AF MANUAL 51-9

# Aircraft Performance

## RECIPROCATING AND TURBINE ENGINE AIRCRAFT

DEPARTMENT OF THE AIR FORCE

1Lt Tony Borda

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## Flying Training

# AIRCRAFT PERFORMANCE—RECIPROCATING AND TURBINE ENGINE AIRCRAFT

*This manual is a reference for flight engineers and for use in the continuous upgrade training of those performing duties of flight engineer. It provides instruction in the techniques of cruise control involving preflight planning, weight distribution, takeoff, climb, cruise, inflight weight control and replanning, and in descent, landing and taxiing. Additional subjects covered are maintenance records, flight evaluation, and flight crew coordination. Since completion of an apprentice level school in aircraft or helicopter maintenance is a prerequisite for flight engineer training, the reader is presumed to know the fundamentals of maintenance as applied to aircraft, their engines and related systems.*

[See summary of revised, deleted, or added material on last text page below signature element.]

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CHAPTER 1

# The Job of The Flight Engineer

The increase in the size and complexity of certain aircraft through the years first brought about the need for a copilot and finally the need for a flight engineer. In this manual, we are concerned primarily with aircraft performance and with the duties of the flight engineer as they relate to *flight*. However, we shall first discuss briefly the nonflying duties of the flight engineer specialist and of the flight engineer technician as reflected by AFM 39-1 and the Specialty Training Standard (STS).

## GROUND DUTIES OF THE FLIGHT ENGINEER

The logistical uses of large aircraft requires that they be able to operate out of many kinds of fields around the world. Since these remote fields or bases may not be equipped to perform maintenance on the aircraft, the crew must be prepared to perform many of these duties. The flight engineer is technically the most highly qualified man aboard the aircraft and, as such, he must assume responsibility for the necessary maintenance en route. He must perform, or be responsible for the performance of visual inspections, nonscheduled aircraft maintenance, and preflight, thru-flight, and postflight inspections. The flight engineer *technician* troubleshoots, removes, replaces, and adjusts components. Both the *specialist* and the *technician* maintain aircraft forms and records when the aircraft is away from the home station.

Certain ground operations relating to inspections and operational checks tend to parallel the duties during flight. The flight engineer specialists and technicians start engines and operate engine controls to provide the necessary balance of engine power, reliability, efficiency, and rate of fuel consumption. They monitor engine instruments throughout the period of engine operation.

The flight engineer specialist and technician compute weight, balance, and performance data and apply the information as required to insure mission accomplishment. This task involves the verification of the weights and the distribution of fuel, of personnel, of cargo, and of emergency and special equipment. The engineer must then determine whether weight and balance specification limits are being maintained.

The flight engineer specialist observes the performance of subordinates to insure compliance with prescribed procedures and technical publications. He instructs subordinates in the specialized techniques used by the flight engineer. In addition, the flight engineer specialist conducts on-the-job training for newly assigned personnel.

The flight engineer technician plans and schedules work assignments. In addition, he develops flight engineer proficiency standards for those duties which relate to aircrew requirements. He studies directives, technical orders, operational policies and procedures, and work standards, then he applies the related information in his evaluation of the performance of flight engineers. He, like the flight engineer specialist, conducts on-the-job training programs in flight engineer ground and flight procedures.

## FLIGHT RESPONSIBILITIES OF THE ENGINEER

The usefulness of the flight engineer was proven during World War II. This specially trained technician demonstrated that, by careful and precise engine management, the range and load-carrying ability of the aircraft and the life of the engines could all be increased. Today, at his station on the flight deck on our larger aircraft, the flight engineer is an important and respected member of the team that "gets 'em there and brings 'em back."

During takeoff, landing, and taxiing, the aircraft engines are controlled and monitored by the flight engineer. He observes all operating conditions and advises the pilots of any abnormalities or any tendency to exceed established limitations. He is responsible for proper operation, performance, and control of the engines and related accessories within design limitations.

It is vitally important, therefore, that he know the operating characteristics of the engines to perfection, and, insofar as possible, their mechanical histories.

The flight engineer must have a comprehensive working knowledge of the complete aircraft, for he is held responsible for the condition and mechanical operation of the entire aircraft. Before any flight is started, he must know what maintenance and repairs have been made to any part of the aircraft, and if any irregularities are present. It follows naturally that the final inspection of the aircraft before flight is also his responsibility.

Before the flight, the engineer is responsible for computing a predicted flight plan to determine:

- Total fuel required for mission.
- Required fuel reserve.
- Airspeeds to be flown.
- That all phases of the mission can be carried out within aircraft and engine operating limits.

During the preflight inspection, the engineer determines that the aircraft is properly loaded for weight and balance purposes by computing this information and recording it on a DD Form 365 (Weight and Balance Form F). This form is filed with the proper authorities before takeoff. In the engineer's takeoff report to the aircraft commander, he is held accountable for all mechanical and operating conditions.

Following this same preflight plan at all times during the flight, he must keep the aircraft commander informed of how the *actual* fuel consumption compares with the *predicted* fuel consumption. He sees that the fuel in the tanks is used in the correct order as prescribed in technical orders (TOs) to maintain proper balance, and adjusts the engine power output periodically to maintain the most efficient airspeed as weight decreases.

The engineer is responsible for keeping a log during the entire time of the flight, from the initial start of the engines to the securing of the aircraft after flight. This log may vary in detail according to its purpose. If it is used during training flights where the crew's project is to be evaluated, it is very detailed. If it is a cross-country flight by a graduate crew, it is detailed just enough so the engineer and crew can sufficiently analyze the flight and see where they could have improved it. In either case, it is a detailed report.

To summarize the duties of the flight engineer, they are to:

- Operate aircraft powerplant and systems controls.
- Observe aircraft powerplant and systems indicators, and control devices.
- Maintain powerplant cruise control and data charts.
- Compute aircraft weight and balance and perform preflight checks.
- Engage in organizational maintenance, repair, replacement, and troubleshooting operations.
- Conduct OJT for airmen aircrew personnel.

The responsibilities of the flight engineer are many, and with the introduction of new types of aircraft and equipment, they become even more extensive.

## KNOWLEDGE OF REPAIRS

The flight engineer can save hours of a maintenance crew's time by diagnosing trouble as it occurs, and reporting it to the line crew chief on landing. Because the engineer has a technical background, he can figure out the probable cause of trouble much more readily than the pilot and can give a more competent report of symptoms. At times, this report may even be radioed ahead so that parts are ready and work can start as soon as the aircraft lands.

Occasionally an aircraft cannot wait until it reaches its destination to be repaired, and an emergency landing must be made. After the emergency landing, the engineer must often perform emergency repairs and obtain substitute spare parts. Some large aircraft contain catwalks inside the wings to the rear sections of the engines and nacelles; thus it is now possible for the engineer to make some repairs while in flight. Accessory breakdowns or faulty fuel and oil lines, which in early days would have meant forced landings, can now be repaired in flight, allowing the aircraft to continue on schedule under normal power.

The necessity for making emergency repairs is often averted by an alert flight engineer who, by cross-referencing his instruments, can see trouble brewing and take the proper steps to avoid it. The ability to anticipate possible trouble and to prolong the life of the engines, which is the natural result of proper handling, are two of the most valuable contributions of the flight engineer.

## TERMINOLOGY

Successful operation of the airplane depends in part upon the ability of the flight engineer to recognize the functional capabilities and limitations of the aircraft and to record data pertinent to aircraft performance. Much of the information pertaining to aircraft performance is presented in the form of symbols, abbreviations, formulas, and special terms. Such terminology must be mastered if the flight engineer is to thoroughly understand the publications and reports pertaining to aircraft operations and maintenance. The attachments to this manual contain terminology which is standard for most aircraft and which is used throughout the remainder of this manual.

CHAPTER 2

# Mathematics and The Slide Rule

Mathematics is a pure science. It is the only science which stands on its own without benefit of related subjects. It is the basis for sound reasoning and common sense application of the many and varied theories, formulas, and calculations required to understand many other scientific subjects.

The flight engineer must have a fundamental knowledge of mathematical principles, definitions, symbols, and formulas to accomplish necessary weight and balance and aircraft performance computations. In addition to mathematics, a thorough understanding of the use of the slide rule is a basic requisite of a successful flight engineer, since it is the tool most used in finding the solutions to the many and varied computations made both on the ground and in flight.

## ARITHMETIC

Arithmetic is the foundation upon which higher branches of mathematics are based. The flight engineer must be able to handle arithmetical problems with ease and assurance to become profieient in his job. The mathematics discussed in this chapter presupposes a fundamental knowledge of arithmetic and algebra, and presents only those advanced mathematical operations used by the flight engineer.

In any phase of mathematics, however simple or complex, there are four fundamental operations. They are *addition, subtraction, multiplication,* and *division.* Since a basic knowledge of these operations is assumed, the following information is concerned with some of the variations and their application.

### Decimals

THE DECIMAL POINT. Adapted for this use by Simon Stevin of Belgium in the 16th Century, the *decimal point* is considered one of the noteworthy devices for facilitating and shortening mathematical calculations. However, this little "character" should be treated with caution and respect. The decimal point is used to indicate fractions having 10, 100, 1000, 10,000, 100,000, and so on as denominators. For instance, the number 76 45/100 is normally written 76.45, 9 12/1000 would be 9.012, and 14 24/10,000 becomes 14.0024.

Observe the result of moving the decimal point one digit to the left, and then one digit to the right in the number 432.613. If the point is moved one place to the left (43.2613), the number in effect has been divided by 10. If moved one place to the right (4326.13) the result is the same as multiplying by 10. The following problems are included to illustrate the correct positioning of the decimal point in the four fundamental operations:

```
        26.203          6489.333
         4.781    (−)    287.9
(+)    476.000          --------
         2.22           6201.433
        21.021
       -------
       530.225

       432.616              .211
(×)      .0422        222 / 46.842
      --------              44 4
        865232              ----
       865232                2 44
      1730464     (÷)        2 22
    ----------               ----
    18.2563952                222
                              222
                              ---
                              000
```

DECIMAL FRACTIONS. A number or portion of a number consisting of a decimal point and succeeding digits is referred to as a *decimal fraction*. It is frequently desirable in mathematical calculations to convert common fractions. This is simply accomplished by placing a decimal point to the right of the numerator, and performing the indicated division:

$$\frac{13}{24} = 24\overline{)13.00}\quad(.54)$$

$$\begin{array}{r} 120 \\ \hline 100 \\ 96 \\ \hline 4 \end{array}$$

The decimal fraction normally is carried out to as many "significant" figures as appear in the smaller of the two numbers used in the operation. Significant figures are discussed later in this chapter. A further phase of this process is *digit count*, which is taken up fully in the slide rule section of this chapter.

### Percentage

You are undoubtedly familiar with the term *percent* or *percentage*, but are you familiar with its actual meaning? Percent means a fraction, either common or decimal, with an understood denominator of 100. For example, 50 percent (%) means 50/100 or .50.

To change from percent to a decimal, move the decimal point two places to the left; that is, divide the number by 100:

42% = .42
9% = .09
⅝% = .625% = .00625

To change a decimal fraction to percent, multiply the decimal fraction by 100 by merely moving the decimal point two places to the right, and add the % symbol. For example:

.45 = 45%
6.47 = 647%
.0048 = .48%

It is common to specify troop strength, population, horsepower, etc., in terms of percent:

If the population of a city was 120,000 in 1950 and increased 7% during the year, what was the population in 1951?

.07 × 120,000 = 8,400
120,000 + 8,400 = 128,400

At a certain altitude and temperature, the true airspeed (TASK) is 14% greater than the indicated airspeed (IASK). If the IASK is 172 knots, what is the TASK?

.14 × 172K = 24K
172K + 24K = 196K

or

114% = 1.14
1.14 × 172K = 196K

## ALGEBRA

### Positive and Negative Numbers

*Positive* and *negative* numbers are numbers that have directional value from a given starting point, or from zero. As shown in figure 2-1, numbers to the right of zero are designated positive (+) numbers. Numbers to the left of zero are designated negative (—) numbers. Movement can be positive or negative from any given position, depending upon the direction of movement.

A positive number, such as +5, is read "plus 5." A negative number, such as —5, is read "minus 5." Any number which is written without a sign is understood to be a positive number.

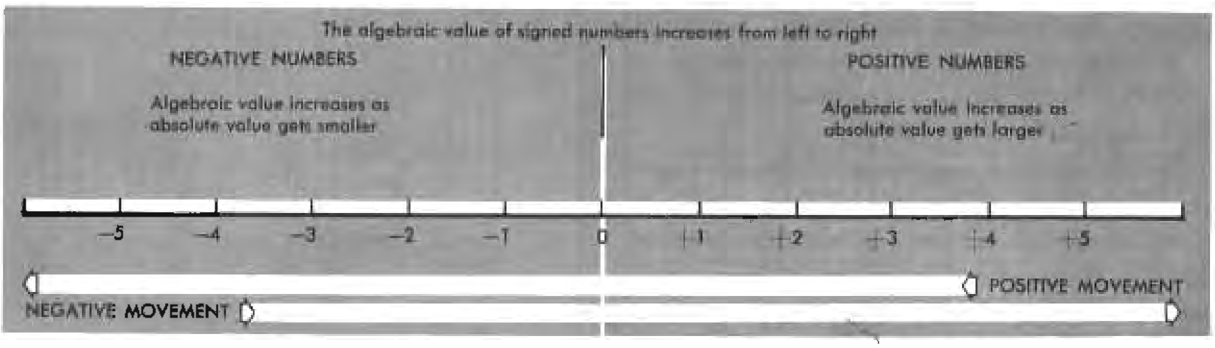



*Figure 2-1. Positive and Negative Numbers*

Rule: *The sum of positive numbers is positive. The sum of negative numbers is negative.*

ADDING AND SUBTRACTING POSITIVE NUMBERS. To add or subtract positive numbers algebraically, perform these functions the same as in arithmetic.

ADDING AND SUBTRACTING NEGATIVE NUMBERS. To add negative numbers algebraically, add as in arithmetic and use the negative sign.

*Examples:*

| | | |
|---|---|---|
| −2 | −6 | −3 |
| −4 | −8 | −6 |
| −6 | −14 | −9 |

To subtract negative numbers algebraically, change the sign of the subtrahend, subtract as in arithmetic, and use the sign of the larger number.

| *Examples:* | | | | |
|---|---|---|---|---|
| Minuend | −2 | −4 | −4 | −8 |
| Subtrahend | −4 | −2 | −8 | −4 |
| Difference | 2 | −2 | 4 | −4 |

ADDING POSITIVE AND NEGATIVE NUMBERS. To add positive and negative numbers algebraically, find the difference arithmetically and give this difference the sign (+ or −) of the larger.

*Examples:*

| | | | |
|---|---|---|---|
| 2 | −2 | −4 | −9 |
| −6 | 6 | 9 | 4 |
| −4 | 4 | 5 | −5 |

SUBTRACTING POSITIVE AND NEGATIVE NUMBERS. To subtract positive and negative numbers algebraically, change the sign of the subtrahend, and proceed as in algebraic addition.

| *Examples:* | | | | |
|---|---|---|---|---|
| Minuend | 2 | −2 | 2 | −2 |
| Subtrahend | 6 | −6 | −6 | 6 |
| Difference | −4 | 4 | 8 | −8 |

MULTIPLYING POSITIVE AND NEGATIVE NUMBERS. When two positive numbers are multiplied, the product is positive (+). The product of two negative numbers is positive (+). The product of a negative and a positive number is negative (−).

*Examples:*

$2 \times 4 = 8$ $\quad -2 \times 4 = -8$

$-2 \times -4 = 8$ $\quad 2 \times -4 = -8$

DIVIDING POSITIVE AND NEGATIVE NUMBERS. The quotient of two positive numbers is positive (+). The quotient of two negative numbers is positive (+). The quotient of a negative and a positive is negative (−).

*Examples:*

$\frac{8}{2} = 4 \quad \frac{-8}{-2} = 4 \quad \frac{-8}{2} = -4 \quad \frac{8}{-2} = -4$

ADDING A SERIES. When a series of positive and negative numbers is to be added, find the sum of all positive numbers and the sum of all negative numbers. Then arithmetically subtract the smaller from the larger and use the sign of the larger sum.

*Example:* Add +5 −3 +56 −36 −18

Step 1. Add all the positive numbers

| |
|---|
| + 5 |
| +56 |
| +61 |

Step 2. Add all the negative numbers

| |
|---|
| − 3 |
| −34 |
| −18 |
| −55 |

Step 3. Apply the sign of the larger to the difference of the two numbers

| |
|---|
| +61 |
| −55 |
| + 6 |

PARENTHESES SYMBOLS. The parentheses symbols, ( ), are used to show that the operation within them is to be performed before the rest of the problem is solved.

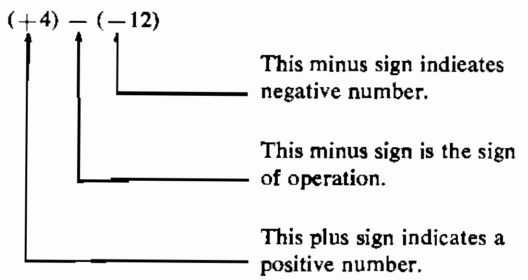
*Example:* $5 + (7 \times 4) = 5 + 28 = 33$

Two parenthetical expressions written together with no sign between them means they are to be multiplied.

*Example:* $(4 - 8)(2 + 3) = (-4)(+5) = -20$

Parentheses are used to separate the sign of operation from the sign of a number.

*Example:*




When there is a plus sign between two expressions, the parentheses and the sign of operation can be removed without any change of signs within the expressions.

*Example:*

$(+4) + (-7)$ Remove parentheses and omit the sign of operation.

$$+4 - 7 = -3$$

When there is a minus sign of operation, change the sign of every number in the parentheses following the operation sign and then drop the sign of operation.

*Example:*

$$(+4) - (-12) = +4 + 12 = +16$$

$$(+7 - 8) - (+9 - 12) = (-1) - (-3) = -1 + 3 = +2$$

Note in the last example that the operation within each set of parentheses is addition, which is always true unless otherwise specified.

## EQUATIONS AND FORMULAS

### Equation

An *equation* is an expression of equality or balance in which a combination of numbers or terms is equal to another combination of numbers or terms. An equation can be compared to a bar balanced across a fulcrum. If the downward forces on one side of the fulcrum are increased or decreased, the forces on the opposite side must be increased or decreased by a like amount to maintain balance. Likewise, an equation is balanced across the equality sign (=). If one side of the equation is increased or decreased, the opposite side must be increased or decreased by the same amount to maintain its equality.

Solving or clearing an equation involves eliminating all the terms from one side of the equation except the desired unknown. This elimination is done by addition, subtraction, multiplication, or division, whichever it takes to eliminate the excess terms from one side of the equation. The only requirement is that the *same operation* must be done to *both sides* of the equation.

The balance of an equation is not destroyed if—

*The same number is added to both sides of the equation.*

*The same number is subtracted from both sides of the equation.*

*Both sides of the equation are multiplied by the same number.*

*Both sides of the equation are divided by the same number other than zero.*

In solving, the equation should first be reduced to its simplest form by collecting like terms on their respective sides of the equation.

*Example:*

Equation:

$$2(3a + 6) - 4 = 50 - 18 - 2(a - 4)$$

Reduce to simplest form:

$$6a + 12 - 4 = 50 - 18 - 2a + 8$$

$$6a + 8 = 40 - 2a$$

Subtract 8:

$$6a = 32 - 2a$$

Add 2a:

$$8a = 32$$

Divide by 8:

$$a = 4$$

### Formula

A *formula* is a rule or law, generally pertaining to some scientific relationship, expressed as an equation by means of letters, symbols, and constant terms. These letters, symbols, and constant terms represent the various dimensions (or factors) which are to be inserted in the formula. To solve a formula, you merely substitute the proper numerical values for the appropriate letters. For example, the mathematical rule which states that *distance is equal to the rate of travel times time,* is stated in formula form as follows:

$$\text{Distance} = \text{rate of travel} \times \text{time} = rt \qquad (1)^*$$

Substituting values,

$$= (320 \text{ mph})(5 \text{ hrs}) = 1600 \text{ miles}$$

*If any two factors in a three-factor formula are known, the unknown factor can be found.*

*When a formula is rearranged, its subject is changed. When the subject is changed, the opposite mathematical operation is indicated by the formula.*

In the formula $d = rt$, the subject of the formula is $d$. If the formula is rearranged to solve for $r$, the subject is changed and the opposite operation is indicated. Since $r$ was multiplied by $t$, the basic formula must be divided by $t$.

$$d = rt, \frac{d}{t} = \frac{rt}{t}, \frac{d}{t} = r, \text{ or } r = \frac{d}{t} \qquad (2 \text{ and } 3)$$

By cancelling the $t$'s the new formula is established, and the subject is now $r$.

To illustrate how formulas are used, let us solve for the lift-drag ratio of an aircraft, using the formulas for lift and drag.

* Formulas are numbered throughout text and listed in attachments.

The formula for lift is in terms of nautical miles:

$$L = C_L S \frac{EASK^2}{295} \qquad (4)$$

Where

$L$ = Lift
$C_L$ = Coefficient of Lift
$S$ = Wing Area in Square Feet
EASK = Equivalent Airspeed in Knots
295 = Constant

The formula for drag is

$$D = C_D S \frac{EASK^2}{295}$$

The factors are the same as in the previous equation, except as follows:

$D$ = Drag
$C_D$ = Coefficient of Drag

An aircraft is flying at an EASK of 175 with an angle of attack of 5°. Find the lift and drag of a wing with an area of 1739 sq. ft.

$$C_L = .781$$

$$C_D = .0451$$

$$L = C_L S \frac{EASK^2}{295}$$

$$= .781 \times 1739 \times \frac{175 \times 175}{295}$$

$$= 148{,}200 \text{ lbs}$$

$$D = C_D S \frac{EASK^2}{295}$$

$$= .0451 \times 1739 \times \frac{175 \times 175}{295}$$

$$= 8{,}100 \text{ lbs.}$$

Thus far in this chapter we have presented some of the basic mathematics that are used by the flight engineer in his work-a-day world. However, if these mathematical computations had to be made without the use of the *slide rule*, the operations would be so lengthy that he would have little time for his many other duties. Therefore, a complete description of the function and use of the slide rule is included later.

## RATIO AND PROPORTION

The flight engineer uses *ratio* and *proportion* to reduce the number of mathematical operations when solving problems. Therefore, the importance of this procedure cannot be overemphasized.

### Ratio

A *ratio* expresses a comparison of one quantity to another in the same units. Two quantities measured in the *same units* can be compared and expressed mathematically by dividing the magnitude of one by the magnitude of the other. The quotient of the two magnitudes is called their ratio. This ratio may appear in *whole number, fraction, decimal,* or *percentage* form.

*Example:* What is the ratio between 5 inches and 10 inches?

$$\frac{5''}{10''} = \frac{1}{2} \text{ or } 1{:}2$$

All ratios may be expressed in several ways without altering the value relationships. For example, the ratio 5:10 may also be written $\frac{5}{10}$, which is the same ratio as $\frac{2}{4}$, $\frac{3}{6}$, $\frac{4}{8}$—each ratio being equal to $\frac{1}{2}$. That is, the numerator is to the denominator as one is to two.

In those instances where a ratio is to be expressed between two things of the same kind, but stated in different units, it is first necessary to state both things in the same units before they are placed in the fractional form.

*Example:* What is the ratio between 5 feet and 15 inches?

The first step is to convert feet to inches, which in this case is 60 inches. Now that both distances are in the same kind of units their ratio may be expressed as previously explained.

$$\frac{60}{15} = \frac{4}{1} \text{ or } 4{:}1.$$

### Proportion

A *proportion* is a statement of the relationship which exists between two or more ratios. The following is a simple proportion: $\frac{6}{8} = \frac{9}{12}$

The above expression means that 6 has the same relationship to 8 as 9 has to 12. Stated simply, "6 is to 8 as 9 is to 12." By inspecting the proportion, you can see that both fractions are equal to $\frac{3}{4}$.

Another way of writing the above proportion is 6:8 = 9:12. We find it convenient to write the proportion this way in order to bring out a few facts about proportions. The first term (6) and the last term (12) are called the *extremes* of the proportion. The two inside terms are called the *means* of the proportion.

means

6:8 = 9:12

extremes

In the above proportion, the product of the extremes, $6 \times 12$, is 72; the product of the means, $8 \times 9$, is also 72. An inspection of any proportion shows this to be true. This rule simplifies the solution of many practical problems as set up for flight engineering computations.

*Example 1:*

$$6:8 = 9:x$$
$$6x = 72$$
$$x = 12$$

Check:

$$6:8 = 9:12$$
$$6 \times 12 = 8 \times 9$$
$$72 = 72$$

*Example 2:* An aircraft flying 200 mph travels 116 miles in a given time. How far will another aircraft traveling 370 mph go in the same time?

$$200:370 = 116:x$$
$$(200)(x) = (370)(116)$$
$$200x = 42920$$
$$x = 214.6$$

The other aircraft will travel 214.6 miles in the same length of time.

## SIGNIFICANT FIGURES

To understand significant figures, consider the following example. A seven-thousand-dollar home is seldom priced at exactly $7,000.00. The only idea the "seven thousand" conveys is that the actual price (say, $7250.05) is closer to $7000 than it is to either $6000 or $8000. The only figure in the number 7000 that has any degree of accuracy is the 7; the zeros are used merely to indicate the decimal position of the 7. The digit 7 is said to be a *significant figure,* and the number 7000 is said to have *one* significant figure. Were the house described as a $7500 house, the number 7500 would have two significant figures (7 and 5) and have a higher degree of accuracy. The number with the most accuracy in the sample would have six significant figures, 7250.05. Note that zeros are insignicant when they appear at the extreme right of a number or to the left of the decimal point and have no other digit following or preceding. In numbers whose values are less than 1 (for example, .00405), zeros are insignificant if they appear between the decimal point and the first integer. The number .00405 has three significant figures.

In aircraft performance calculations, most values seldom have more than three or four significant figures because of the practical limits of accuracy. Although more figures may be obtained as a result of a mathematical process than are present in any of the original numbers, these additional figures do not increase the accuracy of the result. Therefore, it is common practice to round off the result of the number of significant figures in the original number having the least number of significant figures. Thus, $222 \times 110 \times 38 = 927{,}960$, but it should be rounded off to 930,000 because the numbers 38 and 110 each have only two significant figures. Numbers are rounded off as follows:

> If the figure following the last digit to be retained is greater than 5, increase that digit by 1 and substitute 0 for each figure that follows; for example, 47,685 rounded off to three significant figures is 47,700. If the figure following the last digit to be retained is less than 5, substitute 0 for each of the figures that follow. As an example, 97,649 to three significant figures is 97,600. If the figure following the last digit to be retained is exactly 5, increase the last digit by 1 if the last digit is odd, but substitute 0 for the 5 if the last digit is even (8745 to 8740, or 6775 to 6780).

## THE SLIDE RULE

The *slide rule* is a device used to multiply, divide, find proportions, extract square and cube roots, and square and cube numbers. The instrument is accurate within about one-half of one percent. The accuracy of the answer obtained is limited chiefly by the spacing of the lines on the scales and the ability of the user to estimate readings and settings that fall between the lines. This does not seriously limit the use of the slide rule, since its accuracy is sufficient for most practical problems.

### Components

As shown in figure 2-2, the slide rule is constructed in three parts, the *body or stock,* the *slide* which moves in grooves on the stock, and the *transparent index* or indicator which slides over the face of the rule. The line on the indicator is referred to as the *hairline.* Each scale is designated by a letter located on the left end of the rule. The A scale is located on the upper part

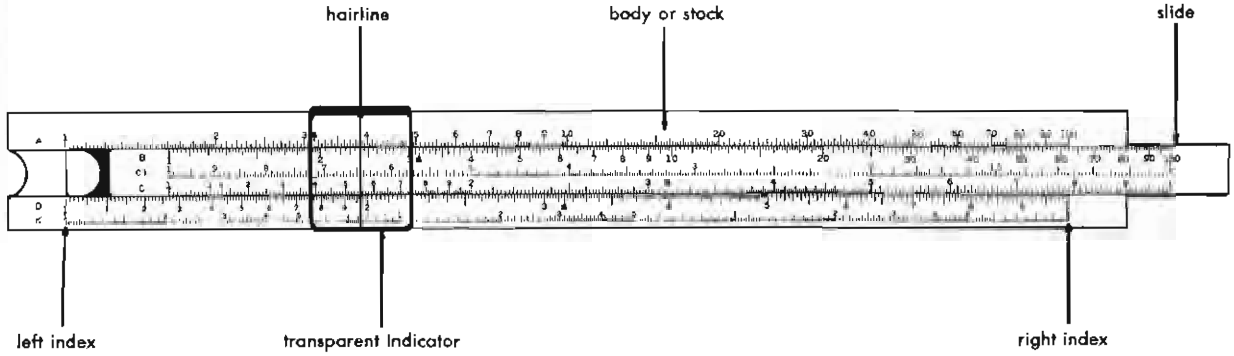



*Figure 2-2. Parts of Slide Rule*

of the stock, the B, CI, and C scales are on the slide, and the D and K scales are on the lower part of the stock. Scales C and D are identical in divisions and markings. These two scales should be studied thoroughly until confidence and accuracy are acquired in locating numbers on them.

**Scales**

In figure 2-3 showing the division breakdown of the C and D scales, note that the figures along the scale and the calibrations are not spaced equally. This is true of all the scales because the slide rule depends on logarithmic principles and the scales are constructed with logarithmic spacing. Although the scales are laid out on these principles, it is not necessary to know logarithms to use the rule.

The C and D scales are the fundamental scales of the slide rule, and may be used to solve problems in multiplication, division, percentage, and proportion. As illustrated, these scales have *main* and *secondary* divisions. The main divisions run from 1 to 10, and the right-hand 1 is called the *right index* of the scale and stands for 10, and the left-hand 1 is called the *left index* and represents 1. There are three groups of subdivisions—one group between the main figures 1 and 2, another between 2 and 4, and another between 4 and 10.

In the main division from 1 to 2 there are 10 subdivisions between each secondary division, thus each has a value of one in the third significant figure.

In the main divisions between 2 and 4 there are five spaces between secondary divisions, and each has a value of 2.

In the main divisions between 5 and 10, the secondary divisions are divided in half; and each subdivision has a value of 5.

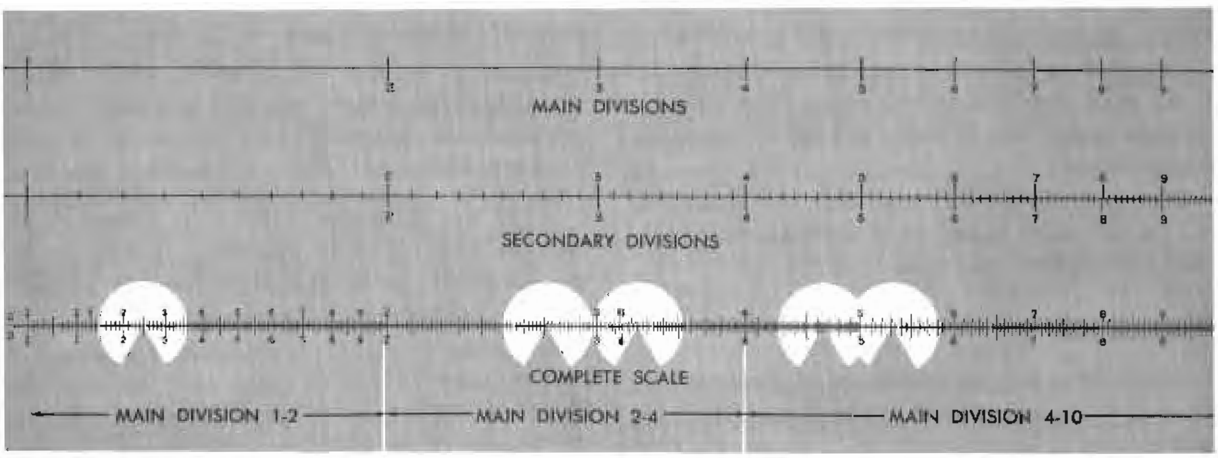



*Figure 2-3. Division Breakdown of C and D Scales*

The A and B scales are also identical. Each consists of two half-size C or D scales placed end to end. The A and B scales are used to represent numbers from 1 to 100: The left-hand 1 stands for 1, the middle 1 stands for 10, and the right-hand 1 for 100. These scales may be used instead of C and D for problems in proportion. Use of the A and B scales in this way will sometimes reduce the number of operations, but since the scales are shorter, they are less accurate. When used with the C or D scale, they enable one to read directly the squares and square roots of numbers.

The K scale is used to read directly the cubes and cube roots of numbers.

The CI scale is an inverse C scale. To distinguish this scale, the numbers, which read from right to left, are marked in red. The CI scale is useful in reading reciprocals directly.

### Locating Numbers

The location of a number on the slide rule depends only on the sequence of digits. The position of the decimal point has no relation to the location of the digits on the scale.

A sequence of three of four digits (significant figures) may be located, depending on which of the three secondary divisions groups is used. In the 1-2 group, four-digit numbers beginning with 1 can be located; for example, 1255, as shown in the illustration. In this group the first three digits are indicated by graduations; the fourth must be estimated.

In the 2-4 group, three digit numbers beginning with 2 and 3 can be located. If the third digit is *odd,* the first two digits are indicated by graduations on the scale, and the third is estimated. An example is 273, as shown in the illustration. If the third digit is even, the graduations indicate all three digits. An example is 326, as shown in the illustration.

Figures such as 465 and 533, for example, cannot be found using three graduations. Such numbers must be estimated.

### Multiplication

Multiplication of two numbers as illustrated in figure 2-4 is accomplished on the C and D scales as follows:

Set the index 1 (right or left, whichever is necessary to keep within scale of the slide rule) of the C scale on the number to be multiplied on the D scale.

Move the hair line of the indicator to the multiplier on the C scale.

Read the answer under the hairline on the D scale.

*Example 1:* Multiply 2 × 4

Set the left index on 1 on the C scale over 2 on the D scale, and move the indicator hairline to 4 on the C scale. Read the answer 8 on the D scale at the top of figure 2-4.

Either the index 1 on the left of the scale or the index 1 on the right may be used. To determine which to use, notice whether the product will fall on the D scale after the index has been set over the number being multiplied.

*Example 2:* Multiply 4 × 5

Set the right index of the C scale opposite 4 on the D scale. Move the hairline to 5 on the C scale. Read the answer 20 on the D scale. (See figure 2-4.)

*Example 3:* Multiply 1.24 × 2.16

Set up the numbers on the rule, disregarding the decimal point. The answer read on the D scale gives three significant figures: 268.

Round off the numbers to be multiplied to the nearest whole number and multiply these mentally: 1 × 2 = 2. This operation gives one digit, 2, which indicates that the answer is approximately 2. This information helps to locate the decimal point in the answer; in this case, 2.68. (See figure 2-4.)

*Example 4:* Multiply 12.4 × 21.6

Rounding off the number and multiplying: 10 × 20 = 200. This operation indicates that the answer is approximately 200.

The slide rule gives the same three significant figures, 268. as in example 3. However, in this case, the decimal should be placed to give 268.

*Example:* Multiply 675 × .0394

Approximating, 700 × .04 = 28
Slide rule reading: 265
Decimal placement: 26.5

There are occasions when it is necessary to multiply three or more numbers. In such cases, the operation can be carried all the way through without writing down intermediate results. The first number is set on the D scale by placing the proper index of the C scale over the number. This is multiplied by the second value by setting the hairline of the indicator to the second number on the C scale, thus locating the product of the first two numbers on the D scale under the in-

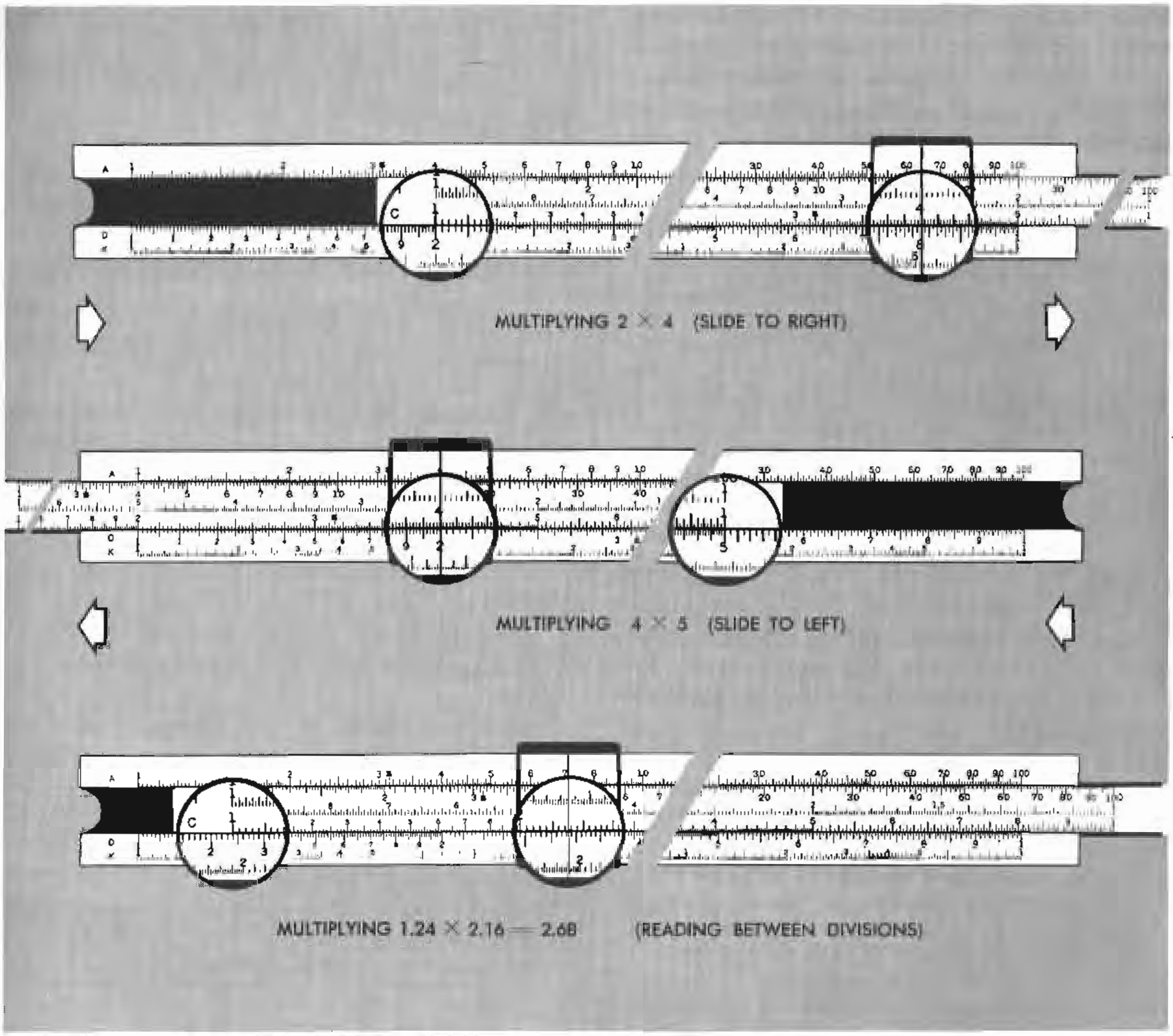



*Figure 2-4. Multiplying With Slide Rule*

dicator hairline. This product is then multiplied by the third number. In this process the indicator is left in position while the proper index of the C scale is moved in line with the indicator hairline. Then the indicator is placed so that the hairline coincides with the third number on the C scale. The final answer is read on the D scale under the indicator hairline.

*Example:* Multiply 157 × 32.3 × 0.636

Place the left index of the C scale over 157 on the D scale.

Set the hairline of the indicator over 32.3 on the C scale, which locates the product of the first two numbers on the scale under the hairline.

Leave the indicator in position and move the right index of the C scale until it is under the hairline.

Place the hairline of the indicator over 0.636 on the C scale.

Read the final answer as the sequence of numbers 323 on the D scale under the hairline.

#### Locating the Decimal Point

There are a number of systems commonly used with the slide rule in locating the decimal point. These vary from a strictly mechanical procedure to a combination of approximation and mental arithmetic. However, they are all based on principles of logarithms or powers of 10. The system described here is known as the *digit count method.*

If a number is equal to or greater than 1, the number of digits in the digit count is equal to the number of figures to the left of the decimal point. If a (positive) number is smaller than 1, the number of digits is indicated by a negative number numerically equal to the number of zeros between the decimal point and the first significant figure (the first figure other than zero).

*Examples:*

| *Number* | *Digit Count* |
|---|---|
| 42,500. | +5 |
| 4,250. | +4 |
| 425. | +3 |
| 42.5 | +2 |
| 4.25 | +1 |
| .425 | +0 |
| .0425 | −1 |
| .00425 | −2 |
| .000425 | −3 |
| .0000425 | −4 |
| .00000425 | −5 |

When two numbers are being multiplied using the C and D scales, the digit count of the product is equal to the algebraic sum of the digit counts of the two factors if the slide projects to the left. It is equal to this sum minus one if the slide projects to the right.

*Example 1:* Multiply 650 × 39.4

Set right index of C scale over 65 on D scale.

Under 394 on C, read the answer 256 on D scale.

The two factors have digit counts of +3 and +2 respectively. The sum of these is +5 and since the slide projects to the left, the product has a digit count of +5.

With a digit count of +5, the answer is 25,600.

*Example 2:* Multiply 22.4 × .00366

Read the answer 82 on the D scale.

The two factors have digit counts of +2 and −2 respectively. The sum of these is 0, but since the slide projects to the right, subtract 1 to obtain a −1 digit count for the answer.

The answer is .082.

If 3 or more factors occur in a problem, the digit count of the product equals the sum of the digit counts of the factors.

**Division**

Division is the reverse of multiplication. See figure 2-5. Only two numbers are involved in the ordinary process of division. The process may be indicated by a division sign or the numbers involved may be written as a fraction. Thus, four divided by two may be expressed as

$$4 \div 2, \text{ or } \frac{4}{2}$$

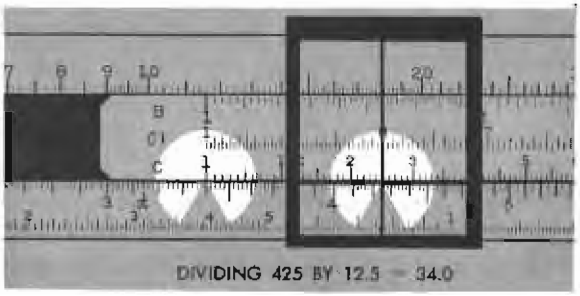



*Figure 2-5. Dividing with Slide Rule*

(In a fraction, the top number is referred to as the numerator, the lower one is the denominator, and the answer is called the quotient.)

Division is accomplished on the C and D scales as follows:

Locate the numerator on the D scale with the hairline.

Move the slide until the denominator on the C scale appears opposite the numerator under the hairline.

Read the answer on the D scale under the index (right or left) of the C scale.

*Example:* (See figure 2-5.) Divide 425 by 12.5, or $\frac{425}{12.5}$

Locate 425 on the D scale with the indicator.

Move slide until 12.5 is over 425.

Read the answer 340 on the D scale opposite the left index of the C scale.

Approximate the decimal location:

$$400 \div 10 = 40$$
$$425 \div 12.5 = 34.0$$

When locating the decimal in division by the digit count method, theoretically the digit count of the denominator is subtracted from the digit count of the numerator to obtain the quotient digit count. In practice, to avoid the confusion encountered in subtracting negative numbers, simply change the sign of the denominator digit count and add it algebraically to the numerator. If the slide projects to the right, add 1 to the quotient digit count.

*Example 1:* Divide 5680 by 365

The quotient 1555 is read on the rule

Numerator digit count: +4

Denominator digit count: +3

Change the sign of the denominator to −3 and add (algebraically) to +4; +4 − 3 = +1

Since the slide projects to the right, add 1 to obtain the quotient digit count: +1 + 1 = 2

The answer reads: 15.55

*Example 2:* Divide $\frac{.00424}{58.6}$

The quotient, 724, is found on the D scale.

Numerator digit count: $-2$

Denominator digit count: $+2$

Change the sign of the denominator digit count and add: $-2-2=-4$.

Since the slide projects to the left, the quotient digit count remains: $-4$.

The answer is: .0000724.

## Multiplication and Division Combined

When several numbers are to be multiplied or divided, it is possible with the slide rule to carry out the successive operations without writing down the intermediate results. This not only saves time, but eliminates some of the error in reading answers. Successive operations are performed by using the result of each operation for the next.

At this point, a few general rules and a simplified table of operations of multiplication and division are included to aid the beginner until he has mastered the procedures. (See figure 2-6)

| TABLE OF OPERATION | | | |
|---|---|---|---|
| **Multiplication and Division** | | **C and D Scales** | |
| | **Set Up** | **Move** | **Read Answer** |
| **Multiply** | Index | Hairline | Hairline |
| **Divide** | Hairline | Slide | Index |

*Figure 2-6. Table of Operation*

Rule 1. *Multiplication always involves moving the indicator.*

Rule 2. *Division always involves moving the slide.*

Rule 3. *The answer to any problem in multiplication, division, or combination of the two is always read on the D scale.*

There are three basic steps to any multiplication or division problem:

*In multiplication, locate the number to be multiplied on the D scale with the index of the C scale; in division, locate the numerator on the D scale with the hairline.*

*In multiplication, move the hairline to the multiplier on the C scale; in division, move the slide until the denominator on the C scale appears under the hairline.*

*In multiplication, read the answer on the D scale under the hairline; in division, read the answer under the C scale index.*

Problems involving multiplication and division can be worked out with great rapidity by starting from the left and dividing and multiplying alternately.

*Example 1:* $\frac{225 \times 52 \times 32}{27 \times 29}$

Set the hairline indicator on the first number in the numerator (225) on the D scale.

Divide by the first number in the denominator (27) by bringing 27 on the C scale under the hairline indicator.

Multiply by the second number in the numerator (52) by setting the hairline indicator to 52 on the C scale.

Divide by the second number of the denominator (29) by bringing 29 on the C scale under the hairline.

Multiply by the third number of the numerator (32) by setting the hairline indicator to 32 on the C scale.

Read the answer, 478, on the D scale under the hairline. The digit counts of numerator and denominator are calculated separately as products and then the digit count of the quotient is calculated as explained previously.

*Example 2:* $\frac{488}{6.27 \times 27.6}$

(Note in this example that 488 is to be divided by both 6.27 and 27.6)

Locate 488 on the D scale with the hairline.

Move the slide until 627 is opposite this setting.

Note, without writing down the answer, that 779 is under the index of the C scale.

Leaving the slide in position, move the hairline to the C scale index in order to divide by the next number.

Move the slide until 276 is under the hairline.

Read the final answer 282 on the D scale under the index of the C scale.

Approximate the decimal location.

$$\frac{500}{6 \times 30} = \frac{500}{180} = 3$$

$$\frac{488}{6.27 \times 27.6} = 2.82$$

*Example 3:* $\frac{32.4 \times 8.85 \times 19.4}{495 \times 6.12}$

Note in this example that the product of $32.4 \times 8.85 \times 19.4$ is to be divided by the product of $495 \times 6.12$. In computing this by the usual longhand means it would be easiest to first multiply the factors of the numerator together, the factors of the denominator together, and then divide the resulting products. However, in using a slide rule, division is no more difficult than multiplication and it is expedient to alternate multiplication and division whenever possible.

Divide 324 by 495, and observe that the quotient 655 is located opposite the index of the C scale. This is the proper setup to multiply this quotient by another number.

Multiply by moving the hairline to 885 on the C scale and observe that the product 579 is located under the hairline on the D scale.

Divide this by 612 by moving the slide until 612 on the C scale appears under the hairline. The answer, 946, is now under the C scale index.

Multiply 946 × 194 by moving the hairline to 194 on the C scale. Read the final result, 1835, on the D scale under the hairline. Now, let us see how we would approximate the decimal location.

Approximate the decimal location by rounding off the original numbers and using cancellation:

$$\frac{\overset{\overset{1}{\cancel{5}}}{\cancel{30}} \times 9 \times \cancel{20}}{\underset{\underset{5}{\cancel{100}}}{\cancel{500}} \times \underset{1}{\cancel{6}}} = \frac{1 \times 9}{5 \times 1} = \frac{9}{5} = 1.8$$

Thus,

$$\frac{32.4 \times 8.85 \times 19.4}{495 \times 6.12} = 1.835$$

The example makes clear the advantages of alternate multiplication and division. On a slide rule, the product of multiplication is properly located for division and the quotient in division is located for multiplication. There is one exception, however, when the number to be multiplied falls off the end of the scale. It is then necessary to exchange indices of the C scale as in the following example.

*Example 4:* $\frac{32.8 \times 2.3}{97.5 \times .707}$

Set the hairline indicator to the first number of the numerator (328) on the D scale.

Divide by bringing 975 on the C scale under the hairline.

You cannot multiply now by the second number of the numerator, 23, because 23 on the C scale is beyond the end of the D scale. Hence, you must exchange indices. Set the hairline on the right index of the C scale and move the slide until the left index of the C scale is under the hairline.

Now multiply by moving the hairline to 23 on the C scale.

Divide by bringing 707 on the C scale under the hairline.

Read the answer 1094 on the D scale under the left index of the C scale.

Approximate the decimal location using cancellation.

$$\frac{\overset{3}{\cancel{30}} \times 2}{\underset{10}{\cancel{100}} \times .7} = \frac{6}{7} = .9$$

Thus,

$$\frac{32.8 \times 2.3}{97.5 \times .707} = 1.094$$

Digit Rules. The digit count of a combination problem is equal to the sum of the digits in the factors of the numerator minus the sum of those in the denominator if the slide always projects to the left. For each time the slide projects to the right in multiplication add −1, and for each time it projects to the right in division add +1. In practice, the best procedure is to add the digits in the numerator and denominator separately, then change the sign of the denominator total and add it to the numerator total. Then proceed with the slide rule operations, marking down a +1 or a −1 each time the slide extends to the right. After the final answer is found on the rule, correct the digit count of the problem for the slide extensions and then place the decimal in the answer.

*Example:*

$$\frac{\overset{+2}{48.6} \times \overset{-1}{.0216} \times \overset{+2}{12}}{\underset{-2}{.00134} \times \underset{+3}{875}}$$

The numerator digit count is:

$+2 - 1 + 2 = +3$

The denominator digit count is:

$-2 + 3 = +1$

Change +1 to −1 and add:

$+3 - 1 = +2$

The slide extends to the right once in division, and once in multiplication.

The corrections (+1 and −1) leave an answer digit count of +2.

The final slide rule reading is 1074 and the decimal is placed to give 10.74 as the answer.

Special Rules. The digit count system will give the correct decimal placement for any problem in multiplication or division with one exception; that is when one of the factors of the problem or an answer falls on an index such as 1, .01, 1000, and so on. Four special rules will take care of this exception.

Rule 1. *When multiplying or dividing by an index, follow rules for a right slide extension.*

Rule 2. *If an answer to a multiplication problem falls on an index, consider it a left slide extension (except where rule No. 1 applies).*

Rule 3. *If an answer to a division problem falls on an index, consider the slide as extending to the right.*

Rule 4. *When dividing an index by another number, follow the rules for a left slide extension.*

## The Square and Square Root

The Square of a Number. The *square* of a number is defined as *the product of the number multiplied by itself.* The proper way to obtain it is to set the hairline indicator to the number on the D scale and read the square of the number on the A scale under the hairline. The A scale consists of two "half-size" C and D scales placed end to end.

THE SQUARE ROOT OF A NUMBER. To find the *square root* of a number, the reverse process is used. Set the hairline at the number on the A scale and read the square root on the D scale under the hairline.

Since the A scale is a double scale and a given number could be located in either half of it, the question arises as to which half to use in each particular problem. Thus, apply the rule that if the digit count is an odd number, locate the number in the left half of the A scale. If the digit count is an even number, locate the number in the right half of the A scale.

*Example 1:* Find the square root of 152.

The digit count for 152 is three. Since three is an odd number, set the hairline indicator to 152 in the left half of the A scale. Read the digits in the square root of 152 on the D scale under the hairline. The digits are 1234. Since the digit count for 152 is odd, add 1 to it and divide by 2. Thus, $3 + 1 = 4 \div 2 = 2$. Hence there are two digits to the left of the decimal point in the square root of 152; and the 12.34 is the square root of 152.

*Example 2:* Find the square root of 1,000.

The digit count is 4 and an even number, so set the hairline indicator to the center index of A scale. Read 316 under the hairline on the D scale. Since the digit count for 1,000 is even, divide it by two: $4 \div 2 = 2$. Hence there are two digits to the left of the decimal point in the square root of 1,000, and the answer is 31.6 as read on the D scale.

## Developing Speed With Accuracy

The initial development of speed and accuracy is most easily accomplished if, while learning, you will repeat each procedure several times, using a different set of values for each repetition. If you do this, you will find that each succeeding repetition becomes easier, quicker, and more accurate. We must remember, of course, that accuracy is more important than speed. The principal value of speed exercises is that speed, with accuracy, indicates that you are completely familiar with the procedure and that you remember the steps.

## Accuracy of Slide Rule Computations

It was stated previously that the slide rule may be read to three or four places (significant figures). The average accuracy of the slide rule is approximately one-tenth of one percent. To understand just what this means, let us see how these conclusions were reached. First, it has been shown that a number with more significant figures is more nearly accurate than one with less. However, if two numbers have the same number of significant figures, the one beginning with the larger digit is more accurate. For example, 999 is more accurate than 101; likewise .999 is more accurate than .101, since the decimal point does not affect accuracy. To show that 999 is more accurate than 101, the relative accuracy should be compared as explained in the following paragraph.

The best standard for accuracy is the relative error, or percentage of error. The relative error is the ratio of the possible error in a number to the number itself. The resulting fraction can be expressed as a percent, and is called the percent of error. For example, locate number 984 on the D scale of a slide rule. As close as you can estimate it, the hairline may not be exactly 984, but it will be between 983 and 985 if you take any care at all. This represents a possible error of 1 in 984 or a relative error of $\frac{1}{984}$; roughly $\frac{1}{1000}$ or 1%. Do the same with the number 1016. This can be estimated betwen 1015 and 1017 to obtain a relative error of $\frac{1}{1010}$; roughly $\frac{1}{1000}$ or 0.1% error, the same as in 984. The spacing of the slide rule markings is such as to give an error of 2 in 2000 and 5 in 5000 which reduce to

$$\frac{2}{2000} = 0.1\% \text{ and } \frac{5}{5000} = 0.1\%$$

From this it is shown that the relative error is approximately the same any place on the scale and amounts to 0.1%. However, this applies to only one setting or one reading on the rule, and multiplying two numbers on a slide rule involves two settings and one reading. If in each operation the maximum error of 0.1% were made, and each were in the same direction (the settings and readings were all 0.1% higher than the correct values), an error of 0.3% would be produced in the answer. Similarly, in multiplying three numbers, four settings and readings are involved, and for four numbers, five operations are necessary, giving a possible error of 0.4% and 0.5% respectively. However, it is unlikely that all of the settings would accidentally have the maximum error in the same direction. For this reason a 0.5% allowable error is liberal for the average problem involving four to six numbers to be multiplied or divided.

To find the final allowable error in any slide rule answer, multiply the answer by 0.5% or 0.005.

## SLIDE RULE PROBLEMS

Problems of time, speed, distance, and fuel are of extreme importance to the flight engineer. Although they are simple problems of arithmetic, the time required to solve them can be reduced to a minimum by the use of the slide rule.

### Time

An important factor to remember when using the slide rule to solve problems of time is that hours and minutes cannot be used together when multiplying by a rate of speed or quantity of fuel. Minutes must be converted to percent or tenths of one hour. Each six minutes is equivalent to 10% or .1 of one hour. The slide rule is a time saver for this conversion. The process is as follows:

Place 60 minutes on the C scale over the right-hand index on the D scale.

Slide the hairline to any given number of minutes on the C scale and read percent or tenths of one hour on the D scale.

When dividing a given number of minutes by 60 the end result is hours and tenths of one hour.

*Example:* 90 minutes divided by 60 equals 1.5 hours.

### Speed

*The speed of a body in motion is defined as the distance it travels per unit of time, which is normally expressed in miles per hour or feet per second.* In equation form this relationship may be indicated as one of the following:

$$\text{Speed} = \frac{\text{distance}}{\text{time}} \tag{5}$$

$$\text{Time} = \frac{\text{distance}}{\text{speed}} \tag{6}$$

$$\text{Distance} = \text{speed} \times \text{time}. \tag{7}$$

When computing aircraft performance, the rate may be expressed in knots, (k), calibrated airspeed (CAS), indicated airspeed (IAS), true airspeed (TAS), etc. These airspeeds with relationship to aircraft performance are discussed later in this manual.

### Distance

The flight engineer and navigator express distances in either *statute* or *nautical* miles and their rate in either *miles per hour* (mph) or *knots* (k) respectively. In certain European and South American countries, distance is expressed as *kilometers* and rate as *kilometers* per hour. The slide rule provides a means for converting distanee expressed in any of the three forms to the form desired. The arithmetical factor for converting nautical miles per hour or knots to miles per hour is 1.152, This value is derived by dividing the number of feet in a nautical mile (6080) by the number of feet in a statute mile (5280). Reversing the division, the factor is approximately .87. The relationship between nautical and statute miles may be expressed by the following equations:

$$\text{Nautical miles} = \text{statute miles} \times 1.152 \tag{8}$$

$$\text{Statute miles} = \frac{\text{nautical miles}}{1.152} \tag{9}$$

### Fuel

Correctly computing the total amount of fuel for a given time or distance is an important concern to the flight engineer. His computation of fuel may determinc whether or not the aircraft will reach its destination. The quantity of fuel and rate of fuel consumption is normally expressed in *pounds* and *pounds per hour*. With the use of the slide rule, the pounds of fuel per hour is multiplied by the hours and tenths of hours to give the total load in pounds for the given time. The relationship of fuel and time is expressed in the following equations.

$$\text{Total fuel pounds} = \text{time} \times \text{fuel lbs/hr}$$

$$\text{Fuel lbs/hr} = \frac{\text{total fuel pounds}}{\text{time}} \tag{10}$$

$$\text{Gallons/hour} = \frac{\text{total gallons}}{\text{time}} \tag{11}$$

$$\text{Total gallons} = \text{time} \times \text{gallons/hr} \tag{12}$$

### Ratio and Proportion

Ratio and proportion performed on the slide rule can shorten mathematical computations considerably. By using the A and B scales on the slide rule and with utmost care in the setup of the ratio and proportion, problems can be worked quickly. Going back to the definitions of ratio and proportion, remember that a ratio expresses a comparison of one quantity to another in the *same units.* A proportion indicates a relationship between *two or more ratios.*

When a ratio and proportion problem is worked on the slide rule, the ratio must be kept in its proper units. As the old saying goes, "you can't mix apples with oranges and get bananas." To explain, *when working a slide rule problem, you must remember to keep like subjects on one scale of the slide rule.* Also, you must determine the unit you will use. To illustrate, let us use a time and distance problem.

*Example:* An aircraft goes 3000 miles in 6½ hours. What is its average speed?

| | | |
|---|---|---|
| Scale A | 3000 | ?(460 mph) |
| Scale B | 6.5 | 1 |

Note that distance values are used on scale A and time values on scale B.

If 6.5 is used for the time, then the answer is read in hours and tenths of hours. If 390 minutes instead of 6.5 hours were used, then the answer would be read in minutes.

To work the problem, set the indicator hairline on 3000 on scale A, and move the slide until 65 is under the hairline. Then move the hairline over the index of the slide and read the answer, 460, on the A scale.

By way of review, let us see how this problem is worked with the longhand method.

6.5 hours is to 3000 miles as 1 hour is to x

$$6.5{:}3000 = 1{:}x$$
$$6.5x = 3000$$
$$x = 460 \text{ miles}$$

In the foregoing problem, two values were given and a constant was used as the third value. In other problems, three given values are commonly used.

*Example:* An aircraft flying at 225 TASK (true airspeed in knots) at a fuel flow of 1600 lbs per hour can go how far with 25,000 lbs of fuel remaining?

| | | |
|---|---|---|
| Scale A | TASK | (Distance) |
| Scale B | F/F | Fuel in lbs |

| | | |
|---|---|---|
| A | 225 | ?(3520 Miles) |
| B | 1600 | 25,000 |

To work this problem, set the hairline at 225 on scale A, and move the slide (scale B) until 1600 is under the hairline. Move the hairline to 25,000 on the slide and read the answer, 3520 on scale B. In this type of problem, the ratio between scale A and scale B is such that the hairline can be placed at any value to indicate either *distance that can be covered for a given fuel load,* or *fuel required to fly a certain distance.*

The importance of knowing how to work such problems on the slide rule cannot be overemphasized, because much of the flight engineer's work involves problems of this type.

## CONSTRUCTION AND USE OF GRAPHS

The graph is a convenient pictorial representation of the relationship between two or more variables and is best presented on regular graph paper. In constructing a graph, two mutually perpendicular axes are chosen, the horizontal X axis and the vertical Y axis. The axes must be marked off to such a scale that all the pertinent figures or data may be plotted.

In aeronautics, graphs are used for such things as showing test data, calibrating instruments, and indicating weather trends, and for saving work and time in making calculations.

There are several types of graphs: *straight-line, curved-line, bar, pie,* and *picture.* Only the straight-line and curved-line graphs are described here, since they are the types most commonly used in flight engineering.

### Straight-Line Graph

If two variables are related so that as one variable is changed at a constant rate, the value of the other also changes at a constant rate, the graph showing the relationship between these two variables is a *straight-line* graph. In figure 2-7, *Straight-line Graph,* as temperature increases in increments of 100° C, the pressure increases in increments of 5 psi. A straight-line graph can be constructed by solving the equation which relates these two variables for two sets of values, plotting these values on the graph, and then connecting them with a straight line. Other values of the

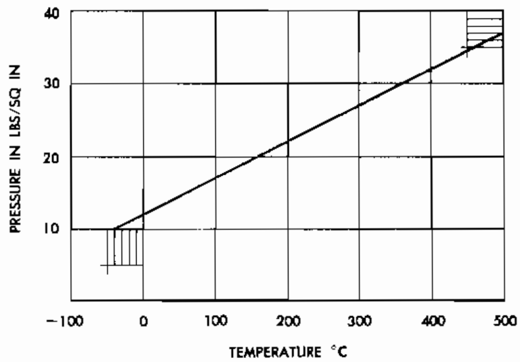



*Figure 2-7. Straight-Line Graph*

variables can be read from the graph without the necessity of computing them.

This straight-line graph illustrates how the pressure of a certain gas varies with a change in temperature as the volume remains constant.

Notice that the pressure varies from 10 to 37 pounds per square inch, while the temperature varies from −40 to 500 degrees C. A suitable scale was chosen to spread these values along the X and Y axes.

### Curved-Line Graph

If two variables are related to each other so that as one of the variables is changed at a constant rate, the other variable changes at a varying rate, the graph showing the relationship between these two variables is a curved-line graph. Note in figure 2-8, that as the height in feet is varied in increments of 300 feet, the distance in miles does not change at a constant rate.

The accompanying curved-line graph represents data which lists a distance (D) in miles at which a light at a height (H) in feet above the surface of the sea can be seen.

| D (Miles) | H (Feet) |
|---|---|
| 0 | 0 |
| 3 | 6 |
| 6 | 24 |
| 12 | 96 |
| 18 | 216 |
| 24 | 384 |
| 36 | 864 |
| 45 | 1350 |

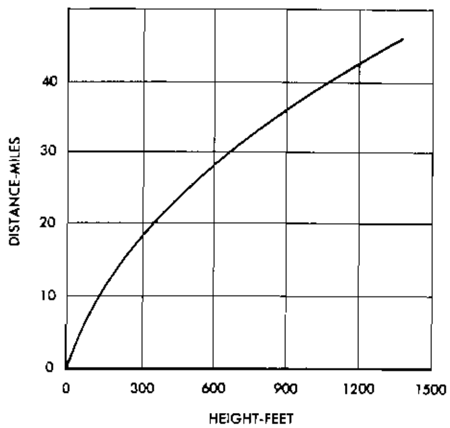



*Figure 2-8. Curved-Line Graph*

To plot the data, a convenient scale must be selected so that all data can be presented in an allowable space without crowding. The scale along the X axis must accommodate a range of data from 0 to 1350 feet, and the scale along the Y axis must accommodate a range of data from 0 to 45 miles. The points on the graph are located at the intersection of each corresponding set of values. After all the points have been located, they are connected with a smooth curved line.

When constructing a curved-line graph, enough points must be plotted from the basic equation or data to make possible the drawing of a smooth and accurate curve. If the relationship between two variables is not known in advance, or if there is no definite relationship between the two variables, a number of pairs of carefully observed values of the two variables may be plotted on graph paper and connected by a series of straight lines or a curved line, whichever best fits the points.

### Interpolation

With an accurate curve, it is possible to read intermediate values directly without further computation. The process of determining the value of points between known points is called *interpolation.* Extending a curve to determine values is called *extrapolation.* Extrapolation is not as accurate as interpolation and should be used with caution and only for short distances.

If it is known that the reading desired will fall between two values, the difference between these two figures should be divided into equal parts. The easiest way would be to divide the total distance or difference into ten equal units. Then the point at which the reading is desired can be said to be so many tenths from either value and added or subtracted to those values to obtain the desired figure.

Using the graph in figure 2-9, assume that you would like to know the amount of drag at 110 mph. Since this value does not fall directly on an indexed ordinate, you have to estimate (interpolate) the 110 mph point. This happens to be midway between 100 and 120. Then you have to read across and interpolate the drag abscissa, preferably in tenths of the distance between 4000 and 6000. This is approximately five-tenths of

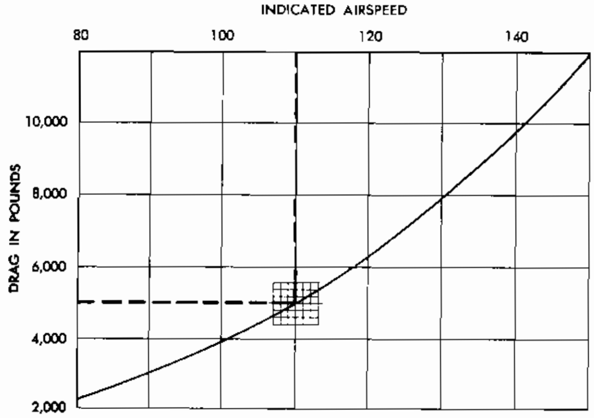



*Figure 2-9. Variation of Aerodynamic Drag with Airspeed*

the way or .5 × 2000 = 1000. This 1000 added to 4000 gives 5000 pounds of drag.

This system can be used whether the value is taken from a table of figures or from a graph. The accuracy of a graph or table of figures is limited by the provision of measurement or by the accuracy with which one can place a figure and interpolate its distance from a known value.

Among flight engineers, the procedure just discussed is commonly called the "eye-balling" technique. However, for precise computations, which are necessary in cruise control work, the "eye-balling" technique is not acceptable.

In order for the flight engineer to interpolate and make accurate computations he must have two tools and a knowledge of their use. These tools are the engineer's rule and the slide rule. The engineer's rule has three sides, six scales, and is 12 inches long. For convenience, one end of the rule (2½" to 3") is normally cut off and used in flight engineering computations. Only one of the six scales is commonly used—the one with 60 increments to the inch.

The most frequently used chart (graph) on which the engineer is required to interpolate precisely is the *Nautical Miles Per Pound (NMPP) chart,* which is discussed in detail in Chapters 9 and 10.

## Critical Values

Probably the most important use of graphs is the purely qualitative study which examines the general shape of the graph rather than the specific values of the variables. From this point of view, attention is paid to the critical values, that is, the highest and lowest points on the graph. At these points, several readings of one variable may correspond to one value of the other variables. Such a condition exists when the slope of the curve tends to change direction radically. It is generally true that such intervals correspond to important physical properties of the variables.

In the science of aerodynamics, there are two important constants known as the *lift coefficient* and the *drag coefficient.* These coefficients are obtained by wind tunnel tests on accurately scaled wing models, and are found to vary with the angle of attack that the wing surface makes with the wind. In order to better compare them, the lift and drag coefficients are shown in figure 2-10, with the two coefficients placed on the same set of axes. Then, in order to make the two curves approximately the same size, a different scale was used for the drag coefficient. Multiple scales are often used in this way as a means of comparison in determining critical values.

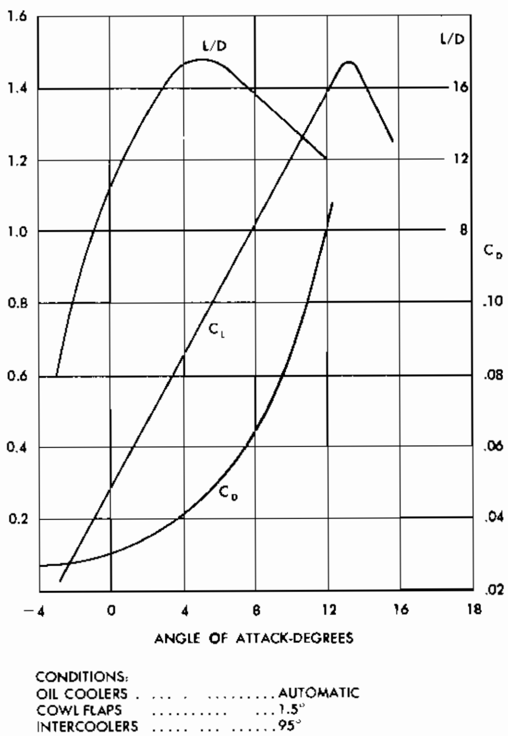



*Figure 2-10. Graphic Comparison of Lift and Drag Coefficients*

When the two curves are put on the same base graph, another advantage accrues. Quite often the two individual elements are related in another way besides through the one common variable as the angle of attack in degrees used in the illustration. This relation between the remaining variables can also be shown. The ratio of lift to drag as shown by the L/D curve in the same illustration exemplifies this.

The information presented thus far, as you must realize, is strictly preliminary and this continues for several more chapters. The duties of the flight engineer are numerous and varied. A large percentage of those duties involves the practical application of mathematical principles and formulas. This in turn commonly calls for use of the slide rule in order to save time. Until a newly-trained flight engineer has used the required mathematical formulas so often that he knows immediately which formula fits a given situation, and until the proper use of the slide rule has become almost second nature with him, it is advisable for him always to have a ready reference available. This chapter was designated so that it might be used for just such a purpose. While the number of examples illustrating any single rule or formula has been somewhat limited, the examples represent typical problems the flight engineer encounters.

## COMPUTER PRINCIPLES

### General Characteristics

The computer is essentially a circular slide rule which, like the standard slide rule, can be used to make time—speed—distance computations as well as gallons per hour—fuel consumed—time elapsed computations. Conversions from statute miles to nautical miles, nautical miles to statute miles, adjustments for density altitude, and determination of Mach number can be made quickly.

The three scales with which the flight engineer is most concerned are (1) the outer or mile scale, (2) the middle or minute scale, and (3) the inner or hour scale. The two time scales rotate together on the inner disc, whereas the mile scale is stationary. We are not concerned here with the two degree scales on the outer edge of the computer. Adjustments for variations in temperature and density are determined by transparent panels of the rotating disc.

### Reading the Computer

Reasoning is required to insure accuracy of computer readings. The placing of the decimal point, for instance, depends on each individual problem. The point marked 2.3 can also correctly designate .23, 23, 230, 2300, 23,000, etc. The correct designation depends on the problem and its solution.

In the same manner as the slide rule, the graduations of the scales change constantly. Notice in figure 2-11 that the *speed index* (large pointer) is located at zero time, and that 3:10 is approximately 180 degrees removed, or approximately ½ the distance around the circle. Observe that approximately 6:50 covers the remaining 180 degrees and that the increments are progressively smaller. All relationships of speed, time, and distance are similarly proportional on the computer.

The ratio between any number on the movable scale and its opposite number on the stationary scale *at any one setting* is the same as the ratio between any other two opposite numbers on these scales at that setting. A one-to-one ratio exists when the number on the movable scale is the same as the number on the stationary scale. In this instance, therefore, all numbers on the movable scale will be the same as the opposing number on the stationary scale. If, on the other hand, a ratio of 3 to 7 exists between two indexed numbers, this ratio will exist for all other indexed numbers. This, as you know, is also a characteristic of the slide rule.

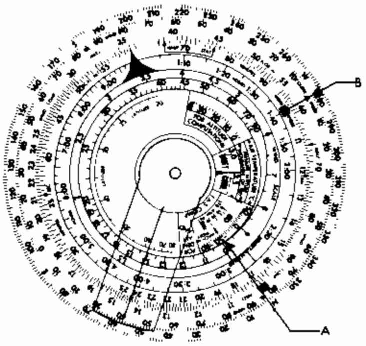



*Figure 2-11. Computer, General Characteristics*

#### Method of Solving Time, Speed, Distance Problems

The speed index is located at 60 on the movable scale so that the answer on the stationary scale can be read directly without dividing by 60.

If you know the speed and either the time or distance, simply rotate the speed index so that the pointer indexes with the speed. This act places all times and the related distances opposite each other. If, in one instance, know the *time,* then read the *distance* opposite the time. If, on the other hand, you know the *distance,* then read the time opposite the distance. In each instance, you must know two of the three elements to determine the unknown element. In problems involving *speed* as the unknown factor, the known time is rotated so as to be opposite the known distance. When this operation is completed, the speed index indicates the speed.

In figure 2-11, you observe that the speed index points to 360 miles. This setting, as we have said, establishes all time and distance relationships. If the known time is 4:04, as indicated by the rotating hairline indicator, the distance is 2435 miles. This position can be the outcome of the need to know any one of the three computation elements.

In figure 2-11, "A" indicates the temperature and altitude scales used for density altitude and TAS computations and "B" indicates the wind index used by the navigator. In problems involving (1) flight time, (2) rate of fuel consumption, and (3) total fuel consumed, the speed index always points to the rate of fuel consumption. If the rate of fuel consumption is known, you place the speed index at the figure representing the rate of fuel consumption in gallons (or pounds) per hour, then, if the *time* is known, read the total of fuel consumed over the time. If, on the other hand, the *consumption* is known, then read the time under the figure representing the number of gallons (or pounds) of fuel consumed. If both the time and the total fuel consumption are known, you place the time under the fuel consumed and read the rate of fuel consumption at the speed index.

#### Density-Pressure Interrelationships

Standard atmospheric conditions exist when, at sea level and 15° C (59° F) a pressure of 29.92 inches of mercury exists. Since this combination of conditions is rare, the airspeed indicator rarely indicates airspeed accurately because this instrument is calibrated to standard pressure. Before we discuss the compensation for density altitude, let us consider briefly the interrelationships which are provided on the computer. In the "For Density Altitude and TAS Computations" panel, you would find that 15° C indexes with zero (sea level altitude) when standard atmospheric conditions exist. With this setting, the standard temperatures for altitude computations are displayed in the panel of that name. Since this is a *standard condition,* the speed index would register 60 and all time and distance values would index and appear in a 1 to 1 ratio.

#### Compensating for Temperature Variations

The difference between TAS and IAS at high altitudes is surprising when one first encounters this information. In using the computer to determine the true airspeed which exists at 30,000 feet with a temperature of —50° C and an indicated airspeed of 300 knots, you would rotate the movable disc so as to index —50° C with 30,000 feet pressure altitude. Then, rotate the hairline indicator to read 485 (TASK) over the 300 IASK. From these computations, you observe that, with a temperature of —50° C and an altitude of 30,000 feet, the aircraft is moving through the airmass at a speed of 185 knots greater than the indicated airspeed.

#### Statute Mile—Nautical Mile Conversion

A small panel defined by two arrows permits

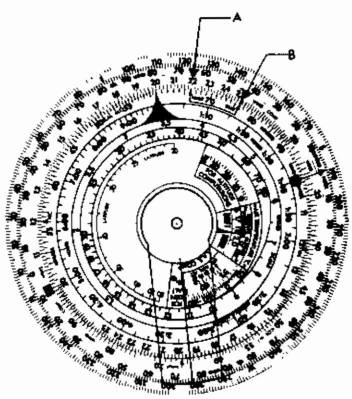



*Figure 2-12. Computer, Nautical Mile—Statute Mile Conversion*

easy conversion from statute miles to nautical miles or vice versa. In figure 2-12 the movable disc has been turned so as to indicate 22 nautical miles as being equal to 25.3 statute miles. As you have learned, these values could be 220 to 253: 2200 to 2530, etc. The procedure, if you know the *nautical miles,* is to rotate the movable disc so as to place the *nautical miles* under the nautical miles arrow and read the statute miles under the statute miles arrow. If, on the other hand, you know the *statute miles,* then place the statute miles under the statute miles arrow and read the nautical miles under the nautical miles arrow.

CHAPTER 3

# Physics for The Flight Engineer

Born an inherently curious creature, man has always had a desire to better understand the world about him. The many phenomena of nature have, at one time or another, presented a challenge to the scientist. Down through the years, scientists have been working to discover laws governing these phenomena by observing and experimenting, and then solving related problems by accurate, logical thinking. The knowledge which man has acquired in this way has made a tremendous contribution toward improving the world we live in.

Such advancements fall within the scope of the science of *physics,* which deals with the laws and properties of inanimate matter, and the forces acting upon it. Physics includes mechanics, electricity, heat, light, sound, and also the branches of science that pertain to radiation and atomic structure.

This chapter includes a discussion of those terms and laws of physics that pertain to the construction and operation of mechanical devices. This is basic information, some of which will be discussed in more detail in later chapters. This chapter provides the flight engineer with fundamental information to help him better understand his duties and the overall functioning of his aircraft.

## MATTER

The universe is made up of *matter.* Matter may be defined as anything that occupies space, and it may exist in the form of a *solid,* a *liquid,* or a *gas.* Iron, copper, water, air, and oxygen are just a few examples of matter.

Matter is composed of tiny particles known as molecules. A molecule is defined as *the smallest particle of a substance (compound) which has all the properties of that substance.* For example, a grain of salt may be theoretically broken into two pieces, then four, and so on, down to the last molecule which, when broken, loses its identity as salt and returns to sodium and chlorine, the two elements that form salt. The molecule no longer exists after the loss of identity.

The tiny molecule is made up of smaller particles called *atoms.* A molecule of water ($H_2O$) consists of 3 atoms, two atoms of hydrogen and one atom of oxygen. The atom is the smallest part of an element which retains the property of the element. Now, to review these relationships:

- The smallest unit of a compound is the molecule;
- The smallest unit of an element is the atom; and
- All compounds are made up of one or more of the elements.

## UNITS AND SYMBOLS

One of the essentials to understanding the subject of physics is a knowledge of the units and symbols used to measure and represent quantities sueh as mass, area, volume, speed, etc. There are two primary systems in use: the *absolute* and the *gravitational,* and each of these is further subdivided into the *British* and the *Metric.* The following table shows these systems.

The British absolute system is based on the foot as the unit of length, the pound as the unit of mass, and the second as the unit of time. This system is commonly known as the *foot-pound-second (fps)* system.

In like manner, the Metric absolute system is also based on length, mass, and time, the basic units of which are the centimeter, gram, and second, respectively. This system is therefore known as the *centimeter-gram-second,* or *cgs,* system.

TABLE OF UNITS AND SYMBOLS

ABSOLUTE UNITS

| *Quantity* | *British (fps)* | *Metric (cgs)* | *Symbols* |
|---|---|---|---|
| *Fundamental* | | | |
| Length | ft | cm | l |
| Mass | lbs | gm | m |
| Time | sec | sec | t |
| *Derived* | | | |
| Area | $ft^2$ | $cm^2$ | A |
| Volume | $ft^3$ | $cm^3$ | v |
| Speed | ft/sec | cm/sec | V |
| Acceleration | $ft/sec^2$ | $cm/sec^2$ | a |
| Force | poundal | dyne | F |
| Density | $lb/ft^3$ | $gm/cm^3$ | *p* (rho) |
| Energy | ft-poundal | erg | E |
| Power | ft-poundal/sec | erg/sec | P |

GRAVITATIONAL UNITS

| *Quantity* | *British* | *Metric* | *Symbols* |
|---|---|---|---|
| *Fundamental* | | | |
| Length | ft | cm | l |
| Force | lb | gm | F |
| Time | sec | sec | t |
| *Derived* | | | |
| Area | $ft^2$ | $cm^2$ | A |
| Volume | $ft^3$ | $cm^3$ | v |
| Speed | ft/sec | cm/sec | V |
| Acceleration | $ft/sec^2$ | $cm/sec^2$ | a |
| Mass | slug | no names | m |
| Density | $slug/ft^3$ | assigned | *p* (rho) |
| Energy | ft-lb | cm-gm | E |
| Power | ft-lb/sec | cm-gm/sec | P |

The *British gravitational system* is based on the same fundamental units (foot, pound, and second) as is the British absolute system, but *force* replaces *mass* as a fundamental quantity. Likewise, the Metric gravitational system uses the same units as does the Metric absolute system, but the *gram* now is the unit of force, not a unit of mass.

Perhaps the most noticeable difference between the two systems is the use of mass in the absolute, and force in the gravitational as fundamental quantities. Furthermore, the three fundamental quantities of the absolute system are *constant* under all conditions. Therefore, all of the derived absolute quantities also have *constant* values. But in the gravitational system, force is the force of gravity, which *varies* with altitude and latitude. Consequently, the derived gravitational quantities that involve force are also variables. However, since the force of gravity varies so slightly within the confines of the earth's atmosphere, the gravitational system can be used for all "everyday" calculations. But where precise calculations are required, such as those related to space travel, for example, the absolute system would have to be used.

## ENERGY

*Energy* is defined as the *ability to do work,* and is of two general typcs—*potential* and *kinetic.* These two types can be more specifically classified as mechanical energy, electrical energy, heat energy, and chemical energy.

### Potential Energy

Potential energy is defined as static energy, which a substance possesses because of (1) its *position,* (2) its *physical state* (distortion), or (3) its *chemical state.* Water in an elevated reservoir, and the lifted weight of a pile driver are examples of the first group. A stretched rubber band or a compressed spring is an example of the second group. The energy of coal, food, and a storage battery is an example of the third group.

The measure of potential energy of any lifted body is equal to the work done in lifting the body. Since energy is measured in work done, it is expressed in *foot-pounds.* The formula for potential energy (PE) is: PE = WH, in which W = weight in pounds and H = height in feet.

*Example:* A bomber is flying at an altitude of 10,000 ft and is carrying a 500-lb bomb. What is the potential energy of the bomb?

$$PE = 10{,}000 \text{ ft} \times 500 \text{ lb} = 5{,}000{,}000 \text{ ft-lb}$$

It required 10,000 feet × 500 pounds, or 5,000,000 foot-pounds of work to elevate the bomb to that height. It follows from the *Law of Conservation of Energy* that there must be 5,000,000 foot-pounds of energy stored in the bomb.

Since energy cannot be destroycd, as soon as the bomb is released from the bomb rack, the bomb loses part of its potential energy. This form of energy becomes less and less until it reaches zero when the bomb hits its objective. As the bomb falls through space its kinetic energy increases. The kinetic energy of the bomb is at its maximum at the time the objective is hit. Remember that the potential energy of the bomb at this point is zero. These facts suggest that the sum of the potential energy and kinetic energy of the bomb at any position in its course is equal to the original potential energy of the bomb. In other words, the sum of the two forms of energy is a constant. In the case of the bomb in the problem, the constant is 5,000,000 foot-pounds.

### Kinetic Energy

*Kinetic energy is the energy that an object possesses because of its motion.* The wind, flowing water, an aircraft in flight, and an automobile skimming over the highway all have kinetic energy, and the faster they go, the more energy they possess.

The formula for arriving at the kinetic energy of a falling body is as follows:

$$KE = \frac{WV^2}{2g} \qquad (13)$$

in which W = weight in pounds of the body, V = speed in feet per second, and g = force of gravity, which is about 32 feet per second for each succeeding second.

When values expressed in the units given are substituted in the formula, the result will be the number of foot pounds of kinetic energy.

It is difficult to appreeiate the tremendous force exerted by the "blockbusters" which were dropped from great heights over enemy territory during World War II.

*Example:* What is the kinetic energy of a 2,000-pound bomb traveling at 1,000 feet per second at the time of impact?

$$KE = \frac{2{,}000 \times (1{,}000)^2}{2 \times 32} = 31{,}250{,}000 \text{ ft-lb}$$

The amount of the kinetic energy of the bomb in this case is somewhat incomprehensible until it is put into more understandable terms. For example, the 31,250,000 foot-pounds is sufficient to raise one ton to an altitude of 15,625 feet (almost 3 miles).

Many of the "blockbusters" weighed four tons instead of one ton, as used in the example. If the veloeity of a 4-ton bomb were the same as that given above, its force would be four times as great as for a 1-ton bomb. In that case, the kinetic energy of a 4-ton bomb would be 125,000,000 foot-pounds, or a force sufficient to raise one ton 62,500 feet (about 12 miles).

### Conservation of Energy

One of the many laws of physics is the *Law of Conversation of Energy,* which states that *energy can be neither created nor destroyed, but its form may change.* That is to say, energy given up by one body doing work is imparted to another body on impact or divided between them without loss. Therefore, the amount of energy in the universe remains unchanged and is only transformed from one kind to another. For example, when a mixture of gasoline and air is ignited inside the cylinders of an engine, the resulting combustion process generates heat energy. The heat is absorbed by the remaining gases in the cylinder (principally nitrogen). As the temperature of the gases is increased, their pressure is also increased (Charles' Law). This high pressure, acting evenly in the closed cylinder and over the entire head of the piston, imparts straightline motion to the piston. The straightline motion of the piston is converted into rotary motion of the crankshaft through the connecting rod.

The mechanical energy of the rotating erankshaft is further transformed into other types. For example, the rotating crankshaft turns the propeller and the generator. The generator transforms mechanical energy into eleetrical energy. The electrical energy is then used to operate motors which convert the electrical energy baek to mechanical energy for the operation of such aircraft units as the retractable landing gear and wing flaps. The generator also supplies electrical energy for aircraft lighting systems, radio operation, and reeharging the aircraft battery. When the battery is being charged, electrical energy is being transformed into chemical energy; when the battery is being discharged, chemical energy is being transformed back into electrical energy.

### Heat Energy

Since the reciprocating aircraft engine is a *heat engine,* a further discussion of heat energy is of considerable importance.

When a gas is compressed, work is done and the gas becomes warm or hot. Conversely, when a gas under high pressure is allowed to expand, the expanding gas becomes cool. In the first case, work was converted into heat energy; in the second case, heat energy was expended. By experimentation, it has been shown that the work required to overcome and the amount of heat produced by friction are proportional. Thus, heat can be regarded as a form of energy.

According to this theory of heat as a form of energy, the molecules, atoms, and electrons in all bodies are in a continuous state of motion. In a hot body, these small particles possess relatively large amounts of kinetic energy, while in cooler bodies they have less. Because the small particles are given motion, and hence kinetic energy, work must be done to slide one body over the other. Mechanical energy apparently is transformed and what we know as heat is really kinetic energy of the small molecular subdivisions of matter.

Two different units are used to express quantities of heat energy. They are the *calorie* and the *British thermal unit* (BTU). One calorie (cal) is equal to the *amount of heat required to raise the temperature of one gram of water one degree Celsius.* This term calorie is spelled with a small c, and is $\frac{1}{1000}$ of the Calorie (spelled with a capital C) used in the measurement of heat-producing or energy-producing value in foods. One British thermal unit (BTU) is defined as *the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.* The calorie and the gram are not used in the field of cruise control. The BTU, however, is commonly referred to in discussions of engine thermal efficiencies and heat content of aviation fuel.

A device known as the calorimeter is used to measure quantities of heat energy. For example, it may be used to determine the quantity of heat energy available in one pound of aviation gasoline. A given weight of the fuel is burned in the calorimeter and the heat energy is absorbed by a large quantity of water. From the weight of the water and the increase in its temperature, it is possible to compute the heat yield of the fuel.

A definite relationship exists between heat and mechanical energy. This relationship has been established and verified by many experiments. By experiments it has been shown that: One British thermal unit = 778 foot-pounds. Thus, if the one-pound sample of fuel were to yield 20,000 BTU, this would be the equivalent of 20,000 BTU $\times$ 778 ft-lb/BTU, or 15,560,000 ft-lb of mechanical energy.

Unfortunately, no heat engine is capable of transforming all of the available heat energy in the fuel it burns into mechanical energy. A large portion of this energy is wasted through heat losses and operational friction.

## GRAVITATION

From his experiments, Sir Isaac Newton concluded that all bodies in the universe attract each other. For example, the earth attracts the moon, and the moon attracts the earth. This mutual attraction is called *gravitation.* More specifically and more commonly, however, the term is used to apply to the attraction between the earth and all things upon it. Because of the great mass of the earth, the attraction in this case is in one direction—toward its center. This force is called *gravity,* which is the force that pulls an aircraft to earth when its engines fail, that makes a kite drop when the wind dies down, and that keeps us from hurtling off the face of this rapidly spinning sphere into space.

### Weight and Mass

The pull of gravity causes objects to have *weight.* Therefore, weight is defined as *the force of gravity acting on an object. Mass* is defined as *the amount of fundamental matter of which an object is composed.*

Since weight depends on gravity, the weight of an object decreases with altitude (distance from the center of the earth), because *the force of gravity decreases with altitude.* For instance, an aircraft that weighs 100,000 pounds on the ground weighs a little less at 50,000 feet. The mass of the aircraft has not changed, however, because mass, unlike weight, is not dependent on gravity. *The mass of an object is the same throughout the universe,* regardless of how far it is from a gravity source.

Within the earth's atmosphere, a change in the force of gravity on an object does not produce any appreciable change in the weight of the object. As a result, in engineering calculations the numerical value for the mass of an object is, for all practical purposes, the same as the weight of the object. To illustrate, the mass of a cubic foot of water is about 62.4 lbs; also, a cubic foot of water weighs 62.4 lbs. Consequently, it is common for the terms mass and weight to be used interchangeably. One must keep in mind, however, that technically the two are not synonomous, and that the distinction between them must be maintained when making precise calculations involving the effect of changing gravity on weight.

Since weight is a force—a force pulling a body toward the center of the earth, the units of measurement which apply to force also apply to weight. The gravitational system units are the *pound* and the *gram.* The absolute system units are the *poundal* and the *dyne.*

The poundal is the basic unit of force in the British absolute system. It is defined as the *force that will give a mass of one pound an acceleration of one foot per second per second.* At 0° latitude (the equator) the force of gravity on a one-pound mass is 32.08 poundals, and at the poles it is 32.25 poundals. The average value is 32.16 poundals, figured at 45° N latitude, which is the value commonly used in engineering calculations.

In the absolute system, mass is measured in pounds and grams, and in the gravitational system in slugs. The *slug* is a British engineering unit of mass, and it is defined as the *mass that will be accelerated one foot per second when acted upon by a one-pound force.* Mathematically, one slug has the same value as the acceleration of gravity. The value commonly used is 32.16 pounds, which is used by the flight engineer to calculate air density.

### Density

The density of a substance is defined as the mass per unit volume. Mathematically, density is represented by the Greek letter rho ($\rho$) and is calculated by dividing mass by volume, or

$$\rho = \frac{m}{v} \qquad (14)$$

The value of m in the formula may be expressed in pounds, grams, or slugs. Consequently, $\rho$ is expressed in pounds, grams, or slugs per unit volume. When $\rho$ is in pounds per cubic foot it can be changed to slugs per cubic foot by dividing by 32.16. For example, the density of air at sea level and 60° F is 0.07608 lb/cubic foot. Dividing 0.07608 by 32.16 gives 0.00237 slugs/cubic foot. Sometimes the term *mass density* is used for density, to remind the reader that the mathematical value of m is in terms of mass and not weight.

### Specific Gravity

The *specific gravity* of a substance is expressed as a number, which tells *how many times the substance is as dense (heavy) as water.* For example, aluminum has a specific gravity of 2.7. This means that a cubic foot of aluminum weighs 2.7 times as much as a cubic foot of water. The reason that lubricating oil floats on top of water is because it is less dense than water—it has a specific gravity of .90 to .93. The physics-book definition of specific gravity *is the ratio of the density of a substance to the density of water.*

### Force

*Force* is defined simply as a *push or pull.* It is further defined as *any action which tends to produce, retard, or modify motion, or change the shape of a body.* In the absolute system, force is measured in either poundals or dynes, and in the gravitational system in either pounds or grams.

Since force is a vector quantity, it may be and frequently is represented by a straight line, called a *vector.* A force has three characteristics: *magnitude, direction,* and *point of application.* Consequently, when we consider a force acting on an object, we cannot know its complete effect unless we know these three things.

Moreover, when several forces act upon a body, they produce the equivalent of a single force, termed the *resultant force,* which in effect is equal to the individual forces. Thus, as far as the effect of the individual forces on the actual motion of the body is concerned, it is the same as though only the resultant force were acting on the object. To find the single force, the rules of vector calculation may be used, and the resultant force is the vector sum of all the acting forces. However, if there are only two vectors or if they are at right angles, simpler methods may be employed, as you will see presently.

In figure 3-1, two forces of 100 pounds each are applied to a barge, one toward the north and one toward the east. What is the resultant force on the barge? First, we shall solve the problem through graphics by using the parallelogram. *According to the parallelogram law, the resultant of two forces acting at a point is indicated by the diagonal of a parallelogram the two adjacent sides of which represent the two forces in both direction and magnitude.* In our example, the two force lines, OA and OC, are each two inches long and represent 100 pounds. The resultant force is the diagonal, OB, which measures 2.82 inches. Thus, since the 2-inch scale represents 100 pounds, by the ratio and proportion method we can determine the resultant force:

$$2:100 = 2.82:x$$
$$2x = 282$$
$$x = 141$$

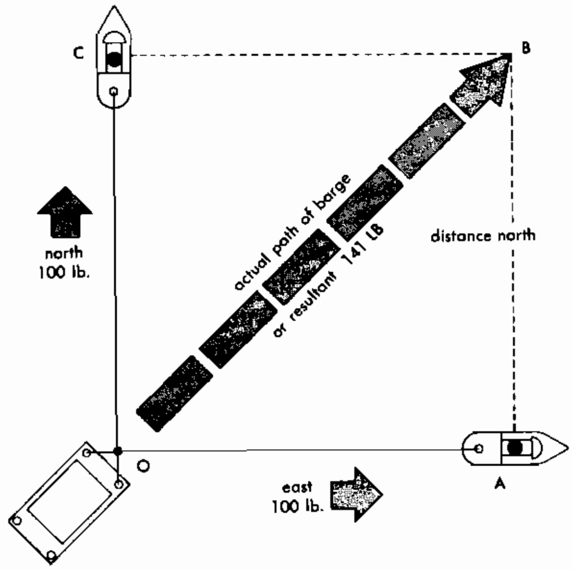



*Figure 3-1. Vector Addition of Forces*

The same problem could have been solved by using the *Pythagorean theorem,* which states that in a right-angle triangle, the square of the hypotenuse equals the sum of the squares of the other two sides.

$$R^2 = A^2 + B^2 \quad (15)$$
$$R^2 = 10{,}000 + 10{,}000$$
$$R = 141 \text{ pounds}$$
$$(R = \text{resultant force})$$

Remember that this theorem can be used only when the forces are at right angles to each other.

If the vector sum of all the forces acting on a body is zero, the body is said to be in *equilibrium,* for there will be no tendency for acceleration in any direction. This condition of equilibrium is merely a balance between all of the forces so that there is a general cancellation by oppositely directed forces.

Mathematically, the rule for equilibrium of several forces is that the algebraic sums of their X and Y components must equal zero. If any body remains at rest or moves at a constant speed, the forces acting on it must be in equilibrium; otherwise, the motion of the body increases in the direction of the resultant of all the exerted forces.

## Pressure

*Pressure is the push or pull (force) per unit area of the surface acted upon.* Pressure is usually expressed in pounds per square inch and is written $lb/in^2$ or psi. In equation form the pressure relationship reads

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \text{ or } P = \frac{F}{A} \quad (16)$$

Figure 3-2, shows how the pressure varies with the area upon which the force is created.

## Speed

The speed of a body in motion is defined as *the distance it travels per unit of time.* In equation form this relationship reads

$$\text{Speed} = \frac{\text{distance}}{\text{time}}, \text{ or } V = \frac{d}{t}$$

The units in which speed is commonly expressed are statute miles per hour (mph), and feet per second (ft/sec). In navigation, the nautical mile is commonly used and speed is expressed in nautical miles per hour (knots, abbreviated k). In this manual, the symbol NM is used in the term nautical miles per pound (NMPP). On cruise control charts the word *statute* is often used with *miles per hour,* even though the phrase miles per hour (mph) alone refers only to statute miles per hour.

## Velocity

In the definition of speed, no reference is made to the direction in which a body moves. *Velocity* includes the inference of direction; therefore, velocity can be defined as *speed in a given direction.* The units in which velocity is expressed are the same as those for speed. The symbol V is used to represent velocity. In aircraft performance, velocity is often referred to as *airspeed.* A full discussion of airspeeds is given in a later chapter.

## Acceleration

The acceleration of a body in motion is defined as *the time rate of change of velocity.* Observe that the definition is not based on the distance traveled, but on the loss or gain of velocity with time. In equation form it may be stated as

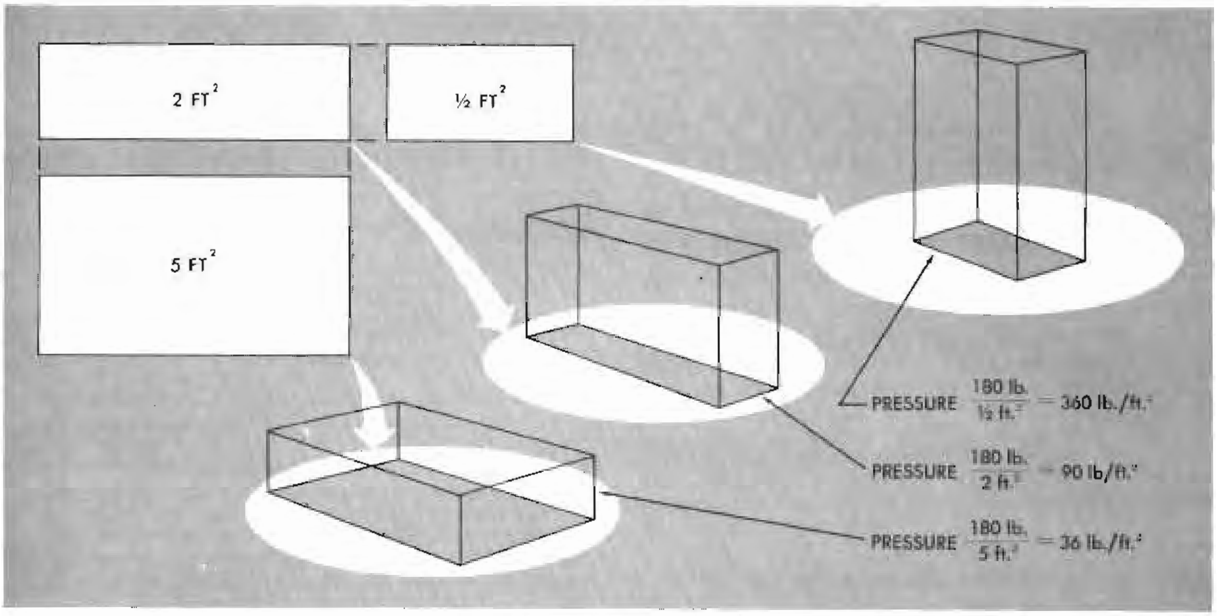



*Figure 3-2. Pressure*

$$\text{Acceleration} = \frac{\text{change of motion}}{\text{unit of time}} \quad (17)$$
$$= \frac{\text{final velocity} - \text{original velocity}}{\text{time}}$$
$$= \frac{V_f - V_o}{t}$$

where $V_o$ is the original velocity, $V_f$ is the final velocity, $V_f - V_o$ is the change of velocity, and t is the time interval during which this change occurs.

Figure 3-3, shows the relationship of time, acceleration, velocity, and distance.

If velocity is expressed in feet per second, then acceleration would logically be expressed in feet per second per second. This measurement may be explained by the following example:

An automobile moves from point A to point B. At point A, its velocity is 40 ft/sec. At point B, its velocity is 70 ft/sec. Ten seconds are required for the automobile to travel from point A to point B. Calculate the average aeceleration per second. Substituting in the formula above, we have:

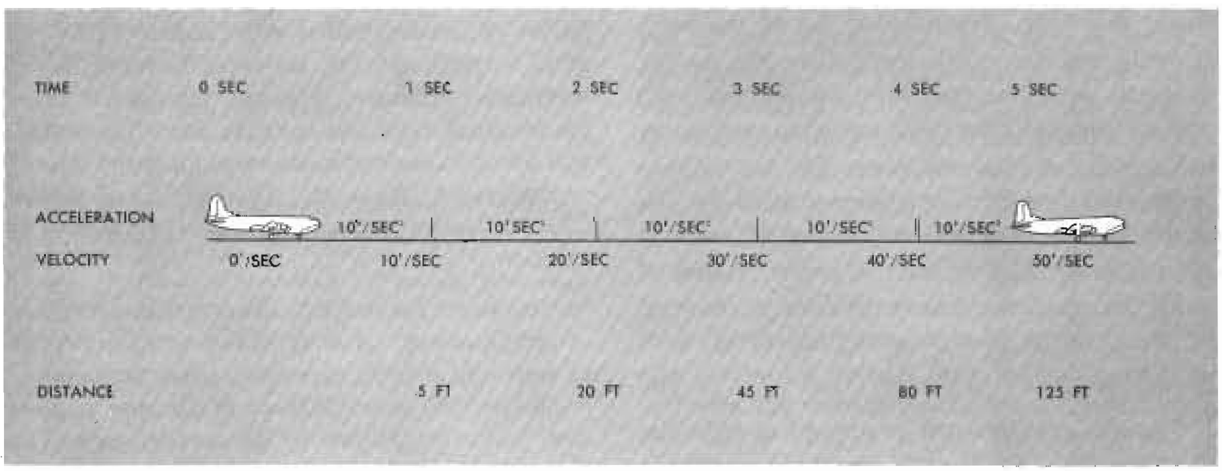



*Figure 3-3. Relationship of Acceleration, Time, Distance, and Velocity*

$$a = \frac{70 - 40}{10}$$
$$= \frac{30}{10}$$
$$= 3 \text{ feet per second per second}$$

The result may be written 3 ft/sec/sec or 3 $ft/sec^2$.

Acceleration is not restricted to increase in velocity. Any change in velocity, whether positive or negative, or merely a change in direction, involves acceleration. The term *deceleration* is commonly used to mean a decrease of velocity.

If a body starts from rest, $V_o$ is zero and the equation can be written

$$a = \frac{V_f}{t} \text{ or } V_f = at \qquad (18)$$

where

V = Velocity in feet per second

a = acceleration in ft per second per second

t = time in seconds

But distance traveled is the product of the average speed and the time, where the average speed (in the case of a uniformly accelerated body) is one-half the sum of the initial speed and the final speed. Therefore, the average speed of a uniformly accelerated body, starting from rest, is equal to ½ $V_f$ and the previous equation can be made to read

$$V_{ave} = \tfrac{1}{2}\, at. \qquad (19)$$

Since the distance (d) is equal to the average velocity for a certain length of time, this relationship can be expressed by the equation, or

$$d = \tfrac{1}{2}\, at \times t, \text{ or } d = \tfrac{1}{2}\, at^2$$

Thus, if one knows the acceleration and the time, he can calculate the distance a body traveled during that time. Since bodies fall to the earth at fairly uniform acceleration, they are usually discussed in connection with acceleration. All over the surface of the earth acceleration of freely falling bodies is nearly the same. The symbol generally used for the acceleration caused by the earth's gravity is g and its numerical value is approximately 32.2 $ft/sec^2$. Using g instead of "a" in the equation, we have the distance equation for freely falling bodies starting from rest. It is

$$d = \tfrac{1}{2}\, gt^2 \qquad (20)$$

Previous equations can be applied to examples of acceleration. Equation $V_f = at$, can be used in problems of aircraft acceleration at takeoff or aircraft braking at landing.

*Example:* An aircraft is decelerated at a rate of 8 $ft/sec^2$. How much runway will it need for stopping if it comes in at a landing speed of 90 miles per hour?

Using equation $V_f = at$, solve for the time in seconds needed to come to a stop. First change 90 miles per hour to feet per second (132 ft/sec), and then substitute. Thus,

$$V_f = at$$
$$132 \text{ ft/sec} = 8 \text{ ft/sec} \times t$$
$$132 = 8t$$
$$t = 16.5 \text{ seconds}$$

To determine distance,

$$d = (\tfrac{1}{2})\, at^2$$
$$= (\tfrac{1}{2})(8)(16.5)^2$$
$$= 1089 \text{ feet}$$

The equation $S = \tfrac{1}{2}\, at^2$ can be used in calculations pertaining to falling bodies, such as bombs.

*Example:* An aircraft is flying at an altitude of 6000 ft. How long in seconds will it take for a bomb to reach the ground if dropped from the aircraft (drag is neglected)?

$$d = \tfrac{1}{2}\, at^2$$
$$6000 = \tfrac{1}{2} \times 32.2 \times t^2$$
$$t^2 = \frac{6000}{16.1}$$
$$t = 19.3 \text{ seconds}$$

Since weight is one of the four main forces acting on an aircraft, it is important to know that the acceleration caused by gravity (g) is a factor in comparing weight to mass. Weight in pounds equals the mass in slugs multiplied by the acceleration caused by gravity (W = mg). In connection with weight, remember that the mass of an object remains the same although the weight may vary slightly.

### Newton's Laws of Motion

An epoch-making investigation into the behavior of moving bodies was carried out by the great English scientist, Sir Isaac Newton, in the seventeenth century. Newton formulated three fundamental laws which relate force to motion, and which have done much to simplify the science of mechanics. These are: (1) *the law of inertia,* (2) *the law of momentum,* and (3) *the law of reaction.*

NEWTON'S FIRST LAW. The first law, the law of inertia, states: *A body at rest tends to remain at rest, and a body in motion tends to continue in motion with constant speed in the same straight line, unless acted upon by an outside force.* The force portion of this law is acceptable by a person's own experiences. For example, when a car starts suddenly, the occupants are thrown backward, and likewise if the car is stopped suddenly, the occupants are thrown forward. It is harder to accept the part that states a body in motion tends to remain in motion. According to the law, if all friction were removed from a bearing, a wheel would coast forever.

NEWTON'S SECOND LAW. The second law, the law of momentum, states: *When a force acts upon a body, it changes the momentum of that body.* This change of momentum is proportional to the applied force, and to the mass of the body.

*Momentum* of a body is defined as *the product of its mass and its velocity.* Thus,

$$\text{Momentum} = \text{mass} \times \text{velocity} \tag{21}$$

A body that has great momentum has a strong tendency to remain in motion and is therefore hard to stop. For example, a train moving at low velocity is difficult to stop because of its large mass. Likewise, the mass of a bullet is small, but its penetrating power (momentum) is tremendous because of its high velocity.

Since the mass of a body cannot be changed, a force can affect the momentum of a body only by changing its velocity; that is, by accelerating it positively or negatively. The law of momentum states, in effect that force always accelerates the body upon which it acts, and that this acceleration is proportional to the force causing it. For example, if a 10-pound force gives a body an acceleration of 10 ft per second per second, a force of 20 pounds would give it twice the acceleration. It is convenient to express this relationship by the following formula:

$$\frac{F}{W} = \frac{a}{g} \tag{22}$$

where

F = force on object
W = weight of object
a = acceleration of object
g = acceleration of gravity

The following examples demonstrate the use of the formula.

*Example 1:* An aircraft weighs 6,400 pounds. How much force is needed to give it an acceleration of 6 ft/sec²?

W = 6,400 lb
a = 6 ft/sec²
g = 32 ft/sec²
F = ?

$$\frac{F}{W} = \frac{a}{g}$$

$$\frac{F}{6{,}400} = \frac{6}{32}$$

$$F = \frac{6{,}400 \times 6}{32} = 1{,}200$$

A force of 1,200 pounds is needed.

*Example 2:* A body that weighs 40 pounds has a resultant force of 10 pounds acting on it. What is the acceleration?

W = 40 lb
F = 10 lb
g = 32 ft/sec²
a = ?

$$\frac{F}{W} = \frac{a}{g}$$

$$\frac{10}{40} = \frac{a}{32}$$

$$a = \frac{10 \times 32}{40} = 8$$

The acceleration is 8 ft/sec²

The second law of motion also may be expressed by the following mathematical equation:

$$F = ma \tag{23}$$

where F is force, "a" is acceleration, and m is mass. This formula is a condensed form of the previous formula, substituting mass (m) for weight (W) and gravity (g).

Using the values for W and g as given in Example 1, we can find m as follows:

$$m = \frac{W}{g} \tag{24}$$

$$= \frac{6400}{32}$$

$$= 200$$

Then using the value 6 ft/sec² for "a" as given, we have

$$F = Ma$$

$$= 200 \times 6$$

$$= 1200 \text{ lbs}$$

NEWTON'S THIRD LAW. This law is the law of action and reaction, which states: *For every action (force) there is an equal and opposite reaction (force).* This means that if a force is applied to an object, the object provides a resistive force exactly equal to and in the opposite direction to the force applied. It is easy to see how this might apply to objects at rest. For example, when you stand on the floor, the floor exerts an upward force on your feet exactly equal to your weight. But this law also applies to the situation where a force is applied to an object and the force sets the object in motion.

When a force applied to an object is more than enough to overcome friction, the excess force produces *acceleration.* The inertia of the object causes a resistive force such that the force opposing the motion equals the force producing the motion. Inertia is that property of matter which causes it either to remain at rest or to maintain uniform motion in a straight line unless acted upon by an exterior force. This resistance to change in velocity due to inertia is usually referred to as *internal force*. When several forces act upon an object to produce accelerated motion, the sums of the external forces are in a state of unbalance; however, the sums of the external and the internal forces are always in a state of balance, whether motion is being either sustained or produced.

Forces always occur in pairs. The term *acting force* means the force one body exerts on a second body, and *reacting force* means the force the second body exerts on the first.

This law may be summed up by two words: *action and reaction*. The principle is demonstrated frequently in everyday life. The recoil of a rifle demonstrates this law of action and reaction. The gunpowder in the charge is ignited by the percussion cap, combustion takes place, and the bullet is rapidly accelerated from the rifle. As a result of this action, the rifle is accelerated rearward against the shoulder of the rifleman. The recoil felt by the person firing the rifle is the reaction of the action which ejected the bullet.

Whenever an aircraft propeller pushes a stream of air backward with a force of 500 pounds, the air pushes the blades forward with a force of 500 pounds. This forward force causes the aircraft to move forward. In like manner the tremendous rush of hot gases from the tailpipe of a jet aircraft is the action which causes the aircraft to move forward rapidly (reaction).

The three laws of motion which have just been discussed are closely related. In many cases, all three laws may be operating on a body at the same time.

## CENTRIFUGAL AND CENTRIPETAL FORCE

The discussion so far has centered around straight-line motion and the forces involved. Now let us consider circular motion and the two forces involved: *centrifugal and centripetal.*

When an object is moving in a circular path, centrifugal force is acting on the object to make it break away and move outward in a straight line. Opposing the centrifugal force is centripetal force, which acts inward to hold the object on its circular path. Both are equal and opposite. For example, when a weight attached to a cord is whirled, it is held in the circle by the tension of the cord (centripetal force); at the same time there is an outward pull by the weight against the cord (centrifugal force). If the cord should break, both forces would instantly disappear and the body would continue in a straight line because of inertia; in other words, the first law of motion would be in effect.

In these days of faster aircraft and faster automobiles, a knowledge of centripetal and centrifugal force is important. You can imagine how many principles of mechanics the designer has to take into account when you consider, for example, that the centrifugal force on a propeller blade may be over 70 tons at takeoff rpm and over 15 tons at maximum rpm on the turbine rotor assembly of a jet engine. We all know the difficulty of making a sharp turn at high speed. Because of centrifugal force, in some cases an automobile in the process of a turn taken at excessive speed, will either skid the rear end outward or roll over. Thus, race track, highway, and railroad curves are laterally inclined (banked) to help nullify the effect of centrifugal force, or to put it simpler, to reduce the tendency to skid. Likewise, it is for this purpose that an aircraft banks when making a turn.

### Moments and Torque

When a body is mounted on a pivot and a force is applied, there is a tendency for rotation to take place. The further the force is from the axis, the greater is the tendency to rotate the body about its axis. Thus, you normally place your hand at the end of a wrench when attempting to tighten or loosen a nut. This tendency to produce rotation is called a *moment of force,* or *torque.* Technically, torque is defined as the *product of a force and the distance of the force from the axis.* Thus we have the following equation:

$$\text{Torque} = \text{force} \times \text{distance (lever arm)} \qquad (25)$$

Torque is a measure of load and is correctly expressed in *pound-feet* or *pound-inches,* and should not be confused with *work,* which is expressed in *inch-pounds* and *foot-pounds.* For example, a certain propeller retaining nut must be tightened to a torque of 720 pound-feet. This job requires a 180-pound force on a 4-foot bar or 120 pounds on a 6-foot bar.

When two forces are applied in the same direction but at different points on a body, the forces are referred to as parallel forces. For example,

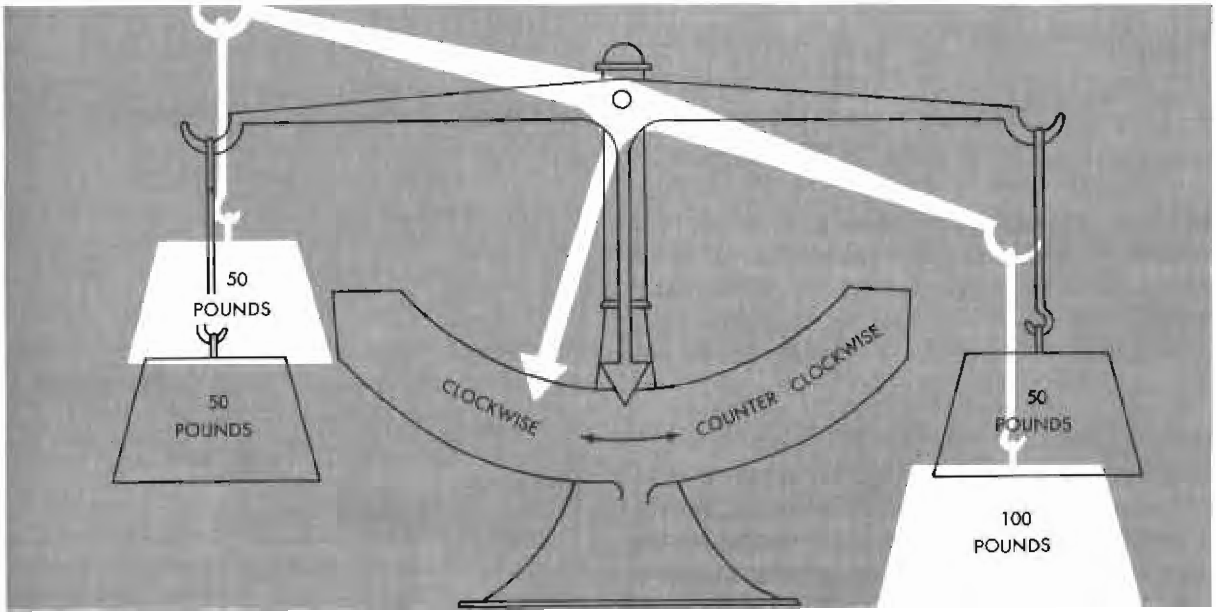



*Figure 3-4. Parallel Forces*

the forces shown in figure 3-4 exert parallel forces on the bar. However, the forces need not be equal to be parallel forces. Furthermore, if force A were greater than force B, the bar would turn about its pivot (fulcrum) in a counterclockwise direction. If force B were heavier than A, the bar would turn in a clockwise direction. If the two moments are equal, as illustrated, the bar remains in equilibrium, for under these conditions the clockwise moments equal the counterclockwise moments. Thus, using the numbers shown in the illustration, we get the following result:

Clockwise moments = counterelockwise moments

$$5 \times 50 = 5 \times 50$$

There are many practical applications of the principle of moments. For example, the principle is used to determine the balance of an aircraft in weight and balance calculations. Although we may not realize it, we see this principle in use in our everyday life. You employed this principle when you moved a wheelbarrow full of dirt or when you put the various weight blocks on the balance scales.

To take an example, go back to the wheelbarrow full of dirt. Did you ever stop to think how much force was required to lift the load? Let us assume that the center of the load was two feet from the fulcrum and that the force was applied six feet from it (see fig. 3-5). Now, to work the problem:

Clockwise moments = counterclockwise moments

$$6 \times F = 2 \times 300$$
$$6F = 600$$
$$F = 100 \text{ pounds}$$

Thus, 100 pounds was required on the wheelbarrow handles to balance (lift) the load of 300 pounds.

**Work**

Earlier in this chapter we defined energy and force. Simply defined, energy is the ability to do work, and force is a push or pull. *When energy is used to produce a force that moves an object, work is done. If there is no motion, no work is done.* For example, if your car gets stuck in the mud and you try to push it out, regardless of how hard you push, technically you do no work unless

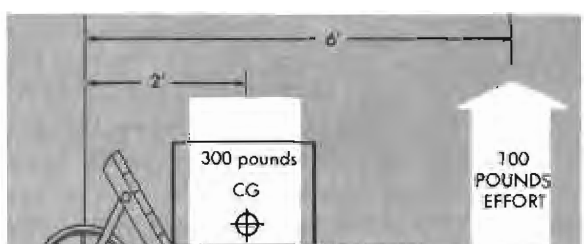



*Figure 3-5. Wheelbarrow Problem*

you move the car. It makes no difference how hard you push, how long you push, or how tired you get, you have done no work until the car moves. Mathematically,

$$\text{Work} = \text{force} \times \text{distance} \qquad (26)$$
$$W = fd$$

If you lift a 20-pound stone to a height of 3 feet, how much work have you done? If when lifting the stone you exerted a force of 20 pounds through a distance of 3 feet, the amount of work you did is the product of the force and the distance.

$$\text{Work} = \text{force} \times \text{distance}$$
$$W = 20 \text{ lb} \times 3 \text{ ft}$$
$$W = 60 \text{ ft-lbs}$$

In the previous section we explained that torque, like force, is force times distance. Perhaps you are wondering what the difference is between work and torque. Torque is the result of force times distance in a rotary direction, as shown in the wheelbarrow problem, and work is the result of force times distance in a straight line, as shown in figure 3-6.

The unit of work, the *foot-pound,* is defined as *the work necessary to move one pound a distance of one foot against the force of gravity.* Further, the work expended in raising a weight or pushing a cart is the same whether done in a minute or in an hour because time has nothing to do with the amount of work. Rather, time determines the rate of working which leads us to our next topic—Power.

**Power**

The term *power* is defined as the *rate of doing work.* The power rating of an electric motor or gasoline engine tells us how much work the machine can do per unit of time. It can be expressed in two ways:

$$\text{Power} = \frac{\text{force} \times \text{distance}}{\text{time}} \qquad (27)$$

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

The commonly used unit of power is the *horsepower.* Although horsepower actually has nothing to do with the horse, the unit was given its name from the amount of work a large dray horse could perform in a given amount of time.

Figure 3-7, shows that *one horsepower is the power required to lift 550 pounds to a height of one foot in one second.* If the time is increased to one minute, the amount of work is 60 times as much as for one second, or 60 × 550 foot-pounds or 33,000 foot-pounds. One horsepower, then, is 550 ft-lb/sec or 33,000 ft-lb/min. The formula for finding horsepower (hp) is

$$hp = \frac{P}{550} \qquad (28)$$

where P = power in foot-pounds per second.

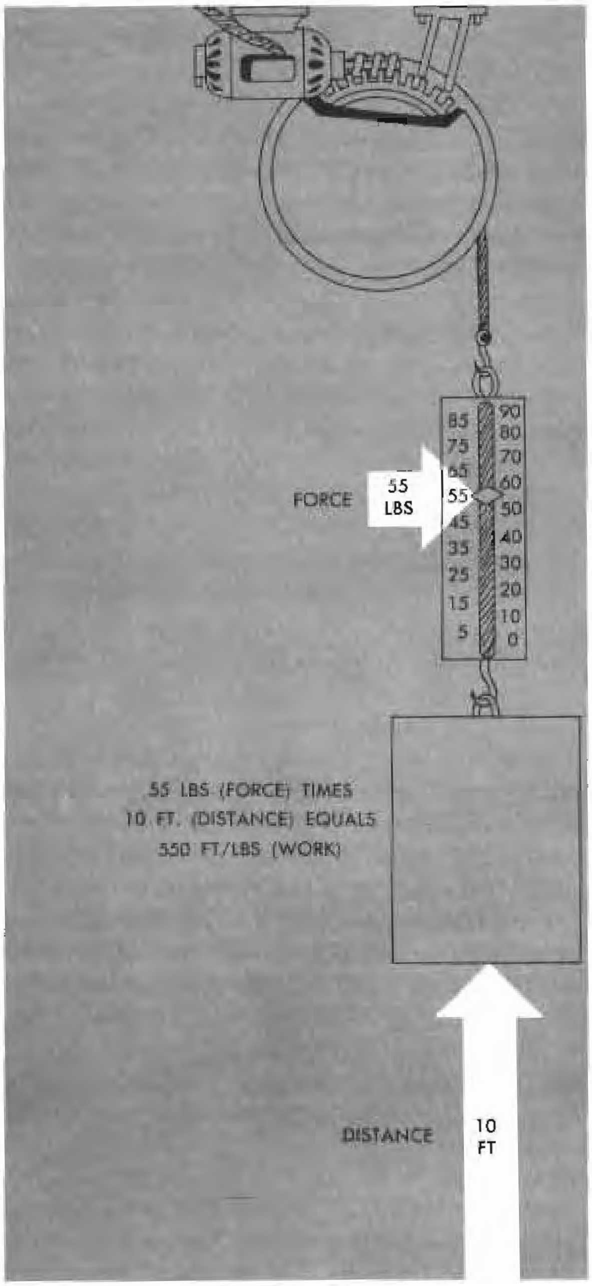



*Figure 3-6. Work Equals Force Times Distance*

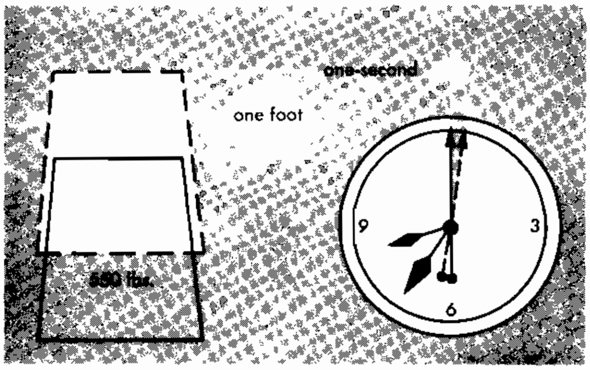



*Figure 3-7. Power*

*Example:* If a man weighing 150 pounds runs upstairs to a vertical height of 12 feet in 3 seconds, how much horsepower does he develop?

$$\text{Work} = 12 \text{ ft} \times 150 \text{ lb} = 1800 \text{ ft-lb}$$

$$\text{Power} = \frac{1800 \text{ ft-lbs}}{3 \text{ sec}} = 600 \text{ ft-lb/sec}$$

$$\text{hp} = \frac{600}{550}$$

$$\text{hp} = 1.09$$

The man develops about 1.1 horsepower.

### Friction

*Friction is the resistance to the relative motion of one body sliding over another.* Friction is important in our everyday lives. Without it we would have trouble walking, for it is the friction between our shoes and the earth that keeps our feet from slipping out from under us, which frequently happens when we try to walk on ice. In mechanical devices, however, friction is a liability rather than an asset, and in order for mechanisms to operate at maximum efficiency, friction must be held to a minimum.

In experiments relating to friction, measurement of the applied forces reveals that there are three kinds of friction. One force is required to start a body moving while another is required to keep the body moving at constant speed. Also, after a body is once in motion, a definitely larger force is required to keep it sliding than to keep it rolling. Thus, the three kinds of friction may be classified as *starting (static) friction, sliding friction, and rolling friction.*

STATIC FRICTION. When you attempt to slide a heavy object along a surface, it has to be broken loose first, and once in motion, it slides more easily. The breaking-loose force is, of course, proportional to the weight of the body. Let us consider F as the force necessary to start the body moving slowly, and $F^1$ as the normal force pressing the body against the surface. Also, the nature of the surfaces rubbing against each other must be considered. This factor is indicated by a coefficient of starting friction, which is designated by the letter k. This coefficient can be established for various materials and is often published in tabular form. Thus, when the load (weight of the object) is known, starting friction can be calculated by the use of the equation,

$$F = kF^1 \qquad (29)$$

For example, if the coefficient of sliding friction of a smooth iron block on a smooth, horizontal surface is 0.3, the force required to start a 10-pound block would be 3 pounds; a 40-pound block, 12 pounds.

Starting friction for objects equipped with wheels and roller bearings is much less than that for sliding objects. Nevertheless, a locomotive would have difficulty getting a long train of cars in motion all at one time. Therefore, the couplers between the cars are purposely made to have a few inches of "play." When the engineer is about to start the train, he backs the engine until all the cars are pushed together. Then, with a quick start forward, the first car is set in motion. This technique is employed to overcome the static friction of each wheel (as well as the inertia of each car). It would be impossible for the engine to start all of the cars at the same instant, for static friction—the resistance to being set in motion—would be greater than the force exerted by the engine. Once the cars are in motion, however, static friction is greatly reduced and a smaller force is required to keep the train in motion than was necessary to start it.

SLIDING FRICTION. Sliding friction is the resistance to motion offered by an object sliding over a surface—after the object has once been set into motion. It is always less than starting friction. The amount of sliding resistance is dependent on the nature of the surface of the object, the surface over which it slides, and the normal force between the object and the surface. This resistive force may be computed by the formula,

$$F = \mu N \qquad (30)$$

where F is the resistive force due to friction expressed in pounds, N is the force exerted on or by the object perpendicular (normal) to the surface over which it slides, and $\mu$ (mu) is the coefficient of sliding friction. (On a horizontal surface, N is equal to the weight of the object in pounds.) The area of the sliding object exposed to the sliding surface has no effect on the results. A block of wood, for example, will not slide any easier on one of the broad sides than it will on a narrow side (assuming all sides have the same smoothness). Therefore, area does not enter into the equation above.

Rolling Friction. Resistance to motion is greatly reduced if an object is mounted on wheels or rollers. The force of friction for objects mounted on wheels or rollers is called rolling friction. This force may be computed by the same equation used in computing sliding friction but the values of $\mu$ will be much smaller. For example, $\mu$ for rubber tires on concrete or macadam is about .02. The value of $\mu$ for roller bearings is very small, usually ranging from .001 to .003 and is often disregarded.

*Example:* A C-141A with a gross weight of 318,000 lbs is towed over a concrete ramp. What force must be exerted by the towing vehicle to keep the aircraft rolling after it has been set in motion.

$$\begin{aligned} F &= \mu N \qquad (31) \\ &= .02 \times 318{,}000 \\ &= 6{,}360 \text{ lbs} \end{aligned}$$