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EXPLORING IN AEROSPACE ROCKETRY
15. ROCKET MEASUREMENTS AND INSTRUMENTATION

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Lewis Research Center
Cleveland, Ohio

Presented to Lewis Aerospace Explorers
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1966-67

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ROCKET ENGINE PERFORMANCE

Expressions which describe the performance of rocket engines involve many variables which cannot be measured directly. These expressions must be written in terms of variables that can be measured. Three equations from chapter 2 will be used to demonstrate how expressions are written in terms of measured quantities.

Total Impulse

When the thrust F is multiplied by the time t during which the engine operates, total impulse I_t is the result. The equation

$$I_t = Ft \tag{1}$$

is simple and meaningful, for from it the final velocity for any given payload can be calculated. The two variables F and t can both be measured directly - thrust with a load cell and time with a clock.

Specific Impulse

The specific impulse is more difficult to determine than total impulse. In the equation

$$I_{sp} = \frac{F}{\dot{W}} \tag{2}$$

the term $\dot{W}$ is the weight flow rate of propellant in pounds per second. This flow rate consists of the weight flow rates of both the fuel $\dot{W}_f$ and of the oxidizer $\dot{W}_o$. Therefore,

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I_{sp} can be written as

$$I_{sp} = \frac{F}{\dot{W}_f + \dot{W}_o} \tag{3}$$

Still, the weight flow rates of the fuel and the oxidizer are almost as difficult to measure separately as combined. However, since weight flow rate is the product of the density ρ and the volume flow rate $\dot{V}$ in gallons per second, the equation may now be shown as

$$I_{sp} = \frac{F}{\rho_f \dot{V}_f + \rho_o \dot{V}_o} \tag{4}$$

The volume flow rates can be measured. The densities, although constant at standard temperature and pressure, must be corrected for the temperature and pressure existing at the time of firing. Fortunately, both temperature and pressure can be measured easily. These two parameters, along with thrust and volume flow rate, enable the specific impulse equation to be reduced into measurable quantities.

Characteristic Gas Velocity

The equation which describes the characteristic gas velocity

$$c^* = \frac{gP_c A_t}{\dot{W}} \tag{5}$$

introduces two new variables for measurement: chamber pressure P_c and throat area A_t. Of the other two factors in the equation, g (the acceleration due to gravity) is a constant, and $\dot{W}$ has already been determined. Chamber pressure can be measured directly; so can throat area, although only when the throat is cold. Therefore, the measurement must be corrected for expansion caused by hot exhaust gases. Consequently, the temperature of the exhaust must also be determined. The equation for characteristic gas velocity modified to include these variables is

$$c^* = \frac{gP_c \left(\frac{\pi d^2}{4}\right)_T}{\rho_f \dot{V}_f + \rho_o \dot{V}_o} \tag{6}$$

where $(\pi d^2/4)_T$ represents the throat area of the nozzle based on its diameter in feet and corrected for temperature.

Summary of Measurable Parameters

Once the equations defining typical characteristics of rocket performance have all been resolved into factors which are readily measurable (as in eqs. (1), (4), and (6)), instruments must be selected to measure thrust F, time t, volume flow rate $\dot{V}$, pressure P, temperature T, and diameter d.

MEASUREMENTS

Force

Strain gage. - The sensing element of many thrust and pressure instruments, the strain gage, relies on the changing electrical properties of a thin wire for its operation. The resistance R of any particular wire is directly proportional to its length L and inversely proportional to its cross-sectional area A. The equation for this is

$$R \propto \frac{L}{A} \tag{7}$$

If the wire is stretched, it becomes longer and its cross-sectional area becomes smaller; thus, the resistance increases. On the other hand, if the wire is compressed, its dimensions change in the opposite direction, and the resistance decreases. The change in

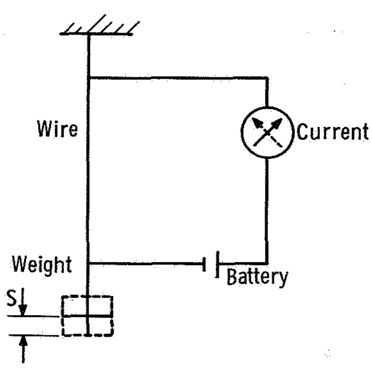

Figure 15-1. - Schematic of resistance change in a weighted hanging wire.

resistance, related to the force applied to the wire and measured with an ohmmeter, will indicate the magnitude of the force. Figure 15-1 shows this arrangement schematically.

Strain gages are not used singly but are arranged in a bridge circuit of four as shown in figure 15-2. This configuration allows the effect of the strain on the wires to be measured directly by a meter. In figure 15-2, the arrows indicate whether the forces are shortening or lengthening the wires. Note that when R1 and R2 get shorter, R3 and R4 get longer.

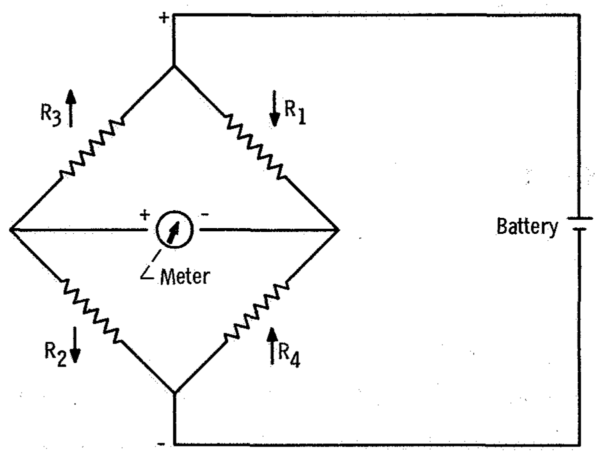

Figure 15-2. - Bridge arrangement of strain gages.

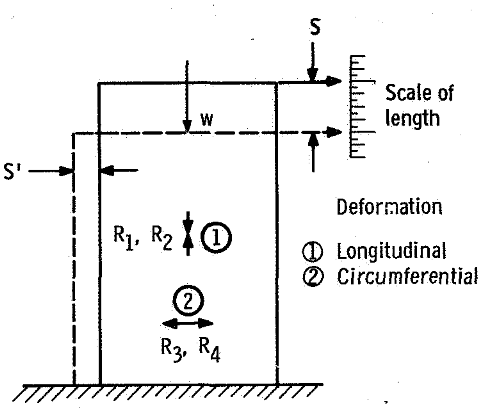

Figure 15-3. - Behavior of a spring under load.

Thrust. - Springs are important parts of both thrust and pressure transducers. A good spring is one that will deflect a given amount with a given load and reproduce the indication over a reasonable temperature range. Figure 15-3 shows the spring used in thrust transducers. The solid line shows the shape of the unloaded spring. When a load w is applied, compressing the spring, the length of the spring changes as indicated by the dotted line. The change of length S is determined largely by the spring material, and with a good spring this change is proportional to the load or force; that is, 1 pound produces 1 unit of deflection, 2 pounds 2 units of deflection, etc. As the sketch indicates, the compressed spring not only changes its length, but also changes its cross-sectional area. The amount of this lateral deformation S' is a material property related to S by Poisson's ratio

$$\mu = \frac{S'}{S} \tag{8}$$

whose value for metals is approximately 0.3; that is, S' = 0.3 S. The problem then is how to measure the deflections S or S', or both, of the spring.

The behavior of a strain gage under load is exactly like that of the spring; that is, the strain wire when loaded in tension increases its resistance because of both a change in length and a decrease in area. The strain gage can measure strains of about 0.0005 inch per inch. Consequently, strain gages are used. If a strain gage is installed on the spring in the orientation indicated in figure 15-3, then a compression of the spring will cause R1 and R2 of figure 15-2 to shorten, decreasing their resistance, and cause R3 and R4 to lengthen, increasing their resistance. The difference in resistances will then indicate the extent of deformation of the spring.

Thrust cells, springs with attached strain gages, are manufactured in many sizes to respond to a range of thrusts. Figure 15-4 shows some examples.

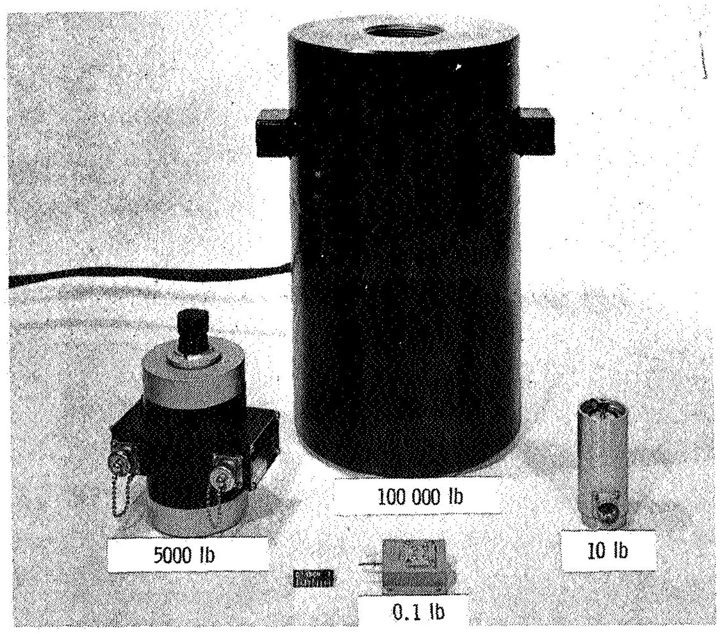

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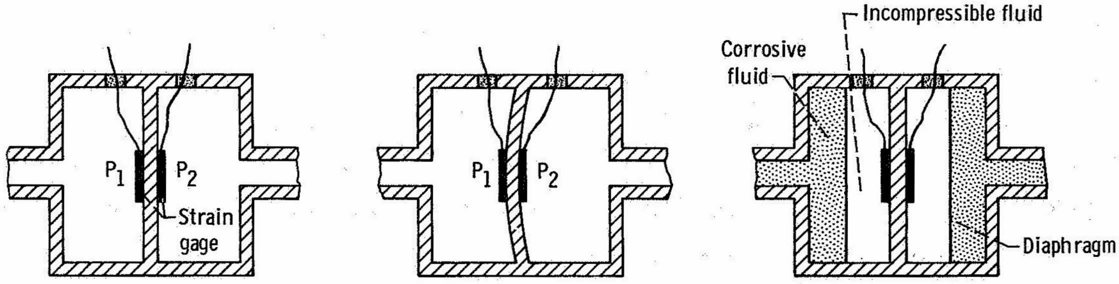
Figure 15-4. - Thrust cells.

Pressure. - Pressures are also measured with strain gages, but, since pressures range from a fraction of a pound per square inch to thousands of pounds per square inch, extremes of spring sensitivity are required. The configuration shown in figure 15-5(a) has equal pressures ($P_1 = P_2$) on both sides of the spring element. When pressure P_2 is made greater than P_1 the spring deflects to the left as shown in figure 15-5(b). This deflection is a measure of the pressure and, in turn, determines the output of the strain gages bonded to the spring.

The pressure gage illustrated in figure 15-5(a) is a differential gage and is of the



(a) $P_1 = P_2$. (b) $P_2 > P_1$. (c) For corrosive fluids.

Figure 15-5. - Schematic diagram of pressure transducers.

simple type in which the strain gages can be exposed to fluids whose pressure is being measured. In the case of corrosive propellants, such as fluorine, the strain gages must be put in suitable noncorrosive incompressible fluid and another diaphragm must be added as shown in figure 15-5(c). Absolute pressures can be measured by evacuating one side ($P_1 = 0$) and measuring the difference between it and another pressure (P_2). Figure 15-6 shows various types of strain gage pressure transducers.

Other spring configurations and deflection measuring schemes are used, and they vary in price from about $1.00 to $500.00, depending largely on the accuracy of the pressure gage.

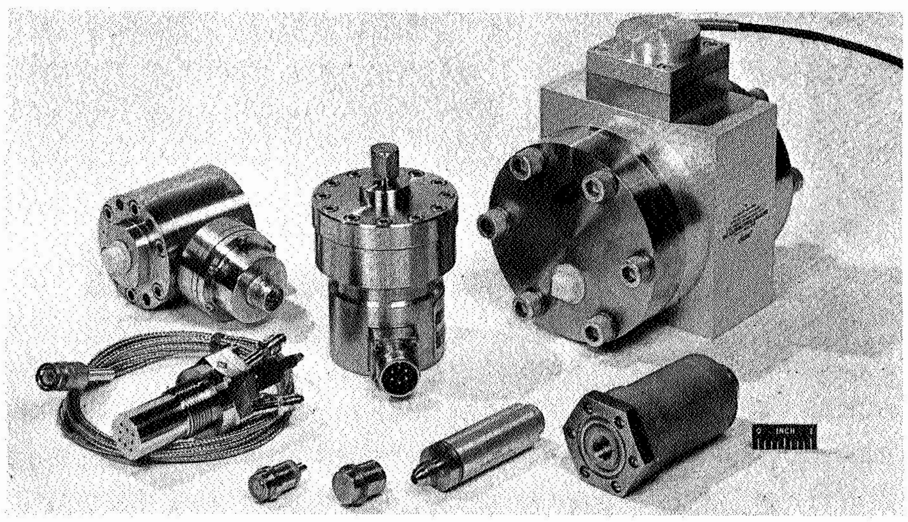


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Figure 15-6. - Commercially available strain-gage pressure transducers.

Temperature

Two devices extensively used to measure temperature are the thermocouple, which is the least expensive and can be made small in size, and the resistance thermometer, which is more accurate, more complicated, and larger in size.

Thermocouple. - The thermocouple is a useful device used to measure temperature. When two thermocouple alloys are joined as shown in figure 15-7, a voltage is generated

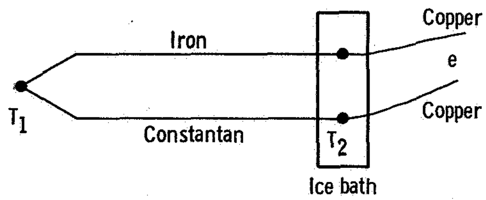


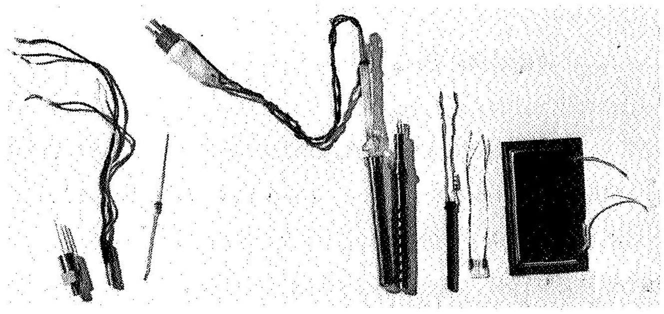
Figure 15-7. - Thermocouple.

which is a function of the difference of the temperature $T_1 - T_2$ between the two alloys. The temperature T_2 is usually controlled by placing that junction in an ice bath or other temperature controlled environment. The voltage e is then a function of the variable temperature T_1. National Bureau of Standards Circular 561 gives the temperature as a function of voltage for the following standard thermocouple alloys:

Chromel - Constantan
Copper - Constantan
Iron - Constantan
Chromel - Alumel
Platinum, 10 percent rhodium - platinum

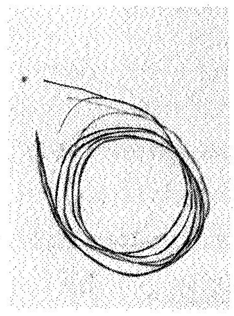
The various alloys are used because of the characteristics such as voltage output, strength, stability, and cost, as functions of temperature level. The voltages generated are approximately 0.000020 volt per degree; hence, good voltage measuring equipment is required. Millions of feet of thermocouple wire are used in this country each year.

Resistance thermometer. - The resistance thermometer is based on the material property which relates temperature change with resistance change. Metals are used for temperatures above 20° K (the temperature of liquid hydrogen), and semiconductors, usually called insulators, are used at temperatures below 20° K. The best metal, because of the purity to which it can be made, is platinum, but where less accuracy is required, nickel may be used. These metals, in the form of wire, are wound so that there will be no strain produced which would also cause a change in resistance. The re-

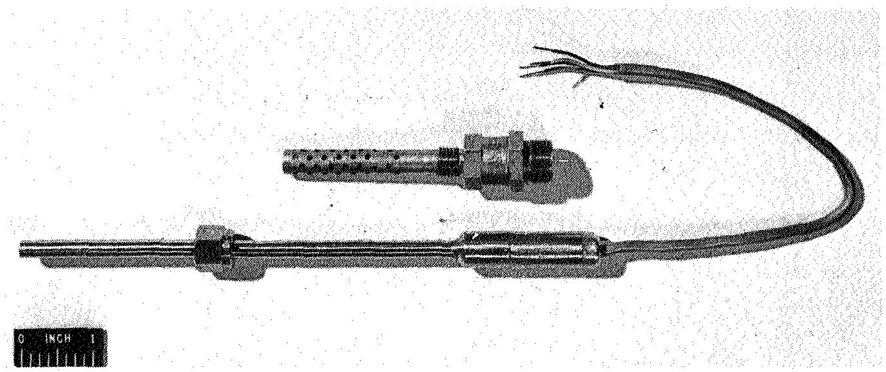


Semiconductor resistors

Metalic resistors



Thermocouple



Probes

Figure 15-8. - Temperature sensors.

sistance of metals increases as a function of temperature. The change of resistance (hence, change of temperature) is read with the same type of circuit used to measure strain (thrust, pressure) previously discussed and illustrated in figure 15-2, except that R_1, R_2, and R_3 are fixed resistors, and R_4 is the one whose resistance varies with temperature. Figure 15-8 shows platinum resistance thermometer elements along with probes suitable for insertion into a rocket-engine component. At temperatures near absolute zero, the change of resistance of metals becomes small and the thermometer looses its sensitivity. However, the resistance of semiconductors such as carbon and germanium increases with a decrease in temperature, and thus they function as resistance thermometers below the temperatures where metals loose their sensitivity.

Volume Flow Rate

Volume flow rate is most commonly measured by a volume displacement method. The gasoline we buy and the water we use are metered by this method. Another method of measuring volume flow rate utilizes the kinetic energy, or energy due to motion, of the fluid.

Volume displacement. - The simplest form of the volume displacement method is filling a known volume, emptying it, and counting the number of times this has been done.

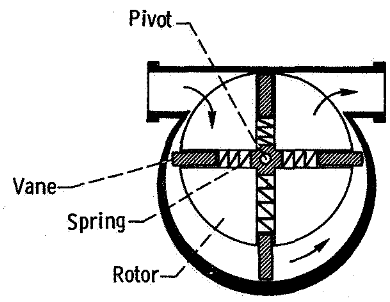


Figure 15-9. - Vane flowmeter.

More complex is the vane meter. This meter (fig. 15-9) has vanes which change length as a function of angle. Moved by the pressure of the fluid, the vanes rotate inside a casing, carrying between them a known quantity of fluid which discharges at the end of each revolution. The volume flow rate is proportional to the speed of rotation of the vanes. Many other devices operate in a similar way. These devices are usually inexpensive and accurate for a single fluid, but they do not work well with a variety of fluids.

Energy of flow. - When a fluid with a velocity v and a density ρ is stopped, it generates a pressure P greater than that which normally exists at that point in the fluid stream. This pressure due to the kinetic energy of the fluid is given by the equation

$$P = \frac{1}{2}\rho v^2 \tag{9}$$

The velocity v can be obtained in terms of the pressure P by rearranging the terms of equation (9)

$$v^2 = \frac{2P}{\rho} \tag{10}$$

or

$$v = \sqrt{\frac{2P}{\rho}} \tag{11}$$

Thus, as illustrated in figure 15-10, the velocity v in a pipe is determined by measuring the pressure generated by virtue of the kinetic energy of the fluid. Note that the velocity is not constant but goes to zero at the wall. The relations given hold only for incompressible fluids. Note that the pressure has to be measured across the diameter of the pipe. This is an accurate but time-consuming process.

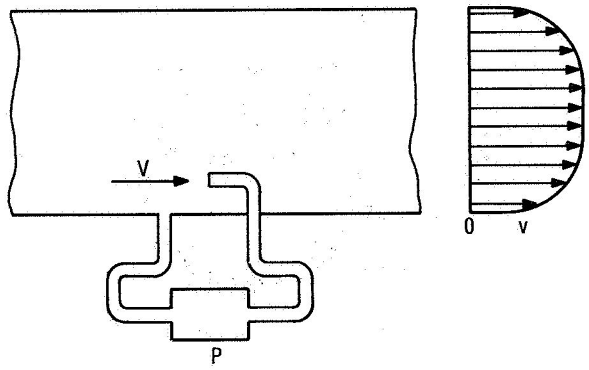


Figure 15-10. - Velocity flowmeter.

Nozzles and orifices utilize the same principle; flow of incompressible fluids of known density can be determined with one pressure measurement. This is made possible because a difference in pressure exists between the two sides of an orifice or nozzle which depends on the speed of flow through the constriction. This difference in pressure can be measured with a strain-gage differential pressure meter as shown in figure 15-11, and can be converted to volume flow.

The most useful device for measuring rocket propellant volume flow is the turbine meter. In this case the kinetic energy of the fluid causes a lightly loaded turbine to turn. The load on the turbine is bearing friction and a small amount of power required to measure the turbine speed. The turbine blade is made of magnetic material which, when it passes a coil-magnet combination, generates a pulse. The frequency of the pulses is a

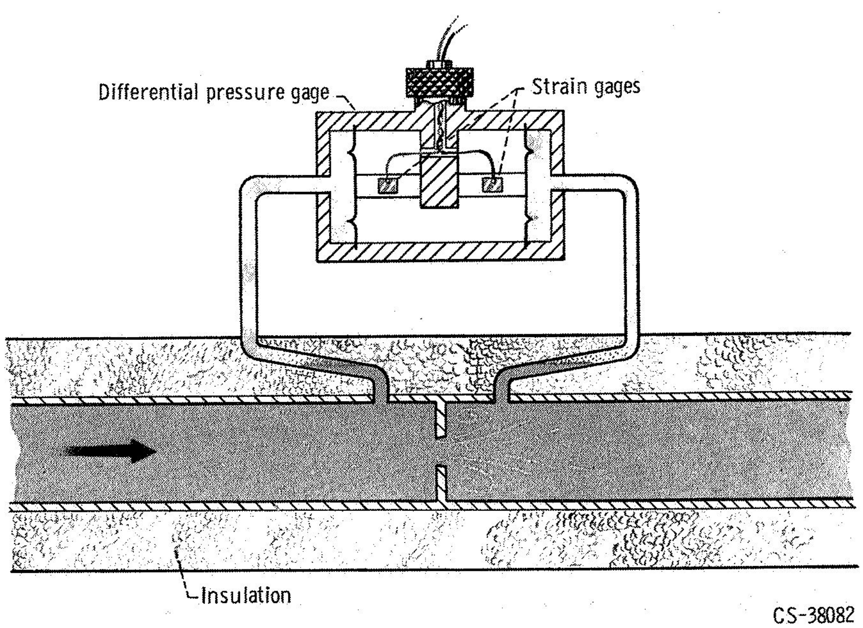


Figure 15-11. - Head flowmeter installation.

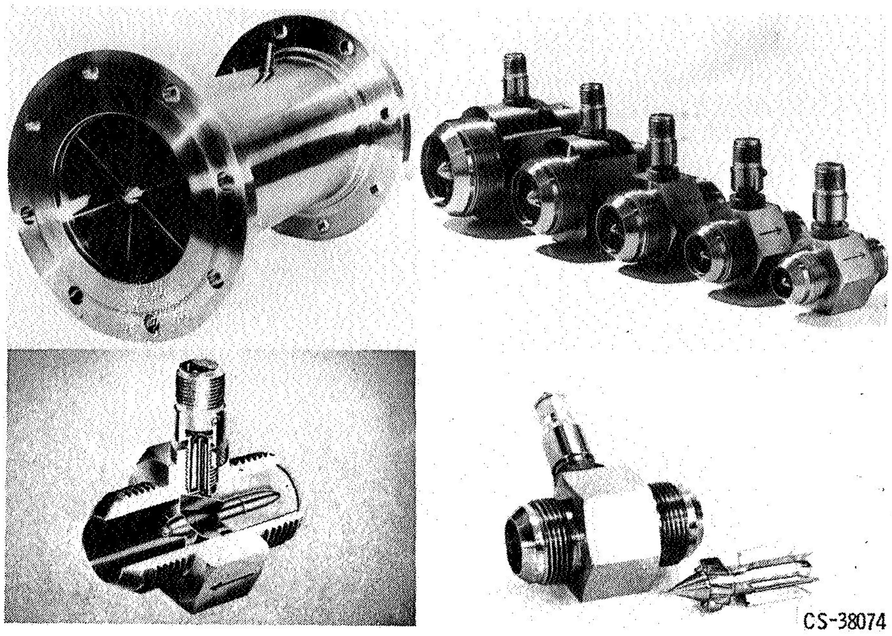


Figure 15-12. - Turbine flowmeters.

measure of turbine speed. These devices are calibrated with water and the same calibration can be used on most of the cryogenic and other fluids used in rocket testing. The calibration is expressed as pulses per gallon. Figure 15-12 shows the parts of the turbine meter, as well as a range of sizes.

The devices we have discussed to this point change some measured variable, such as temperature, to an electrical voltage. With modern data systems this is an essential requirement. Very little data is manually recorded; in fact, the data should be recorded on a system which allows computer entry, such as a digital tape-recording system.

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