of high combustion temperatures and low molecular weight of exhaust products. These conditions, however, do not always go hand in hand. Propellant chemistry, therefore, like other aspects of propulsion, is a matter of compromises.

e. The heaviest propulsion problem is that of launching a vehicle off the face of the earth against full atmospheric pressure and full gravity and boosting it to orbital velocity.

(1) To get the vehicle off the ground, a thrust-to-weight ratio of better than 1 to 1 is required (thrust of first stage to total weight of the vehicle -- all stages). A thrust-to-weight ratio need not be greatly in excess of 1 to 1 to get it into orbit (Saturn V, for instance, has

(J-9033)pp 117-128
(J-9010)pp 52-57
(J-9064)pp 60-62, 67-95

1.17 to 1). Factors making this low ratio sufficient for orbital injection are:

(a) Sustained thrust, with velocity building on velocity for prolonged acceleration.

(b) Rapid loss of weight due to propellant consumption.

(c) Steady decrease of atmospheric pressure, both lowering air resistance to the vehicle and increasing efficiency of thrust. (See above key point c (2) (b).)

(d) Eventually, weakening of force of gravity with distance from the earth.

(2) Mass ratio is the ratio of (a) initial weight of a vehicle when a given rocket stage is ignited to (b) its weight when this stage burns out, but before it is jettisoned. The total mass ratio of a multistage rocket is calculated by multiplying the mass ratios for each stage. Thus, mass ratio differs from gross-weight-to-payload ratio. A high mass ratio may reflect such advantages as reduced dead weight in rocket design and increased weight loss due to propellant consumption. The profit, however, could be taken in increase of payload, which would lower mass ratio.

(3) Gross-weight-to-payload is an easy-to-understand measure of overall booster efficiency. Modern launch vehicles in general have lower gross-weight-to-payload ratios than early models. Increased overall massiveness also permits lower gross weight to payload ratios. In the case of Saturn V, 65 to 1 for moon trajectory, compared to over 1100 to 1 for early satellite boosters.

(4) The total velocity gain achieved by a stage is symbolized by "ΔV" — difference between initial and burnout velocity. Smooth cycles of jettisoning old stages and igniting new ones permit efficient buildup of velocities.

6. SUGGESTIONS FOR TEACHING:

a. Suggested time:

Number of Academic Periods per Week	Recommended Number of Periods for Each Phase					
	1	2	3	4	5	6
2			X			
3					X	
5						X

b. The approach in this chapter is fundamental and theoretical, but the temptation to digress too long into matters of basic science must be avoided. Restudy the objectives and note that understanding not oxidation <u>per se</u> but oxidation <u>as related to propulsion</u> is the goal. Similarly the character of molecules might lead to a discussion on the nature of atoms, but understanding the character of a hot gas under pressure and generating thrust is more pertinent. If a student's interest in chemistry and physics is stimulated by this unit, encourage him to change his academic curriculum to better pursue such interest. This indeed would be a desirable outcome, but the burden of a deeper penetration into basic science or mathematics cannot be assumed by the AFJROTC instructor, who may not be equipped for it.

c. The student whose scientific motivation may be weak must also be kept in mind. If he suffers dismay when confronted with formulas such as those for thrust and specific impulse, reassure him that all that is required is familiarization (Phase objective d, and key point d (2) (3).) with factors affecting thrust. Beyond that there is the enjoyment as well as the responsibility of being an informed citizen when space exploits occupy public attention.

d. Before turning to visual aids, make good use of the illustrations in the text. Spend some time in class discussing tracing the flow of molecules in Figure 6 and comparing nozzle expansion ratios in Figure 7. Figure 7 reveals that the lowest stage (Algol motor) has the most open throat and the lowest expansion ratio, and that the higher stages have more constricted throats and higher expansion ratios. A sense of the size of various launch vehicles is useful. The scale drawings in Figure 9 offer a better comparison than photos of actual missiles. Figure 12, which has a building in it, is also useful.

e. Chemical demonstrations to illustrate different kinds of oxidation may be of benefit to the class. However, do not set these up in a classroom not designed for the purpose. Secure the cooperation of a chemistry instructor and the use of his classroom-laboratory. Also, do not attempt to encourage rocketry experiments without thorough knowledge of safety requirements. One very simple and reasonably safe demonstration is to strike a series of matches (wooden kitchen matches are preferred) to observe how they burn. Explain that the matchhead, somewhat similar to a solid rocket propellant, contains a concentrated oxidizer, which intensifies the fire and causes its faint hissing sound. As long as the matchhead burns audibly, this indicates that <u>physical force</u> is being exerted--enough to disturb the atmosphere and set up sound waves. When the head is consumed and the fire is feeding only on the match stem, the flame dies down. The fire now has wood for fuel and ambient air for oxidizer, both in lower concentration.

f. Key points in this phase can be parcelled out to students as oral reports. Encourage students to draw on outside sources to amplify the text. Another pertinent subject, which also reviews past units, is a comparison of combustion in an air breathing engine with that in a rocket engine. (Be sure student emphasizes the need for <u>compression</u> in an air-breathing engine, to get an adequate concentration of fuel and oxidant, which a rocket provides with its liquid or solid propellants.)

7. INSTRUCTIONAL AIDS:

a. Air Force films.

TF 5618. Atmospheric Penetration. 18 min. Color. 1965.

TF 5621. Rocket Propulsion. 30 min. Color. 1964.

SFP 1560. Titan III, Common Carrier for Space. 10 min. Color. 1965.

8. PROJECTS:

a. Oral reports (see above, Suggestions for Teaching f.)

b. Outdoor rocketry demonstration under proper safety precautions. (See above, Suggestions for Teaching e.

9. FURTHER READING:

a. Space Handbook. Maxwell Air Force Base, Alabama: Air University Institute for Professional Development, Sixth Revision, 1970.

b. Meitner, John G., ed. Astronautics for Science Teachers. New York: John Wiley & Sons, 1965.

PHASE III - CHEMICAL PROPULSION SYSTEMS

This phase moves from the basic features of all rocket motors to the specific characteristics of solid and liquid propellant engines. Historical backgrounds of both types of propulsion are traced. Chemical and physical properties of solid and liquid propellants most frequently used in space programs are described, as well as the mechanical and physical characteristics of solid and liquid engines. A glimpse of future space possibilities of engines applying the ramjet principle is also provided.

1. PHASE III OBJECTIVES: Each student should --

   a. Be familiar with the historical background of solid rocket propulsion.

   b. Understand the relationship between solid propellant grain design and thrust control.

   c. Be familiar with the historical background of liquid rocket propulsion.

   d. Know the basic mechanism of a liquid propellant rocket engine.

   e. Understand the advantages and disadvantages of solid propellant, storable liquid propellant, cryogenic liquid propellant, and hybrid engines in space usage.

2. BEHAVIORAL OBJECTIVES: Each student should be able to --

   a. List the most common solid and liquid propellant combinations and compare their properties and capabilities.

   b. Draw a rough cross section of a typical solid propellant grain and describe its neutral, progressive, or regressive burning properties.

   c. Describe the basic mechanism of a liquid-propellant stage and engine.

   d. Define these terms: double-based solid propellant; composite solid propellant; Piobert's Law; progressive; regressive, and neutral burning; cryogenic; hypergolic; storable liquid propellant; hybrid engine; Scramjet; and Scramlace.

3. SUGGESTED OUTLINE:

   a. Solid-propellant systems.

      (1) Historical background.

(a) Medieval military uses, Chinese and European.

(b) Congreve's rockets (Napoleonic era).

(c) Double-based and other modern propellants.

(d) Beginnings of space applications.

(2) Solid propellants.

(a) Chemical properties (double based and composites).

(b) Physical properties (construction of grain and casing; consistency of propellant mass).

(3) Motor design -- grain shape and thrust control.

(a) Piobert's law and burning rate.

(b) How core design affects burning properties.

(c) Means of thrust vector control.

(4) Applications of solid propulsion.

(a) Military advantages (instant reaction).

(b) Space advantages (high thrust despite low specific impulse).

b. Liquid-propellant systems.

(1) Historical background.

(a) Tsiolkovski and liquid oxygen-kerosene.

(b) Goddard and experiments including liquid oxygen-liquid hydrogen.

(c) German developments to V-2 rocket.

(2) Liquid propellants.

(a) Cryogenics (RP-1/LOX cheapest for heavy boosters; LH_2/LOX highest specific impulse for upper stages).

(b) Storable (includes hypergolic types) -- best for restart capability.

(3) The liquid-propellant engine.

(a) Feed mechanisms.

(b) Thrust vector control by gimbaled engine.

c. Other chemical systems.

(1) Hybrid systems (solid fuel and liquid oxidizer).

(2) Ramjet principle.

(a) Scramjet as weight-saving booster within atmosphere.

(b) Scramlace to make own oxygen supply.

4. ORIENTATION:

a. This phase continues the topic of chemical propulsion, a subject worthy of two phases because it is virtually the whole of launch and in-space propulsion. With some knowledge of oxidation and the physical laws governing combustion chamber, nozzle design, and thrust, gained from the preceding phase, the student now can consider and compare the main designs of solid and liquid propellant engines. Historical background is reserved for this phase so that separate developments of solid and liquid propulsion can be traced.

5. SUGGESTED KEY POINTS:

a. Of the two basic forms of rocket propulsion, solid propellant rocketry has the longer history.

(J-9101)pp 9-19
(J-9111)pp 22-39
(J-9158)pp 18-21, 52-55

(1) Black powder, consisting of charcoal, sulphur and potassium nitrate (KNO_3) or "saltpeter" was the propellant used for medieval Chinese "fire arrows," and medieval European rockets. For several centuries, however, black powder as a military munition was used as a gun propellant and explosive, while weaker mixtures (smaller proportion of KNO_3) were used for fireworks rockets.

(J-9158)pp 57-59

(2) In the early nineteenth century, the British ordnance officer William Congreve, revived the use of rockets for military purposes. These again were eclipsed by later nineteenth century developments in gun technology.

(J-9100)pp 20-25

(3) The development of high explosives and more energetic gun propellants (double based or "smokeless powder" types) began in the late nineteenth century and led the way to a revival of rocketry in World War II.

(J-9111)pp 86-99
(J-9158)pp 60-92

(4) Out of the military solid-propellant rockets of World War II and modern times came the development of larger

solid-propellant rockets feasible for ICBM and space-launch purposes.

(J-9033)pp 110-116
(J-9010)pp 67-73
(J-9023F)pp 38-43

b. Modern solid propellants' performance is based not only on their chemical properties but also on this physical consistency and construction.

(J-9023K)pp 83-87

(1) Most modern solid rocket propellants are of two types: double-based or composite.

(J-9133)pp 473-474

(a) The doubled-based type consists mainly of nitroglycerine and nitrocellulose. Both are self-reacting compounds, containing both fuel and oxidizer in a single molecule. Their combination plus additives produces a high-energy but controllable propellant where either alone would be a high explosive.

(b) In a composite, fuel and oxidizer are different compounds but form a mixture, such as the one most commonly used for space propulsion: polyurethane fuel and ammonium perchlorate oxidizer ($NH_4 Cl O_4$). Higher energy composites are under development.

(c) Various additives control the burning properties of solid propellants. These include a plasticizer, a flash depressor, an opacifier, and a stabilizer.

(J-9132)pp 435-436

(2) In a solid rocket motor, the propellant substance is molded into its motor and casing as a single cylindrical mass or grain. In a large launch booster, several grains may be assembled end to end. Diameters range up to 260 inches. In the commonly used polyurethane-ammonium perchlorate composite, the polyurethane has the consistency of tire rubber and the mass maintains this consistency even though the ammonium perchlorate crystals imbedded in the fuel base outweigh it. An important feature of grain design is the hollow core, which is the combustion chamber and which controls burning characteristics by the cross-sectional design of the way it is bored.

(a) Piobert's Law states that a propellant mass burns only on its surface and the flame eats into it perpendicularly at a fixed rate of a fraction of an inch per second, depending on the type of propellant.

(b) A simple hollow core will immediately expose more surface to the flame than an end-burning grain, permitting immediate high thrust. Burning surface, and consequently thrust, will steadily increase as the hole enlarges. This is an example of a <u>progressive</u> burning grain.

(c) By cutting star or other cross-sectional designs in the core, the grain can be designed so that the burning surface will remain constant (neutral burning) or decrease (regressive burning). These designs, together with the burning rate and total size of a given grain, result in a time-thrust curve indicating the burning properties of a solid rocket stage. With no throttle control possible, burning of a solid rocket stage is in a sense "programmed" in advance by grain composition and structure.

(3) Solid-propellant rocket motors have both military and space uses.

(a) They are preferred in military uses from small rockets to Minuteman, Polaris and Poseidon because of propellant storability and capability of instant reaction without countdown.

(b) Although relatively low in specific impulse, solid-propellant launch vehicles and stages are useful in space programs too. They combine high thrust with high consumption (producing rapid weight loss -- an asset), and compact design. Although restartable solid motors are still largely experimental, all solid motors can be designed for precise thrust termination as well as ignition. The Scout scientific-satellite launcher is all solid. Thor, Delta, and the large Titan IIIC, IIID and IIIM series have solid auxiliary boosters.

c. Liquid-propellant systems are currently the prime means of propulsion into space and in space.

(J-9023A)pp 62-97
(J-9145)pp 40-53

(1) Historically, theories based on liquid propulsion as well as actual experiments with liquid propulsion lie behind man's development of a space capability.

(J-9028A)pp 90-110
(J-9158)pp 60-64

(a) The Russian, Konstantin Tsiolkovski, predicted in 1898 that liquid-propellant rocketry would provide the means for man to venture into space. More specifically, he mentioned liquid oxygen/kerosene -- today's liquid propellant staples.

(J-9028A)pp 23-46
(J-9038)pp 19-21
(J-9158)pp 65-69

(b) The American, Robert Goddard (1882-1945), from his student days through the rest of his life not only theorized about liquid propulsion but put together numerous experimental rockets built in stages and employing liquid propellants.

(J-9028A)pp 133-156

(c) In Germany, Hermann Oberth and his pupils (including Wernher von Braun) similarly experimented and dreamed

(J-9158) pp 70-76

of space travel. They turned their efforts to military programs in World War II, and developed the V-2 rocket (liquid oxygen and alcohol).

(J-9158) pp 77-81

(d) Captured V-2 rockets provided the basis of both the US and Soviet space programs of post World War II.

(2) There are various ways of classifying liquid propellants. The most convenient and practical is to class them as cryogenic and storable.

(J-9010) pp 73-76
(J-9033) pp 91-97
(J-9023F) pp 44-51
(J-9023K) pp 76-83

(a) A cryogenic substance is gaseous at normal temperatures and must be brought down to extremely cold temperatures to liquefy and become useful as a propellant. Oxygen liquefies at -297° F.; fluorine (oxidant) at -306° F.; hydrogen (fuel) at -423° F. They cannot remain in a propellant tank indefinitely at such temperatures but must be loaded into the missile or booster within a few hours of launch as part of an elaborate countdown procedure. RP-1 (kerosene) and LOX are low in cost and especially useful as a massive first-stage propellant. Liquid hydrogen and LOX provide a high-energy combination for upper-stage use. In general, all cryogenic combinations are higher in specific impulse.

(J-9132) p 436

(b) A storable propellant is liquid at normal temperatures and can be kept for long periods of time in missile tanks, thus making missiles capable of instant reaction for military use. Although somewhat lower in specific impulse than cryogenic propellants, storable liquid propellants have special advantages for space use, including ease of stopping and restarting the engine. Some are hypergolic.

(3) Liquid-propellant engines are more complex than solid-propellant motors. In a large stage of more than one engine, a pair of tanks provides fuel and oxidizer to all engines. It must have a pressurizing system to force the fluids through the feed lines. Each engine is equipped with fuel and oxidizer pumps, a turbine, and valves. Cryogenic-propellant engines circulate cold fluid through a cooling jacket around the nozzle.

(J-9008) pp 59-67

(4) In space programs, RP-1/LOX engines are favored as heavy first-stage boosters and Liquid H2/LOX engines for high-energy upper stages such as in Saturn V, the moon rocket. Storable-propellant engines, however, have also played an important part in space programs. The Titan II used in the Gemini program was an all-storable-liquid propellant vehicle. The Titan III series combines storable Liquid with solid propulsion.

d. Other chemical systems include the hybrid engine and possible future engines based on the ramjet principle.

(J-9033)pp 116-117

(1) The hybrid engine employs a solid fuel and a liquid oxidizer. So far it has not been adapted to space uses, but is considered to have possibilities.

(2) The ramjet engine in its present form is limited to aviation use because it depends on air for its oxidizer. Two possible future developments, however, have space applications.

(J-9002)pp 214-215

(a) The Scramjet (supersonic combustion ramjet), with a speed potential of mach 5 and upward, might develop enough velocity in the upper atmosphere to pitch up into orbit. It also might serve as an auxiliary booster for the atmospheric portion of launch. Its advantage is mainly that of saving weight, since it would carry no oxidizer, which normally outweighs fuel.

(b) The Scramlace (supersonic combustion ramjet liquid air cycle engine, is a Scramjet which would compress and liquefy air during transit through the atmosphere. It would then use this liquid air as oxidizer in conventional rocket engine fashion during the space portion of its flight.

6. SUGGESTIONS FOR TEACHING:

a. Suggested time

Number of Academic Periods per Week	Recommended Number of Periods for Each Phase					
	1	2	3	4	5	6
2		X				
3				X		
4					X	

b. This phase should present fewer technical difficulties than the preceding one, since it deals with actual propulsion systems and their history, construction, and performance, rather than the scientific basis. The opportunity for more direct study of space boosters in the NASA/Air Force family of Standard Launch Vehicles is present.

c. Since this phase makes use of some historical and biographical material, it provides an opportunity for student reports on famous pioneers of rocketry such as Congreve, Goddard, Tsiolkovski, Oberth, Von Braun, and others. The textbook itself is skimpy in this area, and students can bring quite a bit of new material. Keep the emphasis on solid vs. liquid propulsion in mind, and stress the contribution of these men to one or the other of these technologies.

d. Using kitchen matches again, make one simple demonstration to show the burning characteristics of solid propellants and the "time-thrust curve." A typical kitchen match might take about three seconds to flare up to its peak, and about seven seconds to die down as the head is consumed. (Again, kitchen matches are preferable to paper matches, because the "time to peak" is slower and more observable.) Strike several matches and have the class observe their peaking and dying-down properties, counting seconds audibly. Let a student plot the "curve" of the match's burning by a simple graph on the chalkboard. During the rising part of the curve, the flame is spreading over the surface of the matchhead. After all the surface is aflame, the fire eats its way inward, shrinking the burning surface, and the flame diminishes. This is analogous to the time thrust curve of a rocket propellant.

7. INSTRUCTIONAL AIDS:

a. Besides simple demonstration mentioned above, good films and visual aids are available for this phase. Some have been listed for the preceding phase but are equally good, if not better, for this one. Two cautions might be noted: (1) The one space launcher emphasized in Air Force films is Titan III, designed for the Air Force Manned Orbiting Laboratory program, which has been eliminated. If the listed films on Titan III are still available, be sure to emphasize their instructional value toward an understanding of propulsion principles, and not the prospects of a MOL in the near future. (2) Since ramjets are part of this phase, exhibits or films on ramjets are pertinent. Aviation uses are emphasized, but the films are still of value both for a consideration of space possibilities and for a review of air-breathing propulsion principles which is always desirable for a better understanding of rocket propulsion.

b. Air Force films.

TF 5621. <u>Rocket Propulsion</u>. 30 min. Color. 1964.

SFP1560. <u>Common Carrier for Space</u>. 10 min. Color. 1965.

AFMR 637. <u>Titan III Standard Space Launch System</u>. 11 min. Color. 1965.

FR 527. <u>Titan III Research and Development for Today and Tomorrow</u>.

SFP 686. <u>Power for Bomarc</u> (ramjet) 14 min. Color. 1959.

SFP 1146. <u>Out of This World</u>. (History of Liquid Propulsion). 14 1/2 min. Color. 1962.

c. Overhead Transparencies:

T 33, T 38, T 39, and 8013.

8. PROJECTS:

a. Biographical oral or written reports. (See above: Suggestions for Teachers, item d.) Another possibility for a report is to have a student describe one launch vehicle, citing propulsion data for each stage, as well as the purposes of the vehicle.

9. FURTHER READING:

Air Force Manual 52-31, <u>Guided Missile Fundamentals</u>. 15 Jan 1964.

Braun, Wernher von. <u>Space Frontier</u>. New York: Holt, Rinehart and Winston, 1967.

Meitner, John G., ed. <u>Astronautics for Science Teachers</u>. New York: John Wiley and Sons, 1965.

<u>Space Handbook</u>. Maxwell Air Force Base, Alabama: Air University Institute for Professional Development, 1970.

PHASE IV -- BEYOND CHEMICAL PROPULSION

This phase deals with two related subjects: generation of electric power in space vehicles and nonchemical propulsion. Topics in order of textbook presentation are space propulsion requirements (which are lower than those of launching from the earth and hence make electrical propulsion feasible); nonnuclear and nuclear systems for generating electric power in space; electric rocket propulsion; nuclear rocket propulsion; and finally, certain concepts of rocket propulsion, some of which may some day open the way to inter-stellar travel.

1. PHASE IV OBJECTIVES: Each student should --

   a. Be familiar with the differences between the problems of in-space propulsion and those of launching from the earth.

   b. Know the basic principles of the following means of supplying electric power to space vehicles: batteries, fuel cells, solar cells, radioisotopes, and nuclear reactors.

   c. Understand the potential usefulness of electric rocket propulsion.

   d. Be familiar with nuclear reactor, nuclear fusion, and photon propulsion concepts.

2. BEHAVIORAL OBJECTIVES: Each student should be able to --

   a. Compare the problems of in-space propulsion with those of launching from the earth.

   b. List and describe the principal methods under development for providing in-space electric power.

   c. Define and explain the following: resistojet, arc jet, ion engine, plasma engine.

   d. Describe the current status and future prospects of nuclear and other advanced propulsion concepts.

3. SUGGESTED OUTLINE:

   a. Propulsion in space.

      (1) Smaller requirements than launch because of acquired velocity.

      (2) Types of tasks.

(a) Changes in orbit or trajectory.

(b) Thrust vector control.

(c) Station keeping.

(d) Attitude control.

b. Electric power in space vehicles.

(1) Problems and requirements.

(a) Lack of constant and abundant source (such as aircraft engine).

(b) Requirements for communications and systems operation.

(c) Extremely limited space and weight allowances.

(2) Chemical and solar power sources.

(a) Batteries.

(b) Fuel cells.

(c) Solar cells.

(3) Systems for Nuclear Auxiliary Power (SNAP)

(a) Radioisotope for low-level power.

(b) Reactor for high power.

c. Electric rocket propulsion.

(1) General characteristics.

(a) High specific impulses.

(b) Low thrust.

(c) Long endurance.

(2) Types.

(a) Gaseous heating -- resistojet and arc jet.

(b) Ion (electrostatic) and plasma (electromagnetic).

d. Nuclear and other advanced propulsion systems.

   (1) Current NASA-AEC development project "Rover."

      (a) NERVA engine — nuclear heating of hydrogen.

      (b) Problems are weight and radioactivity hazards.

   (2) Gas core nuclear concept.

      (a) Coaxial flow nuclear rocket.

      (b) Nuclear light bulb.

   (3) Futuristic concepts.

      (a) Fusion (thermonuclear reactor).

      (b) Photon: solar sail and direct-conversion rockets.

4. ORIENTATION:

   a. This chapter offers varying degrees of challenge. The most important parts are built directly on preceding chapters. If the student understands the problems and characteristics of chemical propulsion and its massive thrust requirements, the brief introductory section on the lesser requirements of in-space propulsion should equip him to understand the rationale for low-thrust electric rocket motors. In terms of the objectives of this phase, the section on current means of providing electric power for space vehicles should not be too difficult. Advanced solar and nuclear power-source concepts are discussed mainly so that students can appreciated their potentialities and, at some future date, understand the significance of a news story announcing that one of these devices has become operational. The same principle holds true of advanced propulsion concepts themselves. A limited understanding is enough to keep the student abreast of the times as an informed layman.

   b. The more difficult parts of this phase, therefore, should not slow down the class. There is, for instance, a discussion of different approaches to the meaning of "specific impulse" other than as a measure of combustion energy. The better-equipped student can get something out of this, but if another student is thrown by this hurdle, let him pick himself up and move on. The instructor should not insist on mastery of this concept as a necessary prelude to following sections or phases.

c. Nuclear energy comes into discussion in this phase -- as source of auxiliary electric power, as source of electric propulsion, and as direct source of propulsion. A more basic discussion of nuclear energy itself is lacking. It is hoped that the student can understand these potential applications of nuclear energy without back-tracking into the basic subject of nuclear energy itself. Student interest and demand should determine whether or not such a digression is desirable.

5. SUGGESTED KEY POINTS:

a. As a preliminary to a discussion of nonchemical propulsion, a few facts about the nature of propulsion in space (as differentiated from launching) are worth reviewing.

(1) Thrust requirements are much lower than those for launching. The vehicle already has orbital speed and can be maneuvered by means of varying amounts of thrust for such purposes as --

(a) Changes of orbit.

(b) Steering by thrust vector control.

(c) Gradual acceleration.

(d) Station keeping, attitude control, and other minor thrust applications.

(J-9023F)pp 148-152

(2) Gradual acceleration is possible with a low-thrust nonchemical rocket capable of sustaining this low thrust for a long period of time. Such gradual acceleration can build up to a substantial velocity boost.

b. If electric rockets are possible, where does the electricity come from? Even in present-day operations, providing electric power for communications and systems operation of space vehicles is a vital part of space technology.

(J-9023E)pp 48-65
(J-9023B)pp 129-138
(J-9023K)pp117-135

(1) The electric-power requirements of both manned and unmanned space vehicles are heavy; yet the power sources are limited.

(a) Space vehicles do not have a constant source of abundant auxiliary power and heat such as it provided by aircraft engines. Space vehicle rockets operate in brief spurts and must devote all their energy to the task of thrusting; therefore, an independent electric power source is necessary.

(b) Requirements for electric power include communications over vast distances - both receiving and transmitting television, radar, voice, and other signals. High-powered ground installations can compensate for weak on-board equipment, but heavy ground installations have their drawbacks (especially in military usage). "Narrowcasting" rather than "broadcasting" can conserve power. (LASER is already effective and has even greater potentialities in this respect.). Noncommunications power requirements include operation of all systems aboard the vehicle, including life-support equipment in manned vehicles.

(c) Because of the limited space and weight allowances for power sources aboard a space vehicle, these power sources are limited in both wattage and duration of operation. When a satellite's power sources go dead, the satellite itself is useless, even though it may continue in orbit. A new satellite must be launched to take its place in a continuing operation such as weather surveillance. The search for in-space power sources of improved strength and duration is thus economically important.

(J-9033)pp 168-171
(J-9064)pp 125-126
(J-9008)pp 44-46

(2) Present methods of supplying power to space vehicles are mainly nonnuclear, classed as chemical (including batteries and fuel cells) and solar.

(a) Silver zinc batteries have the advantage of relatively high energy yield (70 to 100 watthours per pound) but are difficult to recharge. Hence they ordinarily are used as "once through" batteries of short life (up to two weeks). Nickel-cadmium batteries are solar rechargeable with a lifetime potential of more than two years, but yield only 2 to 20 watthours per pound, depending on required lifetime.

(b) Fuel cells are the main on-board power source of the Apollo moon vehicles. They use chemical fuels and oxidizers stored outside the cell and reacting within it to produce both electric power and potable water. They can operate from a few days to several months producing powers of 200 to 1000 watthours per pound.

(J-9100)pp 118-123

(c) Solar cells work on the principle of photovoltaic conversion of sunlight to electricity. For greatest efficiency, these flat cells are arrayed on paddles and oriented so that the sun's rays always fall on them perpendicularly. Orienting the array, however, requires some use of power. Body-mounted solar cells are simpler and are found on many satellities with small power requirements. Solar cells must be used in conjunction with storage batteries to permit operation on the dark side of the earth.

(3) Nuclear power sources, under development jointly by AEC, NASA, and DOD are of two basic types:

(J-9033)pp 158-168

(a) Radioisotope thermoelectric generators (RTG) produce low-level but long-lasting power through decay of radio active materials. These are designated as SNAP (systems for nuclear auxiliary power) odd numbers. (The Pioneer deep space probe uses RTG power.)

(b) Nuclear-reactor generators (SNAP even numbers) would provide both long-lasting and high-level power, and in turn a means of operating electric rocket engines. Much progress in the space field depends on their development. Present barriers to their development are radioactivity hazard and engine weight. Reactors employ the energy of fissioning atoms, like nuclear bombs, but at a controllable rate.

(J-9064)pp 163-216
(J-9010)pp 62-66

c. Electric rocket propulsion is mostly in the developmental state. It is of interest because of its potential for prolonged operation, although thrust levels for the most part would be low.

(1) In evaluating non-chemical rockets, specific impulse is still an important yardstick. In gaseous-heating rockets it is measured by molecular weight of the working fluid and temperature of heating (rather than combustion). Working fluid can be pure hydrogen, which has much lower molecular weight than any product of combustion. In ion and plasma engines, extreme particle velocity produces high specific impulse despite high molecular weight in some cases.

(2) Gaseous heating rockets include resistojet and arc jet.

(J-9033)pp 141-143

(a) Resistojet works like any common electric heating element, building heat by passing current through a resistor. Thrust is provided by passing a stream of hydrogen over the heating element.

(b) Arc jet employs same basic principle as resistojet but passes hydrogen through arc at much higher temperatures. Teamed with a reactor power source, the arc jet would have potential as a rocket of high thrust <u>and</u> long duration, with specific impulse of 2,000 or more.

(3) Ions (electrostatic) and plasma (electromagnetic) engines have extremely high specific impulse, producing low thrust of very long duration.

(J-9033) pp 143-149
(J-9008) pp 71-72

(a) The electrostatic engine vaporizes and ionizes a metal and propels ions and electrons through a nozzle at extremely high speed. Specific impulse is about 10,000 seconds.

(J-9023K) pp 95-115
(J-9023C) pp 28-29

(b) Plasma engine would break a gas down into a plasma and propel it by electromagnetic fields of force. Specific impulses might reach 20,000 seconds.

d. Beyond the aforementioned low-thrust electric rockets are projects and concepts for nuclear and other advanced propulsion systems for carrying heavier payloads into space or venturing beyond the solar system.

(J-9064) pp 238-264

(1) Rockets producing direct thrust by nuclear-reactor heating of hydrogen working fluid are in the developmental stage.

(J-9023F) pp 152-157
(J-9033) pp 149-158
(J-9008) pp 68-70

(a) The AEC-NASA project "Rover" has so far reached the static-testing stage of a nuclear rocket called NERVA (nuclear energy for rocket vehicle application). It would produce specific impulses of 800-1,000 seconds. As with SNAP reactors, radioactivity hazard and engine weight are problems. Two nuclear engines under development are the coaxial flow gas core reactor and the "nuclear light bulb" developers claim potential specific impulses beyond 2,000 seconds as well as adaptability to a recoverable aerospace vehicle.

(2) Other advanced concepts (and they are no more than concepts) include:

(a) Fusion propulsion, which would employ a reactor working on the nuclear fusion rather than fission principle. Problems would be creating enough heat to initiate fusion, taming the latter reaction so that it could be sustained and controlled -- possibly containing it within an electromagnetic field or electronic "bottle."

(J-9023J) pp 82-91

(b) Photon propulsion, either by solar pressure or "wind," using a solar sail; or by extremely advanced photon rockets that would effect the complete conversion of matter to energy and move at speeds approaching that of light.

6. SUGGESTIONS TO TEACHERS:

a. Suggested time

Number of Academic Periods per Week	Recommended Number of Periods for Each Phase					
	1	2	3	4	5	6
2			X			
3				X		
4					X	

b. Whatever the difficulties that may be encountered in this phase (discussed above in section 4, Orientation), the teacher should find that diversity of topics should provide interesting changes of pace. Propulsion in space, power generation in space by present chemical and solar means, by nuclear means, electric rockets, nuclear rockets, and other futuristic space propulsion concepts--all these are different subjects, even though thematically united. The teacher will have to budget classroom time carefully in order to get all these topics in. However, there is little harm in minor deviations from such a schedule to permit extended discussion on topics that prove to be interesting and shortening of time allotted to topics that arouse less interest.

c. Instructional aids listed below are helpful. Overhead transparency T-40 is especially recommended. The Teacher's Data Sheet with this transparency should be studied carefully, for here is a more thorough and explicit discussion of the ion rocket than the textbook provides.

7. INSTRUCTIONAL AIDS:

a. Air Force 35-mm slides.

SVA-60. Future Propulsion Systems. 6 slides.

b. Air Force films.

FR-882. Hot Line Through Space. (Defense Communications).

TF-5621 Rocket Propulsion. 30 min. Color. 1964.

SFP-1796 About Our Missiles. 15 min. Color. 1970.

c. NASA films.

HQ 155. Electric Power Generation in Space. 26 1/2 min. Color. 1967.

HQ 152. Nuclear Propulsion in Space. 24 min. Color. 1968.

d. Transparency

T-40. Ion Rocket.

8. PROJECTS:

Because of the diversity of topics in this phase, and the necessary brevity with which each is treated, any one topic could be amplified by a student or team of students in an oral or written report. The following topics could be so treated: space ship batteries, fuel cells, solar cells, resistojet, arc jet, plasma jet, ion rocket, nuclear reactors for power, nuclear reactors for gaseous-heating propulsion, nuclear impulse engine, propulsion for interstellar travel.

9. FURTHER READING:

Space Flight Beyond the Moon (nonchemical propulsion). Cleveland, Ohio: National Aeronautics and Space Administration, Lewis Research Center, 1965.

Braun, Wernher von. Space Frontier. New York: Holt, Rinehart and Winston, 1967.

Meitner, John G. (ed.). Astronautics for Science Teachers. New York: John Wiley and Sons, 1965.

Space Handbook. Institute for Professional Development, Air University, Maxwell Air Force Base, Alabama. 1970.

PHASE V - CONTROL AND GUIDANCE SYSTEMS

This phase describes in turn the physical means by which the flight of a space vehicle is controlled, the servomechanisms and computers that provide the links between these controls and human will to provide guidance, and the principal systems for guidance: command, inertial, and celestial.

1. PHASE V OBJECTIVES: Each student should --

   a. Understand the specific functions of "control," "guidance," and "navigation," and how they are interrelated.

   b. Know that a vehicle in space is controlled by deflecting and regulating thrust.

   c. Be familiar with the functions of servomechanisms and computers in everyday life and in space guidance.

   d. Understand the different problems involved in the launch, midcourse, and terminal phases of guidance.

   e. Understand the basic principles (but not necessarily the technical details) of command, inertial, and celestial guidance.

2. BEHAVIORAL OBJECTIVES: Each student should be able to --

   a. Define the following words or terms as applied to astronautics: control, guidance, navigation, thrust vector control, attitude control, vernier engine, servomechanism, analog computer, digital computer, command guidance, accelerometer, inertial platform, cone of position.

   b. Describe at least three means of thrust vector control.

   c. Compare the basic functions of servomechanisms in space vehicles with such everyday servomechanisms as are found in automobiles, washing machines, and heating systems.

   d. Describe the basic processes of command, inertial, and celestial guidance.

3. SUGGESTED OUTLINE:

   a. Introduction.

      (1) Automatic, programmed nature of control and guidance.

      (2) Definitions.

(a) Control — physical maneuvering of vehicle.

(b) Guidance — link between control and human will.

(c) Navigation — determining position.

b. Physical control of space vehicles.

(1) A matter of applying and vectoring thrust.

(2) Main engine thrust control.

(a) Liquid and hybrid controllable with valves.

(b) Solid — precise termination but no operational restart.

(3) Thrust vector and attitude control.

(a) Main engine: gimbals, vanes, flexible nozzle, jetavator, fluid injection.

(b) Use of small auxiliary or vernier engines.

(c) Smallest devices for attitude control.

c. Servomechanisms and computers.

(1) Servomechanisms similar to those found in commonplace machines.

(a) Automobile power steering and feedback principle.

(b) Washing machine and timed sequence.

(c) Heating thermostat and error signals.

(2) Computers.

(a) Analog and quantity measurement.

(b) Digital and binary-system counting.

(c) Functions with servomechanisms: mixing, integrating, comparing and differentiating.

d. Phases of guidance.

(1) Launch guidance — sometimes the only guidance.

(2) Midcourse — corrective maneuver if necessary.

(3) Terminal -- rendezvous or reentry.

e. Types of guidance systems.

(1) Command (transmitted signals from earth.)

(a) Demands elaborate ground tracking network.

(b) Can be compromised by enemy in wartime.

(2) Inertial.

(a) Measuring stresses on vehicle in motion.

(b) Use of accelerometers for stress measurement.

(c) Gyroscopes for attitude reference.

(d) Most useful in launch phase.

(3) Position fixing or celestial navigation.

(a) Cone of position -- earth and star

(b) Line of position -- earth and second star

(c) Point of position — second near body (moon).

(d) Shortcuts to above procedure.

4. ORIENTATION:

Although highly technical subjects are suggested by the title, there is nothing in this phase that should be difficult for the student of average background who has studied the preceding phases of this unit. He has already been introduced to the fact that control in space differs from aerodynamic flight control, and he knows the potentialities of rocket propulsion systems. He should even have a sense of how the forces of celestial mechanics affect space flight control, although this aspect is postponed until the next phase. Here the approach is nontechnical and functional. First we develop a general sense of what control systems can do through thrust modulation and vector control. Similarly, technical discussion of space vehicle servomechanisms, computers, and guidance components is avoided in favor of simple analogies to point out the most fundamental aspects of these devices -- for example, the on-off switching of a heating plant accomplished by a thermostat. The discussion of computers is elementary and limited; and the barest fundamentals of command, inertial, and celestial guidance are presented. It all adds up to an awareness of how a space vehicle can maneuver and find its way through space.

5. SUGGESTED KEY POINTS:

a. Guidance is the operation of human will on a vehicle. In the case of a space vehicle, man must plan every detail of the journey in advance and leave little choice to the astronaut in flight. Three terms describe the total process:

(J-9010)pp 86-89
(J-9023h) glossary pp 162-171

(1) Control is the physical steering of the vehicle and regulation of its thrust output.

(J-9132)pp 453-458

(2) Guidance is the link between control and human will to make the vehicle ~~follow a~~ prescribed path.

(3) Navigation is the determination of the vehicle's location in space at a given moment in time as a basis for guidance.

(NOTE: All sources do not agree on these definitions, especially "navigation," but they are useful for school purposes.)

b. All flight control in space is achieved through aiming of thrust (thrust vector control or TVC) or the regulation of its output.

(J-9010)pp 117-119
(J-9008)pp 46-48
(J-9021B)p R-274 left, p R-290, right, p R-298

(1) Thrust control is easier to achieve with a liquid or hybrid engine because flow of propellant can be controlled by valves, just as in an airplane or automobile. Stopping an engine before its propellant supply is consumed and later restarting it is possible. With a solid motor, precise thrust termination is possible, but not restarting.

(2) Steering - or thrust vector control - and attitude control are done by a variety of methods.

(J-9033)pp 202-205

(a) With main engines of the liquid-propellant type, the whole engine can be mounted on gimbals and swiveled in the desired direction. Solid motors cannot use this method because engine and propellant load are one unit. Other methods of thrust vector control are deflecting vanes within the nozzle, swiveling nozzle, "jetavator" rings at nozzle exit which encroach on one side of the exhaust stream, or injection of a pressurized stream of liquid or gas within the nozzle. (As illustrated in Figure 21 of the textbook.)

(J-9033)pp 210-211
(J-9021B)pp R280-281

(b) Velocity and thrust vector controls can also be achieved by means of auxiliary or vernier engines.

(c) Devices of very low thrust can be used for attitude control without affecting its line of flight.

c. Guidance, or the action of human will upon control devices, is achieved through use of servomechanisms and computers.

(J-9026)pp 123-144
(J-9033)p 206
(J-9008)pp 36-40
(J-9023B)pp 70-71
(J-9021B)p R 225 left, 243 left.

(1) Servomechanisms of space vehicles are very complex, but their principles can be understood by comparing them with the servomechanisms found in everyday machines such as automobiles, washing machines, and heating plants.

(a) Automobile power steering, for example, is a servomechanism that responds to a signal sent by a steering wheel. A mismatch between the steering mechanism and the car wheel generates an "error signal." Position of car wheels produces a "feedback" signal.

(b) A washing machine provides an example of a timed sequence of operations. Similarly a rocket can be programmed with a time schedule (usually combined with an inertial or other guidance system.)

(c) A thermostat, such as one controlling a domestic heating plant, illustrates a concept basic to digital computers. It generates only two error signals: "too hot" and "too cold," which produce respectively the responses "off" and "on" (vice versa with air conditioning). A digital computer operating on the binary number system is really a complex array of such "go" and "no go" circuits.

(J-9041)pp 86-92
(J-9010)pp 104-109
(J-9021B)p R-259, R-260 right.

(2) Development of computers was a breakthrough of importance equal to that of development of high thrust rockets in making the space age possible. Without computers it would be impossible to maneuver space vehicles to the necessary degree of precision. Computers are of two basic types: analog and digital.

(a) Analog computers, like slide rules, measure rather than count. Numerical values are represented by voltages on a continuous scale. A simple example would be a speedometer, which registers voltages <u>analogous</u> to the speed of revolution of the car wheels.

(b) Digital computers do not measure but count. They have numerous tiny positions through which current either flows or does not flow, and on which current strength has no effect. These can be programmed as "go" or "no go" circuits, or as yes or no answers to specific programmed questions or inputs, or as a calculating machine capable of working complex problems on the binary number system. The binary system uses only two digits, 1 and 0. Miniaturization of circuits permits use of many positions for complex mathematical operations.

(c) In combination, digital and analog computers aboard a spacecraft can perform such functions as mixing, integrating, comparing, and differentiating to provide links between sensors, servomechanisms, and controls.

d. Guidance systems function in three basic phases of space flight: launch, midcourse, and terminal.

(J-9023B)pp 66-69
(J-9033)pp 209-210
(J-9041)pp 79-85
(J-9132)pp 453-454

(1) The launch phase is that from liftoff to injection into a chosen orbit or space trajectory. Propulsion is going on, velocities keep changing; therefore, inertial guidance is possible. Vernier rockets can make precise adjustments for desired burnout velocity. In numerous instances, launch guidance is the only guidance received, just as gun-barrel guidance is the only guidance a bullet receives.

(2) Midcourse guidance consists of a correctional maneuver applied to a vehicle moving in space. It is best made during the early part of a trajectory, after enough movement to determine the need for correction, but before the vehicle strays so far off course that too much energy is required to correct it.

(3) Terminal guidance may mean guidance just before hitting a target, making a rendezvous with another vehicle in space, or reentering the earth's atmosphere through a precisely-defined corridor through the atmosphere.

SUPPLEMENTARY NOTE: In the Apollo 11 mission of July 1969, the last-minute decision of the astronauts to overshoot the planned landing spot on the moon and pick a better landing spot was an example of manned, unprogrammed terminal guidance. The return of the command module through its planned reentry corridor into the Pacific Ocean was an example of a long trajectory so precisely determined that not even a midcourse, let alone a terminal, correction was necessary.

e. Military rockets have many types of guidance systems, operating with aerodynamic controls. Launch and space vehicles have essentially only three: command, inertial, and celestial, used singly or in combination.

(J-9041)pp 101-124
(J-9033)pp 217-239

(1) Command guidance - that is, guidance accomplished from the ground by tracking the vehicle with sensors and transmitting correctional signals - can be employed in all three phases of space flight. An elaborate world-wide tracking network is often required for orbital, moon, or interplanetary flights. A disadvantage of the system occurs in wartime, for such a communications network would be vulnernable to detection, attack, jamming, or deception.

(2) Inertial guidance is completely self contained within the vehicle and emits no signals for an enemy to detect or jam.

(J-9033)pp 190-197
(J-9010)pp 96-104

(a) Through time lapses correlated with the tugs and pulls of inertial forces, and inertially-guided vehicle can "feel" its way through space.

(b) Devices for measuring inertial forces are called "accelerometers." A spring mass accelerometer can illustrate the principle, although more refined instruments are required. Accelerometers along three axes can measure inertial forces in any direction.

(J-9033)pp 183-190

(c) Gyroscopes, through their ability to maintain "rigidity in space" by spinning, can be mounted on a platform to provide signals to keep the platform rigid in space and thus provide a stable reference platform for accelerometers. They also can guide attitude control thrustors to stabilize the vehicle.

(J-9023B)pp 92-95
(J-9023)pp 198-199

(3) Celestial navigation provides a means of finding a vehicle's position in space through reference to stars and nearer bodies like the earth and moon. It cannot follow the principles of sea or air navigation on or near the surface of the earth since there is no time reference in space. Nor can it work purely with reference to fixed stars, since all fixed stars are located so far out in space that triangulation between them would only establish a position as "somewhere in the solar system." In cislunar space, celestial position-finding can be done as follows:

(a) Angle between center of earth and a fixed star can establish position as somewhere on the surface of a cone.

(b) Angle between center of earth and another star establishes position on another cone. Since this cone intersects the other cone along two lines, one of which can be assumed to be the correct one,

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location along a line is now established.

(c) A sighting to the moon provides another cone which intersects the line at one point, establishing position.

(d) The above method is complicated. However, when used as a means of checking position against a programmed course, or in conjunction with inertial or command guidance, it is practical.

6. SUGGESTIONS FOR TEACHING:

a. Suggested time

Number of Academic Periods per Week	Recommended Number of Periods for Each Phase					
	1	2	3	4	5	6
2		X				
3				X		
4					X	

b. Note the explanatory notes among the suggested key points listed above. These should be brought to the attention of students and might provide interesting discussion material.

c. The "blindfolded passenger in an automobile" analogy (textbook) can be amplified by playing a game with students. Map out an imaginary route following streets in the vicinity of the school, with which students are familiar. Begin by saying, "as you leave the front parking lot of A --- High School, your body sways to the left. Which way are you heading?" Obviously the car is turning right on B --- Street. Continue asking the students their location after various turns, stops, and time lapses. Thus guidance by inertial sensations is illustrated.

d. A simple spring-mass accelerometer can be constructed by placing a small box inside a larger box open at the top (a matchbox inside a stationary box or shoe box, for example). Put a small weight in the inner box and attach the inner box to the inside end panels of the larger box by means of rubber bands secured with staples. Shift the larger box around and observe how the inner box lags behind, pushes ahead, or recovers to neutral or mid position. A pointer on the inner box aimed at a "scale" on the side of the larger box would provide a "measure" of the G forces of motion.

7. INSTRUCTIONAL AIDS:

a. Air Force films.

TF 5619. <u>Space Rendezvous</u>. 25 min. 1964.

FR 882. <u>Hot Line Through Space</u> (Defense Communications Satellites). 12 min. Color. 1967.

TF 1-5294. <u>Space Guidance and Control</u>. 10 min. Color. 1959.

TF 1-5295. <u>Space Navigation</u>. 13 min. Color. 1959.

b. NASA films.

HQ 116. <u>Space Navigation</u>. 21 min. Color. 1967.

HQ 152. <u>Nuclear Propulsion in Space</u>. 24 min. 1968.

HQa 159. <u>Log of Mariner 4</u> (guidance). 27 min. Color. 1966.

HQ 200. Houston, We've Got a Problem. 28 min. 1970.

c. Commercial films.

McDonnell Douglas Corporation

<u>Planetary Missions</u>. 10 min. Color. 1968.

<u>Planetary Landings</u>. 10 min. Color. 1967.

<u>Planetary Entry</u>. 10 min. Color. 1966.

8. PROJECTS:

a. Certain "Suggestions to Teachers" noted above could be assigned as projects to a student or group of students. The blindfolded passenger experiment could be conducted in an actual automobile, with blindfolded student later reporting on whether he succeeded or failed in tracing his route through inertial sensations. Lest the experiment tempt the driver into an exhibition of "teenage driving," point out that abrupt turns, stops, and sudden accelerations are unnecessary, and that normal turns and velocity changes should produce inertial sensations. A student or team of students could also construct a spring-mass accelerometer. School scientific equipment can be borrowed for experiments or demonstrations involving a gyroscope.

9. FURTHER READING:

Corliss, William R. Scientific Satellites. Washington, D. C. National Aeronautics and Space Administration, 1967.

Meitner, John G., ed. Astronautics for Science Teachers. New York: John Wiley and Sons, 1965.

Space: The New Frontier. Washington, D. C. National Aeronautics and Space Administration, 1967.

Space Handbook. Maxwell Air Force Base, Alabama; Air University Institute for Professional Development, 1970.

PHASE VI - PATHWAYS THROUGH SPACE

The final phase of Unit II returns to the subject of celestial mechanics touched upon in Chapter 1 and now examined in greater detail to describe the interplay between natural and man-made forces that is space flight. The basic types of space flight are taken up in order of increasing magnitude: (1) suborbital trajectories of missiles and sounding rockets, (2) earth orbits, coplanar and noncoplanar, and their ground tracks, (3) lunar flights, and (4) interplanetary flights.

1. PHASE VI OBJECTIVES: Each student should --

   a. Know that any trajectory from a ballistic missile flight to an interplanetary voyage is basically the product of two forces: (1) man-made velocity, and (2) gravitation.

   b. Know the velocity requirements for reaching various space objectives.

   c. Understand the limitations on freedom of movement of a vehicle in space.

   d. Be familiar with the maneuvers of which Earth-orbiting vehicles are capable, such as circularizing an elliptical orbit, Hohmann transfer, fast transfer, noncoplanar transfer, determination of ground track, and achieving synchronous orbit.

   e. Be familiar with the basic steps of a Moon voyage: launch to parking orbit, lunar trajectory, transposition of modules, lunar orbit, separation of LM, lunar landing, lunar takeoff, rendezvous with command module, earth trajectory, and atmosphere reentry.

   f. Understand the principles of using the Earth's heliocentric velocity in both inward (to Venus) and outward (to Mars) interplanetary voyages.

   SPELLING NOTE: Sun, Moon, and Earth are capitalized in this phase because proper names of planets are also mentioned.

2. BEHAVIORAL OBJECTIVES: Each student should be able to --

   a. Explain what is meant by "burnout velocity requirement" and "total velocity requirement."

   b. Explain the reasons why all space vehicles from ICBMs to interplanetary vehicles must follow limited pathways and cannot navigate freely.

c. Trace on a world map typical satellite ground tracks and explain the reasons why they take the form they do.

d. Describe in sequence the basic maneuvers of an Apollo manned Moon probe.

e. Compare the heliocentric velocities required for a vehicle to reach Mars or Venus.

3. SUGGESTED OUTLINE:

a. Introduction -- harmonizing man-made power and control with celestial mechanics.

b. Velocity Requirements.

(1) Question of <u>where</u> as well as <u>how fast</u>.

(2) Burnout velocity requirements (Fig. 46).

(a) Suborbital.

(b) Orbital.

(c) Lunar and escape.

(d) Interplanetary.

(3) Total velocity requirements.

c. Suborbital trajectories.

(1) Ballistic missile.

(2) Sounding rocket.

d. Earth orbits, transfers, and ground tracks.

(1) Value of continuing earth satellite program.

(2) Elliptical orbits.

(a) Perigee corresponds to injection point.

(b) Apogee established by injection velocity.

(3) Circular orbits and coplanar transfers.

(a) "Kick in apogee" circularizes an orbit.

(b) Hohmann transfer uses "minimum energy."

(c) Fast transfer applies thrust below apogee.

(4) Noncoplanar transfers and ground tracks.

(a) Deflected thrust and noncoplanar transfers.

(b) Synchronous satellites.

(c) Different orbits make different ground tracks.

e. To the Moon and beyond.

(1) Velocity requirement very near escape.

(2) Lunar voyages.

(a) Unmanned.

(b) Apollo missions (See phase objective e).

(3) Interplanetary voyages.

(a) Characteristics of solar system.

(b) The head start -- 97,600 feet per second.

(c). Outward voyages -- plus velocity in direction of Earth orbit.

(d) Inward voyages -- minus velocity by rearward launch.

(e) Oddities and problems: variations from Hohmann transfer, absence or presence of atmosphere on another planet, free boost from a planet's gravitational field, spiral trajectory of electric rocket, assembling a booster in orbit.

4. ORIENTATION:

a. This is a "wrap up" phase for which the student should be well prepared by the preceding phases. It returns to concepts of celestial mechanics -- the laws of Kepler and Newton -- introduced in the first phase. In relating these laws to man-made vehicle propulsion and control, as discussed in phases II to V, it creates a concept of all space flight from that of a ballistic missile to an interplanetary voyage as being a series of ballistic trajectories of greater and greater magnitude as determined by two forces -- launch and gravitation. New concepts are indeed introduced in this chapter: ways of maneuvering in space, from tracing a desired ground track to exploiting a free boost from Jupiter to reach more remote planets. Nevertheless, they are the outgrowth of what is known.

5. SUGGESTED KEY POINTS:

a. Propulsion, control, and guidance of space vehicles is dependent on nature's propulsion, control and guidance -- the forces of celestial mechanics. Man-made forces must be harmonized with these natural forces.

b. The velocity of a vehicle in space determines not only how fast it travels but how far against the forces of gravitation, comparable to the muzzle velocity of a bullet rather than the velocity of an airplane.

(J-9033) pp 41-56
(J-9008) pp 23-29

(1) Trajectories in space are established by a burnout velocity requirement -- the velocity established by launch. The table in Figure 46 shows requirements for achieving given space objectives assuming burnout at an altitude of 100 nautical miles.

(a) Burnout velocity for suborbital flights determines range (for missiles) and altitude (for sounding rockets).

(b) Burnout velocity for Earth orbital flights determines altitude of apogee.

(c) A range of burnout velocities is available for Moon flights, the highest of which would result in escape from Earth's gravity if Moon is missed.

(d) Still higher burnout velocities would be required for reaching various interplanetary objectives. Note that inward or "falling" trajectories require as much energy as outward or "climbing" trajectories. Shooting a missile into the Sun would require a higher burnout velocity than escaping the solar system.

(2) Not all burnouts are timed for 100 nm altitude. The concept of "total velocity requirement" should be understood as an addition of all increments of velocity needed to complete a space mission, without subtracting for decreases of velocity between rocket burns. The total velocity requirement for a round trip to the Moon is about 53,400 fps. At no time does the vehicle travel that fast, although it does reach the equivalent of burnout velocity requirement just before reentry.

c. Suborbital trajectories (missiles and sounding rockets) illustrate basic principles of orbital and longer space flights.

(1) The trajectory of a ballistic missile is a part of an ellipse which, if completed, would describe an imaginary

(J-9023F)pp 52-53

orbit around the center of the earth. The orbital plane must pass through the center of the Earth as it must pass through the center of mass of any attracting body in any kind of space flight. The ground track of a ballistic missile is thus a great circle and its path is predictable.

(J-9033)pp 30-32

(2) Sounding rocket flights, assuming that they are not perfectly straight up and down, would also be described as portions of ellipses passing through the center of the Earth. The sounding rocket with a less than orbital velocity would provide the cheapest way of reaching a given altitude, up to more than 1,000 miles. Higher altitudes would be reached more economically by orbiting a satellite and transfering it upward as discussed below.

d. Earth-orbiting satellites are not a mere preliminary step toward lunar and interplanetary flight. They continue to serve useful purposes, and their guidance into precise paths and stations remains an important part of the space effort.

(J-9033)pp 56-82
(J-9023K)pp 53-77
(J-9023B)pp 70-81
(J-9023H)pp 53-75

(1) The simplest class of Earth orbits is that established by burnout at injection point. The minimum orbit is circular at about 100 nm altitude, established by balance between man-made velocity and gravity as the vehicle keeps falling around the Earth. Higher apogees are achieved by higher burnout velocities, but the vehicle continues to return to the same perigee, which is at the point of injection. At this point it has regained the original velocity of its injection and will, therefore, climb back to the same apogee in the same elliptical orbit.

(2) Other types of orbits are achieved in steps. Here are described several "coplanar" maneuvers -- that is, changes of orbit that do not involve moving out of the same orbital plane.

(a) To circularize an elliptical orbit, apply rocket thrust at apogee. In the correct amount, this thrust will circularize the orbit at the altitude of the apogee where applied.

(b) To move a vehicle from a lower circular to a higher circular orbit, with minimum use of rocket energy, apply rocket thrust in lower ("parking") orbit and again at apogee to circularize. This maneuver is known as the "Hohmann Transfer," after the man who conceived of it back in 1925.

(c) To achieve a high circular orbit in shorter time, the "fast transfer" method is used. Transfer velocity is higher than that which would take the vehicle to apogee at the desired altitude. When the desired altitude is reached, deflected thrust is applied (that is, "thrust vector control" as described in Phase V is employed) to aim the vehicle into the desired orbital path. This procedure involves use of more energy than in the Hohmann transfer.

(d) Use of continuous low thrust such as would be provided by an electric rocket would transfer a vehicle upward in a spiral path, requiring several orbits to reach the desired altitude.

(e) To move from a higher to a lower orbit, retrothrust is applied to reduce velocity. Paradoxically, this causes the vehicle to move faster as it is drawn into a lower orbit by gravity. The maneuver can be used to cause a vehicle to catch up with a vehicle ahead of it by drawing it into a downward transfer ellipse.

NOTE: Retrothrust applied in a circular orbit would do the opposite of circularizing an orbit. It would change a circular orbit to an elliptical one. The vehicle would again rise to apogee at its original altitude where, if timing is right, rendezvous could be made.

(3) Another class of Earth-orbital maneuvers is that involving moving out of the same plane or orbit (noncoplanar transfer). Numerous combinations of coplanar and noncoplanar maneuvers may be employed to achieve certain desired ground tracks and other purposes.

(a) A noncoplanar transfer is achieved by deflecting thrust in orbit sideways. The new orbit would also be on a plane passing through the center of the Earth, or have a "great circle" ground track. An orbit around the equator, unless the launch occurred on the equator, must be achieved by a noncoplanar transfer.

(J-9023E)pp 122-140
(J-9061)pp 119-136

(b) To put up a synchronous satellite designed to orbit the earth in a 24-hour period hovering over the same meridian all the time requires a combination of maneuvers. Reaching synchronous altitude is necessary The orbit must be circular. To make the satellite hover over one point instead of moving back and forth along the same meridian, that one point must be on the equator, and a noncoplanar transfer is required to put it there.

(c) A satellite's "ground track" is its path as projected downward onto the surface of the Earth. Various types of orbits produce various ground tracks, and many scientific, commercial, and military aims are achieved by causing a satellite to follow a preplanned ground track that will place it above certain objectives at certain times.

(J-9061)pp 59-68

e. Lunar and interplanetary flights are achieved by the same gravitational principles that govern the orbits of earth satellites. The problems are complicated by the effects of other gravitational fields than that of the Earth.

(J-9023F)pp 78-115

(1) Man's achievements so far include manned and unmanned missions to the Moon; fly-bys of Mars and Venus; and Soviet landings on Venus.

(J-9072)pp 21-31

(2) To reexamine velocity requirements (Fig. 46 in textbook), it is notable that the Moon orbits at a range such that very small velocity changes make a great difference in the trajectory to reach it, and velocity must be determined very precisely. Possible trajectories, used on unmanned missions in the past, include long elliptical Earth orbits swinging around the Moon with apogee beyond the Moon; direct ascent at escape velocity; and ascent at slower velocity to permit capture in Moon orbit.

(3) Apollo missions have followed this program:

(J-9023B)pp 81-85
(J-9023H)pp 107-131
(J-9033)pp 870-881
(J-9113) entire
(J-9026) entire
(J-9158)pp 163-179
(J-9145)pp 144-179

(a) Launch employs three stages of Saturn V to reach orbital velocity. Third stage injects vehicle into parking orbit but remains attached.

(b) Third stage (LOX/LH_2) restarts to launch vehicle to Moon and is jettisoned at 10,000 nm altitude.

(c) Transposition of modules occurs shortly after step (b). Vehicle is reassembled for Moon capture and landing.

(d) Retrothrust is used on approaching the Moon for capture in Moon orbit.

(e) Vehicle in lunar orbit is separated with two crewmen in lunar excursion module (LM) and one remaining in command and service modules, still attached to each other.

(f) LM makes Moon landing, and EVA (extravehicular activity) is performed.

(g) Part of LM takes off from Moon, using remaining part as launch pad and leaving it on Moon.

(h) LM makes rendezvous and docking with command-service modules. All crewmen enter command module and LM is jettisoned, usually to crash on the Moon's surface.

(i) The service module and its rocket engine are retained for providing escape from lunar orbit and injection into Earth trajectory, and later for making a mid-course correction if necessary. Then the service module is jettisoned, leaving only command module to make an unbraked reentry, depending entirely on attitude-control jets and parachutes for splash-down at sea.

(4) Interplanetary voyages are subject to these conditions:

(J-9008) pp 83-84
(J-9023H) pp 123-125
(J-9072) pp 40-47
(J-9061) pp 29-38
(J-9023F) pp 63-68
(J-9100) pp 112-146
(J-9145) pp 180-195
(J-9150) pp 189-208

(a) The Sun serves as a powerful gravitational engine, with 300,000 times the mass of the Earth. Outer planets move very slowly in large orbits, with periods ranging into centuries. All planets orbit in the same direction and on planes varying only a few degrees from that of the Earth (plane of the ecliptic). The solar system is a flat, dish-shaped world. This is an advantage for space travel, since it minimizes noncoplanar transfers.

(b) The heliocentric velocity of the Earth, 97,600 fps, provides all interplanetary vehicles with this substantial head start.

(c) To move on an outward trajectory, to Mars or planets beyond it, a vehicle must be given an excess velocity over that of escape from the Earth's gravitational field. A range of velocities around 2,000 fps in excess of Earth-escape velocities will put a vehicle in the orbital path of Mars and, with precise timing, will intercept Mars.

(d) To move on an inward trajectory - for example, to Venus - the velocity requirement is equally as high as that to reach Mars. The vehicle is launched at such a time that, taking advantage of the Earth's rotation, it is launched in a direction opposite that of the Earth's travel around the sun. This amounts to a braking velocity, which is subtracted from the Earth's velocity to draw the vehicle inward.

(e) Other oddities and problems of interplanetary travel include:

- The possibility of boosting to a higher orbit to take advantage of a smaller velocity change to move lower.
- Use of a planet's gravitational force to gain velocity away from the planet and shorten a voyage to the outer limits of the solar system.
- The variations in the number of rocket burns necessary to program a space journey.
- The nature of continuous low-thrust propulsion such as that of an electric rocket. Velocity gain on a spiral trajectory would be very gradual, but on a very long journey an eventual crossover point would be reached where the vehicle would begin traveling faster than that of a chemically-propelled vehicle, thus shortening a journey to the outer planets.
- The advantages <u>and</u> disadvantages of atmosphere on another planet. The atmosphere would provide free-braking velocity for a landing, but impede launch from the planet.
- The advantages of building a space vehicle in orbit so that it could be launched out of orbit without the massive boost required to launch it from the earth.

6. SUGGESTIONS TO TEACHERS:

a. Suggested time

Number of Academic Periods per Week	Recommended Number of Periods for Each Phase					
	1	2	3	4	5	6
2		X				
3			X			
4				X		

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b. Because of the broadening of discussion to include Moon missions and solar-system astronomy, temptations to digress will be plentiful. Stick to the subject, which is the effect of celestial mechanics on space travel. Moon geology, possibility of life on other planets, conditions of human life support on other planets have varying degrees of relevance and should not dominate class discussion.

c. Keep abreast of the news. Since the textbook was written, several lunar and non-lunar missions have occurred, and other missions may have taken place by the time these words are read. There has been a change in emphasis away from manned planetary exploration. Current periodicals may provide ideas and details not present in book references. In class discussions and student projects, try to construct a practical view of what a Mars or other interplanetary manned or unmanned mission might entail in regard to payload and velocity requirements.

7. INSTRUCTIONAL AIDS:

a. NASA films.

HQ 217. Apollo 15: In the Mountains of the Moon - 1971. 28 min. Color. 1971.

HQ 208. Mariner Mans '69. 21 min. 1971.

HQ 206. Space in the 70s - Man in Space - The Second Decade. 28 min. 1971.

b. Air Force films.

SFP 1016. Celestial Mechanics and the Lunar Probe. 10 min. Color. 1959.

FR 882. Hot Line Through Space (Defense Communications Satellites). 12 min. Color. 1967.

TF 5733. Satellite Ground Tracks. 10 min. Color. 1965.

TF 1-5293. Space Orbits. 18 min. Color. 1960.

TF 5619. Space Rendezvous (coplanar and non-coplanar orbits), 25 min. Color. 1964.

c. Overhead transparencies.

T 26. Air Slows Satellites.

T-27. Satellite heights.

T-32. Kinds of orbis.

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8. PROJECTS:

a. Depending on availability of a planetarium and suitability of program, a visit to a planetarium could be worth while. Program should relate to celestial mechanics and its effects on space travel.

b. Student oral or written reports could include: satellite ground tracks (oral report making use of flat world map and chalkboard); a mission to Mars; unmanned exploration of outer solar system, making use of gravitational force of Jupiter and other planets.

9. FURTHER READING:

Corliss, William R. Scientific Satellites. Washington, D. C. NASA, 1967.