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EMPIRICAL ROCKET DESIGN FORMULAS

Practical Formulas for the Reaction and Efficiency of Rocket Motors

The results of the proving stand tests conducted by the Experimental Committee during 1935 were highly gratifying in view of the absolute lack of precedence for making such tests. Three outstanding things were accomplished. The fundamental problems of rocket research were brought out quite clearly; empirical formulas for predicting rocket motor performance in actual flight were derived from the test data; and a standard test form was developed for comparing the performance of various motors by their thermal efficiencies.

I. Problems of Rocket Research

Probably the most important of these to the practical experimenter is the metal problem. The melting of the nichrome nozzles in the fourth series of tests made it pretty definite that the combustion temperature is well over 3000 degrees Fahr. Four methods of getting around this difficulty are being investigated: use of a metal like molybdenum or tungsten whose melting point exceeds that of the flame temperature; cooling the motor by circulating the fuels and the liquid-oxygen through its walls; use of a refractory such as carborundum for a lining; and injection of water to create a layer of insulating steam on the inner walls of the chamber and nozzle.

Other practical problems for the experimenter to work on were found to be: proper construction of the tanks and connections to withstand the high pressures while at the same time subjected to sharp temperature changes; methods of supplying a constant feed pressure as for example by the use of a small high pressure nitrogen tank with a reducing valve; and, in general, dependable apparatus for the continuous measurement of: the fuel and liquid-oxygen flow, the jet reaction, the tank and combustion chamber pressures, the exact flame temperature, the jet velocity, and the chemical analysis of the jet gases.

II. Empirical Rocket Design Formulas

For the past thousand years, the powder type of rocket has been manufactured by rule-of-thumb methods, handed down in certain families from generation to generation. A well-known fireworks manufacturer, upon seeing thrust curves and calculations showing that his best powder rockets developed only 2½% thermal efficiency said it was the first time in the fifty years he had been selling rockets that he had seen any such calculations. The explanation of this situation is no doubt that the limitations set by the use of gunpowder prevented the rocket's scientific development for any use other than the fourth of July type of firework it has been for centuries.*

The application of liquid-oxygen

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*Coast guard rockets and war rockets for projecting illuminating flares may be cited as practical applications, though very inefficient, thermo dynamically.

has changed the situation completely. Whereas combustion in the gunpowder rocket is uncertain and generally uncontrollable, combustion in the liquid fuel rocket can be controlled quite easily by valves. The liquids in themselves are not explosive, so that the rocket reaction motor is quite analogous to the ordinary internal combustion engine in this respect. A rational design of a liquid fuel rocket is consequently practical. The duplication of high jet reactions in test after test for like conditions clearly demonstrated this. By plotting all values of the jet reactions corresponding to various combustion chamber pressures, as shown in the typical motor performance curves published in the last three issues of *Astronautics*, the following fundamental relationship was obtained:

$$R = 1.55\ A\ P_c \qquad (1)$$

where R is the jet reaction in lbs, A is the area of the nozzle in sq. in., and P_c is the chamber pressure in lbs per sq. in. gage. For a ½ inch diamter nozzle (area .20 sq. in.) and 300 lbs. per sq. in. chamber pressure, this equation shows that 93 lbs will be the probable reaction.

A second empirical formula resulted when the average weight of liquids flowing into the motor during each run was plotted against the average combustion chamber pressure of the run.

$$w = .0135\ A\ P_c \qquad (2)$$

where w is the jet flow in lbs. per sec. Thus the flow of the liquids for the example can be calculated from this formula to be .81 lbs. per sec.

A third empirical formula was similarly found to show the drop in pressure between the feed tanks and the motor. This of course depends upon the length and size of the connections; for the proving stand setup this relation was:

$$P_c = 75\ P_f \qquad (3)$$

where P_f is the average of the two tank pressures, lbs. per sq. in. Therefore, for similar conditions, the feed pressure required to maintain 300 lbs. per sq. in. chamber pressure will be 400 lbs. per sq. in. in the tanks.

Combining Equations 1 and 2 gives a convenient relation between the jet reaction and the jet flow.

$$R = 115w \qquad (4)$$

Upon examination these formulas are seen to be based on an average jet velocity of 3700 ft. per sec., and an average thermal efficiency of about 7%. It is probable that the jet velocity was limited since the incomplete expansion in the nozzle made it little better than a simple orifice, where the maximum exit velocity is that of sound at the temperature and other conditions of the hot gases. Use of a constant feed pressure as contemplated in the new proving stand should increase this velocity since the nozzle expansion ratio will then be designed for a definite chamber pressure. As soon as additional data is available, these formulas will be checked and the coefficient revised, if necessary.

III. Thermal Efficiency of Various Rocket Motors

Convenient formulas can be derived for expressing the jet velocity and the thermal efficiency of a rocket motor in terms of the reported test data. Newton's famous 2nd Law of Motion states that a force, F, equals the mass, m, times the acceleration, a, which the application of the force produces on the mass. Now consider that the jet velocity, c, is reached after one second's acceleration of the mass of ejected gases that would flow out in one second. This acceleration must obviously have been produced by a force *acting in the same direction,* which is equal to the mass times the acceleration. Then since the velocity after one second is numerically the same as the acceleration in one second, it is evident that this force also equals the mass flow in one second times the jet velocity. (Check this by the Theory of Dimensions.)

The next step in the derivation of the fundamental formula for reaction is based on Newton's 3rd Law; to every force, or action, there is an equal and opposite *reaction.* Therefore, the force acting on the gases to eject them away from the rocket has an equal and opposite reaction which acts on the rocket, thus driving it *forward.* Stated mathematically, $F = R = mc$. Shifting the terms of this equation so that the unknown jet velocity, c, is on the left, and the measurable quantities, R and m (or its equivalent w/g) are on the right of the equality sign:

$$c = R/m = \frac{Rg}{w} \qquad (5)$$

where w, the flow in ℔s. per sec. is obtained approximately by dividing the total liquid input by the time of combustion in seconds, if no continuous flow meter is available. ("g" is the acceleration of gravity, taken as 32 ft. per second per second.)

Having this jet velocity, it is then a simple matter to calculate the jet kinetic energy output, which is $\frac{mc^2}{2}$ Dividing this result (ft. ℔s. per sec. output) by the heat or "thermal" energy contained in the fuel-liquid-oxygen mixture (ft. ℔s. per sec. input) gives the thermal efficiency of the motor. This reduces to:

$$E_{th} = \frac{c^2}{2g\ H} \qquad (6)$$

where E_{th} is the thermal efficiency of the rocket motor (combustion chamber and nozzle) and H is the heat content of the explosive mixture per pound, in ft. ℔s.

Table I shows the jet velocity and thermal efficiency calculated for various motors by substituting the reported test data in Equations 5 and 6. The data for Dr. Goddard's motor can be found on page 5 of his March 16th report to the Smithsonian Institution. The data for Mr. Shesta's motor (the one reported in the table was the best of about 25 runs with similar motors) can be found on page 5 of the writer's technical report of the August 25, 1935, tests in the March, 1936, issue of *Astronautics.* Mr. Ley's motor data is also given in this report. The data for Oberth's famous "Kegelduse" type rocket motor can be found on page 7 of "The Story of European Rocketry", by Willy Ley, in the October, 1935, issue of *Astronautics,* and the data

Table I. Rocket Motor Efficiencies

Investigator	Jet Reaction, lbs.	Time of run secs.	Jet Flow lbs. per sec.	Jet velocity ft. per sec.	Kind of Fuel	Energy input per sec ft. lbs. (thous.)	Average Thermal efficiency of run %
(a) Liquid Fuels with Liquid Oxygen							
Dr. Robert Goddard	220	20	1.40	5000	Gasoline	4600	12.0
American Rocket Soc. (Motor by John Shesta)	47	16	.35	4350	Alcohol	1100	9.4
American Rocket Soc. (Motor by Willy Ley)	36	14	.37	3100	Alcohol	1180	4.7
Prof. Dr. Ritter (Motor by Hermann Oberth)	15	90	.17	2880	Gasoline	353	6.3
(b) Liquid Fuel with Gaseous Oxygen							
E. Sanger	55	1200	.18	9800	Oil	620	43.6
H. Bull	2	56	.012	5400	Gasoline	39	13.7
(c) Liquid Fuel with Atmospheric Air							
Armengaude-Lemale (Gas turbine jet)	4	no limit	.032	4000	Gasoline	148	5.4
G. P. Warren	38	2700	.324	3790	Gasoline	234	33
(d) Powder Rockets							
L. Damblanc	95	4.0	1.66	1780	Gunpowder	1680	5.0
A. Africano and P. van Dresser	27	1.12	.67	1300	Gunpowder	670	2.6

for all the other motors but one can be found in Mr. van Dresser's article on "The Rocket Motor", in the March, 1936, *Astronautics.*

In the case of Sanger's motor there is some question as to his jet velocity and the resulting thermal efficiency since he used a heavy Bosch fuel pump to give a feed pressure of about 2200 lbs. per sq. in. The energy input due to the pressure may not be negligible in this case as it was assumed to be for the motors with the low nitrogen-pressure fuel feed.* For the other motors, the results are fairly reliable, and will serve as a simple index of the expected motor perfomance in an actual flight.

— Alfred Africano, M. E.

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*Arrangements are being entered upon to permit of satisfactorily complete reports of Dr. Sanger's researches in a coming issue of Astronautics. — Editor.

ROCKET MOTOR TESTS OF OCTOBER 20, 1935

In the fourth series of tests conducted by the Experimental Committee at Crestwood on October 20, 1935, the procedure and general results were similar to those reported for previous tests in *Astronautics.* However, for the first time the nichrome nozzles which had already been used successfully, burned out after 10 to 15 seconds of firing. A new and especially massive one, with walls ⅜ inch thick, resisted the firing no better. This was taken as proof

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THE HISTORY OF THE REP-HIRSCH AWARD

Translated from an Account Prepared for Astronautics*

For some years past, a French engineer, Robert Esnault-Pelterie, whose scientific researches have been numerous and varied, and who is above all known to the American public for his work in avaition, has particularly interested himself in the many problems tied up with interstellar navigation.

As early as 1912, he presented a lecture to the French Physical Society under the title, "Considerations concerning the results of lightening motors to an indefinite extent", in which he presented in public his personal views on the subject.

Renewing and developing his thesis, he gave, in 1927, another lecture at the Sorbonne in Paris (under the auspices of the Astronomical Society of France) and later published this lecture in a pamphlet entitled, "Rockets and the Possibility of Interplantary Voyages".

Although in 1912 the most optimistic of his audience had called him a "dreamer", in 1927 he felt that the public listened with much more sympathy and comprehension.. The reverberations of this lecture were quite considerable; they resulted in bringing to the knowledge of Mr. Esnault-Pelterie that in addition to Professor Goddard, a number of other investigators had already been deeply interested in this new science of "astronautics".

Having discussed the matter with one of his French friends, Mr. Andre Hirsch, who had a similar interest in it, they agreed to found an annual award to stimulate research and reward serious scientific work leading towards the solution of any of the numerous problems connected with interstellar navigation — in other words, the science of astronautics. In this way there was founded, in 1928, the new International Astronautical Award (Prix REP-HIRSCH).

Desiring that the distribution of their award should be as authoritative as possible, they placed it under the *aegis* of the French Astronomical Society, which seemed the best qualified organization in the country. An Astronautical Committee was formed to receive and study the papers submitted; this Committee transmits a report to the Astronomical Society which accords the prize.

The first Astronautical Committee was organized under the presidency of General Ferrie, the well-known radio expert, member of the Academy of Sciences, and included six members of this distinguished group. Unfortunately this president and several other members soon after were called away; at present the membership is as follows:

President, E. Fichot; Vice-President, Jean Perrin; H. Deslandres, G. Urbain, Ch. Fabry, A. Caquot, P.

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*The present REP-Hirsch Award is to be announced this month, and an account of the history of this institution is therefore of current interest. — Editor.

Langevin (all members of the Academy of Sciences); Ch. Maurain, Doyen of the Faculty of Sciences; E. Esclangon, Director of the Paris Observatory; H. Chretien, Professor at the College of France and the Institute of Optics; Jos. Bethenod; A. Lambert, Astronomer at the Paris Observatory; Charbonnier, Marine Engineer-General; Em. Belot; Dr. A. Bing, and the donors, Robert Esnault-Pelterie and Andre Hirsch.

It can be seen that this committee still represents very great French scientific authority.

The REP-HIRSCH Award was allotted for the first time, in 1928, to Professor Hermann Oberth for his work "Die Rakete zu den Planetenraumen", published in 1923. In this work, which was at its time greatly in advance of all others, the author pointed out the possibility of raising the exhaust velocity of rocket gases to some 4000 meters a second through practical methods; from this fact he had shown the way to lower the ratio of masses (initial mass over final mass) of a rocket from about 500 to 25, thus bringing much closer the possibility of building a rocket able to escape from terrestrial attraction.

In addition to this important consideration, he had studied the question of most favorable velocities for an interplanetary vehicle; had foreseen the danger of heating at the return to earth; had studied, in addition to the hydrogen rocket, the alcohol rocket.

This contribution to the science was judged so important that not only was the REP-HIRSCH Award allotted to Professor Oberth, but the donators doubled its value for this year.

In 1929 no work worthy of interest having been submitted by the appointed time, no award was made.

In 1930, the recipient of the prize was a French engineer, Mr. Pierre Montagne, former student at the Polytechnic School, Assistant at the National School of Mines; the paper he submitted had for title; "A Study of gaseous mixtures utilizable in the propulsion of rockets". It is a purely theoretical study of the chemical equilibriums and the temperature of the gases within a combustion chamber under constant conditions.

This considerable work makes possible the calculation in a very precise fashion of the reactions which take place under a given pressure in the motor of a rocket fed by liquid propellants.*

In the years 1931, 1932, the REP-HIRSCH Award was not competed for.

In 1933, the Award in its original form, was not given out; however Mr. Montagne was honored by a renewal of the "First Prize" without allocation, for the pursuit of his studies of chemical equilibriums and their relation to rockets; and a young Polish engineer, Mr. Ary Sternfeld, having presented a work worthy of interest received a prize of encouragement with a sum of two thousand francs. His work was entitled "Initi-

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*A summary of M. Montagne's work appears in Chapter V of M. Pelterie's "Complement d'Astronautique". It is published in full by Gauthier-Villars, 55 Quai des Grands- Augustine, Paris, 6e. — Editor.

THE PROBLEM OF ROCKET FUEL FEED

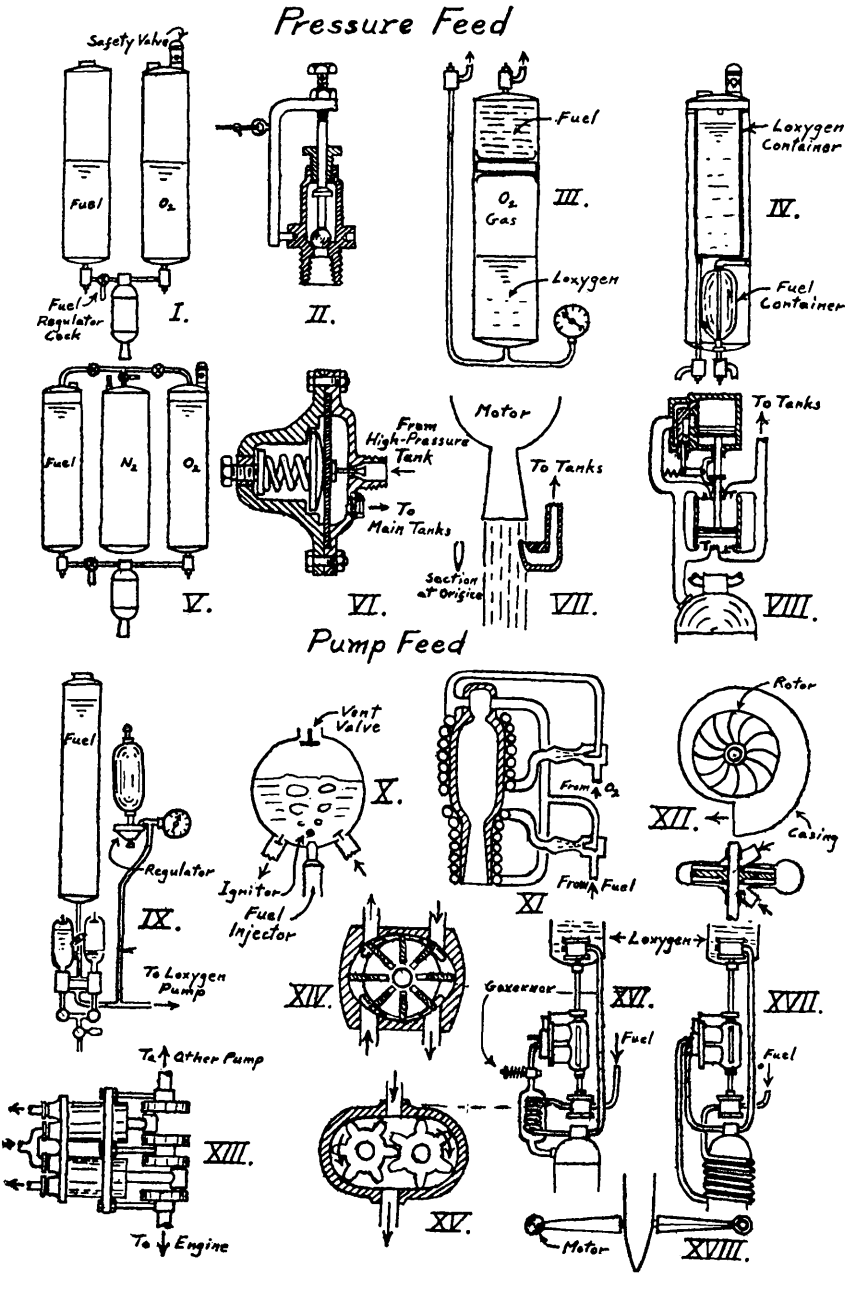
The feeding of propellant to the combustion chamber of a liquid-fuel rocket presents many and complex problems. A succesful fuel-feed system must feed large quantities of fuel in accurately metered amounts at high pressure and under wide temperature extremes, and must be rapid and dependible in its action, besides being light and reasonably simple to construct, operate or repair. Many mechanical difficulties must be surmounted, such as frosting up of loxygen lines, back-firing, overheating of parts near motor, vapor-lock effects, and lubrication and adjustment of any moving parts.

Numerous fuel feed methods have been suggested. They may be roughly divided into two classes: *pressure feed,* in which the fuel is blown out into the combustion chamber by gas pressure in the fuel tanks, and *pump feed,* in which the fuel tanks are at atmospheric pressure and the fuel is fed by a pump of some kind.

The "classic" type of fuel feed, first used by Pedro Paulet in 1895 and later employed by Goddard, the Verein fur Raumschiffahrt, and the American Rocket Society, etc., is the familiar two-tank pressure system. (I.) Here the pressure in the loxygen tank is built up by the oxygen gas as it boils off, while high-pressure nitrogen (or sometimes carbon-dioxide) is injected into the fuel tank. The propellants are allowed to blow off thru the feed lines into the combustion chamber when the fuel valves are opened. The type of valve used by our own Society (II.) was designed by Mr. John Shesta. When the C-clamp shown is pulled off by a long cord, the spindle rises and rests on its ground, leak-proof seat, while the ball below it acts as an anti-backfiring check valve.

Despite its simplicity and reliability, the two-tank system has the serious disadvantage that the fuel-tank pressures are entirely independent of one another, so that if one pressure decreases faster than the other a disproportion in the feed-rates of the loxygen and the fuel quickly arises. This is especially true if the tank pressures are not much in excess of the chamber pressure, since it is the *difference* between tank and chamber pressure that determines the feed rate. Examination of the results of the 1935 motor tests shows that considerable variations in the mixture proportions must have occurred during a single run; the changes in flame coloration observed support this conclusion. Obviously too rich a mixture results in waste of fuel, while too lean a mixture causes excessive oxidation of the motor and nozzle.

One method of getting around this difficulty is to apply the same pressure to both tanks. The simplest method is to connect a pressure by-pass tube between the two tanks; but this is very dangerous, as an explosive mixture of oxygen and fuel vapor may readily form. Floating a film of non-volatile oil on top of the fuel in


Pressure Feed
Safety Valve
Fuel
O₂
Fuel Regulator Cock
I.
II.
Fuel
O₂ Gas
III.
Loxygen
Loxygen Container
IV.
Fuel Container
Fuel
N₂
O₂
V.
From High-Pressure Tank
To Main Tanks
VI.
Motor
To Tanks
Section at Orifice
VII.
To Tanks
VIII.
Pump Feed
Fuel
Regulator
IX.
To Loxygen Pump
Vent Valve
X.
Ignitor
Fuel Injector
From O₂
From Fuel
XI
Rotor
XII.
Casing
XIV.
Loxygen
Governor
XVI.
XVII.
Fuel
Fuel
To Other Pump
XIII.
To Engine
XV.
Motor
XVIII.

order to avoid evaporation might serve as a preventive measure, and various schemes involving pistons or diaphragms have been proposed. One clever idea (by Carver and Pierce, in their proposed "Rocket No. 5") is shown in Fig. III; the piston is pressed up against the fuel by the oxygen gas in the lower part of the tank, which thus feeds both fuel and loxygen. Another arrangement (IV.) employs a flexible rubber or oilcloth container for the fuel, subjected externally to the gas pressure developed by the boiling loxygen.

Still another plan (employed by Prof. Goddard and others) is to use an entirely separate tank for the nitrogen gas and introduce it into both of the other tanks thru check valves (V.). This is a great improvement over the two-tank system but is rather more complicated and heavy, though quite foolproof.

All of the previously mentioned arrangements have the defect of having a large gas-filled clearance space in the tanks, which increases the size and weight of the tanks and hence of the whole rocket. Since this gas space cannot be cut down without causing a great drop in feed pressure during the firing period, auxiliary contrivances have been suggested for maintaining pressure in the tanks. One plan (which is to be used on the Society's new proving stand, now being built by Mr. Shesta) is to use a small high-pressure tank for the nitrogen, and expand the latter down from some 2000 pounds per square inch to normal tank pressue thru a reducing valve such as is used in oxy-acetylene apparatus. The principle of such a valve is shown in Fig. VI. The metal diaphragm shown is forced out against a strong spring by the gas pressure in the diaphragm case, thus seating a tapered pin or stem attached to the diaphragm. If the pressure falls, the spring pushes the diaphragm in, unseating the stem and allowing gas to enter from the high-pressure tank, till normal pressure is restored. The fuel and loxygen tanks are supplied with gas from the regulator thru check-valves. This arrangement both reduces the size of the rocket and maintains constant pressure in the combustion chamber thruout the run.

Oberth has suggested that small quantities of fuel might be injected into the oxygen tank and burnt there, thus developing pressure; but this seems very dangerous and uncertain. Various chemical devices (on the principle of an acetylene generator, for instance, or utilizing "dry ice" or liquid nitrogen) might be used, but would be complicated and heavy. Electric heating coils immersed in the loxygen, worked by small batteries, have also been thought of. Another idea is to pass part of the loxygen or fuel or both thru a boiler coil heated either by the motor or by a small auxiliary burner. It is interesting to note that a device of this kind was used on the first liquid-fuel rocket ever built and fired (by Prof. Goddard in 1926).

Another source of high-pressure gas might be a small Pilot tube projecting into the stream of high-velocity exhaust gas (VII). This is attractively simple; but the tube would be very liable to melt off, and would produce a considerable drag on the rocket.

The pressure in the rocket motor might be tapped off and boosted a few pounds by means of a little compressor driven by any of the prime movers discussed later in this article; for example, by means of the motor pressure in a power cylinder (VIII).

The fundamental difficulty with pressure feed, common to all the previous devices, is the weight of the tanks, owing to their having to stand the full chamber pressure of two hundred pounds or more per square inch. The high pressure also is apt to cause leaks and involves difficulty and danger in charging up and starting the rocket. For larger rockets in particular, some sort of pump feed seems very desirable. Very little practical work has been done along this line, aside from some interesting experiments by Goddard several years ago — about which, however, little is known. The theoretical advantages of pump feed are obvious — light weight, safety, constant and high feed pressure, and compactness. On the other hand, pump systems would be more complex in construction, operation, and control, expensive, and probably less reliable, and would require rather elaborate arrangements to start them.

The simplest type of pump is the "pulsometer" type, in which fuel is admitted to a small pump chamber thru a check valve, then gas pressure is applied and the fuel is blown out thru an outlet valve into the motor. The pressure is then turned off and a vent opened; more fuel is admitted and the cycle is repeated. Such a device may be operated from a compressed-gas tank (IX.) or fuel might be injected into the pump and burnt there to build up pressure, as Oberth proposes (X). A small piston-compressor or any of the other pressure-generators already suggested might likewise be employed. All these pulsometer-feed arrangements, however, are complex and intermittent in their action and suffer from all the fuel-metering difficulties of pressure-feed in an exaggerated form; and the saving in weight due to their use is problematical, especially since multiple units must be used.

An intriguingly simple type of pump feed is shown in Fig. XI. The fuel and loxygen are vaporized in waste-heat jackets surrounding the motor, thus keeping the latter cool. Most of the vapor is burnt in the motor as fuel, but part of it is tapped off to operate small feed injectors similar to ordinary steam injectors, which pump fuel from the tanks into the vaporizing jackets. Unfortunately this device would involve serious difficulties in starting and in governing the flow of fuel; but it is so light and simple and serves so many ends at once that is seems well worth an experimental trial.

If we turn to the use of mechanical types of pump we must consider first the possible varieties of pump and secondly the necessary prime movers. A centrifugal pump (XII) might be used; it is simple and reliable, but would have to operate at very high speed and with several rotor "stages" in series to develop sufficient pressure. Moreover, it would not be positive-acting and hence would involve fuel-metering difficulties. Piston pumps (XIII.) will readily develop the necessary pressures but are limited as to speed by the difficulty of getting their valves to work sufficiently fast. Rotary pumps such as the Vickers pump (XIV.) or gear pump (XV.) are simple, light, positive-acting, run at high R. P. M., feed continuously, and can be made to work well at high pressure, but must be very accurately made to avoid leakage. The gear pump appears to me to offer the best possibilities of any type of pump.

It might be mentioned here that no serious difficulty would occur in lubricating such a pump. Ordinary oil (or graphite, if gasoline is used for fuel) would serve for the fuel pump, and the loxygen itself would lubricate the other pump (as in the Claude expansion engine used in liquid-air plants). The loxygen pump would be immersed in the loxygen tank to avoid boiling of the loxygen in the pump.

Among the many possible prime movers are electric motors, flywheels, airscrews, spring motors, rocket motor recoil, gas or steam turbines, and compressed-air, gasoline, or steam engines. Electric, spring, or flywheel motors are very heavy in comparison to their power and would be inadequate except for shots of very short duration. Airscrews create a large air-resistance and would be difficult to govern or to start. Recoil devices require intermittent action of the rocket motor with consequent inefficiency. Gas turbines, operating either from the rocket exhaust or from an auxiliary jet, involve very great mechancial problems and would have to be geared down, besides being hard to start or control; and similar objections apply to steam turbines, which also (together with reciprocating steam engines) require a waste-heat boiler and water tank. Gasoline engines are light and fairly simple but would require supercharging arrangements or an auiliary air or oxygen supply in order to work at great altitudes. Compressed-air engines would require a heavy air-tank, unless operated by gas tapped off from the rocket motor and passed thru an intercooler on the outside of the rocket or in one of the fuel tanks or feed lines (XVI). This is probably as simple and reliable a device as any, and could easily be started on the ground by a compressed-air fittting mounted on the launching rack. Suitable engines have already been built for model speedboat flash-steam plants, working on very superheated high-pressure steam.

Another possibility is to generate alcohol vapor at high pressure in a waste-heat boiler, and expand it down to chamber pressure thru an engine driving the feed pumps. But this offers starting and control difficulties.

Finally, an ingenious scheme has been suggested by various inventors for what may be termed a "rotor-motor" (XVIII). Two small rocket motors are mounted at the tips of a small propellor, and the feed pressure is developed by the centrifugal force acting on the fuel in the feed-lines inside the blades. The rocket starts its flight as a helicopter, and as its speed increases an automatic variable-pitch mechanism in the body of the rocket gradually increases the blade angle, so that at a great altitude the motors are only inclined from the vertical sufficiently to maintain the rotation and keep the fuel pressure up. This device obviously has great mechancial difficulties, but it so ingeniously solves so many problems at once (including that of providing a good velocity-ratio efficiency at low rocket velocities) that it is to be hoped it will soon be given an actual trial.

It appears at the present time that the most promising plan for rockets of the near future is the three-tank pressure system, with high-pressure tank and regulator. As motor efficiencies are improved, and larger rockets constructed, pump feed will undoubtedly be resorted to in an effort to reduce the rocket size and weight. Probably gear pumps operated by a compressed-air engine worked by combustion-chamber pressure will prove the most satisfactory arrangement. The rotor-motor will doubtless also find extensive use, especially for the "starting step" of large multi-step rockets.

The ideas suggested in this article are of course largely tentative, and many minor details have necessarily been omitted. It is hoped, however, that they will lead to profitable discussion.

— **J. H. Wyld**

The History of the REP-Hirsch Award

(concluded from page 7)

ation to Cosmonautics".

Mr. Louis Damblanc, a French engineer, presented in 1934 a work entitled "Auto - propulsive Explosive Rockets—Proving Stand Tests—Application of the experimental results to the study of their movement", for which the Astronautical Committee awarded him a prize of encouragement with the sum of two thousand francs. This paper contained the results of proving stand tests made by the author with powder rockets.*

It is evident from this brief account that the distribution of the REP-HIRSCH Award for Astronautics recompenses work of real scientific or practical value, and though the amount of the prize is not very great, the composition of the judging committee gives it a very considerable moral value.

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*See Astronautics, No. 33, pages 16, 17.

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that either the flame temperature was well above 2700 degrees F. (the melting point of nichrome) or inaccuracies in the metering of the fuel and oxygen permitted an excess of the latter to come in contact with the metal of the nozzle and burn it out after the manner of a cutting torch. Some difficulty was also experienced with ice and sediment in the oxygen feed line, and a new fuel port ar-

(concluded on page 20)

THE LAWS OF ROCKET MOTION

There is discussed in this memorandum the fundamental equations for use in the calculation of rocket trajectories. The formulas given assume a stationary earth with no wind. The nomenclature and methods used in exterior ballistics are applied; especially as regards air resistance. The formulas are general in their application. A discussion of the factors involved will follow.

A rocket may or may not have an initial velocity. The rocket will receive an acceleration from its motor during the first part of its flight. Air resistance acts thruout the entire trajectory.

Fundamental Equations

Consider the rocket at any point P, t seconds after leaving the earth's surface at N, then from Figure 1;

$$x' = \frac{R}{R+y}\, v \cos O \quad \text{and} \qquad (1)$$

$$y' = v \sin O \quad \text{where} \qquad (2)$$

x = the range to P measured along the curved surface of the earth

y = the height of P above the surface of the earth

v = the velocity

O = the inclination of the trajectory to the horizontal

R = the radius of the earth

and primes denote derivatives with respect to time. These formulas are independent of any retardation or acceleration effects present.

The relations for retardation and acceleration effects are:

$$\frac{d(v \cos O)}{dt} = -E v \cos O + f \cos O \qquad (3)$$

$$\frac{d(v \sin O)}{dt} = -E v \sin O - g + f \sin O \qquad (4)$$

Eliminating cos O from 1 and 3 there results;

$$x'' = -E x' - \frac{x' y'}{R+y} + f \frac{x'}{v} \qquad (5)$$

Likewise from 2 and 4;

$$y'' = -E y' - g + f \frac{y'}{v} \qquad (6)$$

The intensity of gravity at altitude y is expressed in terms of gravity at altitude zero by;

$$g = g_0 \frac{R^2}{(R+y)^2} \qquad (7)$$

Expressions for the velocity and inclination are:

$$v^2 = (y')^2 + (x')^2 \frac{(R+y)^2}{R} \qquad (8)$$

$$\tan O = \frac{y' R}{x'(R+y)} \qquad (9)$$

Air Resistance

E v is the retardation of the rocket due to air resistance. E. is a function of the rocket's shape and weight, its velocity and the density of the air.

$$E = \frac{G H}{C} \qquad (10)$$

G is a function of the velocity alone. H is the ratio of air density at altitude y to the density at elevation zero.

$$H = a(10)^{-hy} \qquad (11)$$

Up to an altitude of 10,000 meters

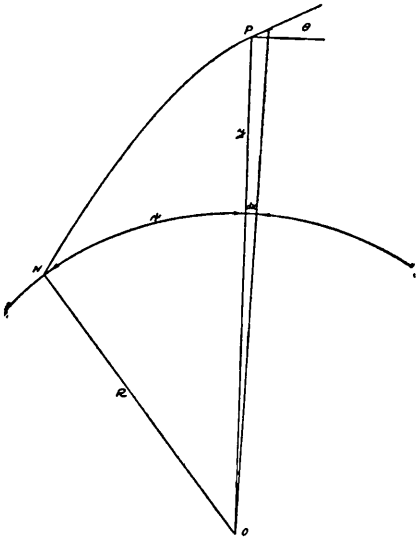

Figure 1

a = 1 and h = 0.000045
Above 10,000 meters

a = 1.5849 and b = 0.000065
(These constants are for y in meters). C is the ballistic coefficient of exterior ballistics.

$$C = \frac{w}{i\,d^2} \quad \text{where} \qquad (12)$$

w is the weight of the rocket in pounds, i is a coefficient depending on the rocket's shape and d is the maximum diameter of the rocket in inches.

Acceleration*

Rockets using reaction gas jets for their propulsion will be considered here. Let F be the thrust delivered to the rocket and z the weight of gas flowing per second after any time t. Considering the flow as in the critical range then;

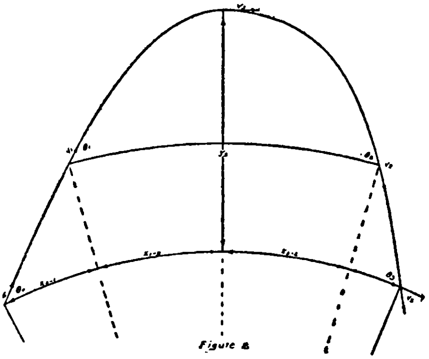

Figure 2

$$z = j\frac{A\,R}{R \div y}\sqrt{\frac{P}{V}} \qquad (13)$$

and,

$$F = k\,A\,P\sqrt{1-\left\{\frac{p}{p}\right\}^{\frac{n-1}{n}}} \qquad (14)$$

w is given by;

$$w = w_0 - \int_0^t z\,dt \quad \text{where} \qquad (15)$$

P = the absolute chamber pressure
V = the chamber specific volume
p = the atmospheric pressure
w_0 = the initial weight of the rocket
A = the area of the nozzles
n = a gas constant

and j and k are constants depending on the efficiency of the system.

Since critical flow only is considered, P and V become functions of the time alone. Each rocket motor would be rated by plotting P and V against time for a particular fuel loading. The acceleration is given by,

$$f = \frac{F\,g}{w} \qquad (16)$$

Formulas (13) and (14) are theoretical and need not fit the actual conditions such that j and k will be constant thruout the range of P.

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*See Astronautics, No. 30, pages 7-11.

Empirical equations will no doubt replace (15) and (16) as testing proceeds.

p is a function of the altitude in the form;

$$p = b\,(10)^{-hy} - c \qquad (17)$$

All of the factors involved in equations (5) and (6) are now evaluated as functions of y, v and the characteristics of the particular rocket at hand. Equations (5), (6), (7), (8), and (9) may now be used to calculate the entire trajectory. It is logical this be accomplished by numerical integration methods.*

A Method For Tables

The powered portion of a rocket's trajectory will be on the ascending branch and most logically under the 10,000 meter level. Call this region Zone I. Zone II will refer to that region above 10,000 meters. With this consideration and a view to simplicity the following is suggested as a method for tables.

Considering first that portion of the trajectory within Zone II. v_1 is the velocity, and O_1 the angle of inclination at the 10,000 meter level. (Figure 2). Combining H with C there results;

$$\log C = \log C_k + h\,y - \log a \text{ and}$$

$$\log C_1 = \log C_k + 0.45000 \qquad (18)$$

Also note that, $C_1 = C_2$, $C_k = C_3$ &

$$\log C_s = \log C_k - 0.20000 + 0.000065\,y_s \qquad (19)$$

Two tables would be desirable; one to give values of y_s v_s $x_{1\text{-}s}$ and $t_{1\text{-}s}$ for arguments of v_1, O_1, and C_1 ; another to gives values of v_2 , O_2 , $x_{s\text{-}2}$ and $t_{s\text{-}2}$ for arguments of y_s , v_s and C_s . These tables would allow several points to be located on the trajectory. This is the method employed by the Ordnance Department.

Tables may also be built to give $x_{2\text{-}3}$, v_3 , O_3 and $t_{2\text{-}3}$ for entries of v_2 , O_2 , and C_2 .

With tables as outlined above only that portion of the trajectory within Zone I, which includes the powered portion, need be calculated for any particular rocket. The problem now permits of a more ready solution. Corrections for nonstandard conditions in Zone I could be treated independent of Zone II. If the trajectory lies entirely within Zone I, Vol. I of "Exterior Ballistic Tables Based on Numerical Integration" 1924, may be used for the descending branch provided no acceleration exists after the summit has been reached.

Much labor lies ahead in the computation of the above suggested tables. Once computed, however, they are ready to assist in the solution of any rocket trajectory problem.

It may not be stated that the preceding suggested methods are final. Progress is continually being made in design and computation methods.

— Robert A. Goodpasture
Colorado State College Hydraulic
Laboratory

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*"The Method of Numerical Integration in Exterior Ballistics" — Government Printing Office, 1919.

BOOKS

Liquid Propellant Rocket Development, by Robert H. Goddard. Smithsonian Miscellaneous Collections, Volume 95, Number 3, Washington, March 16, 1936. 25 cents.

In this paper Dr. Goddard gives a brief resume of his studies and experiments with rockets since the publication in 1919 of his well known paper, "A Method of Reaching Extreme Altitudes". He enumerates the various agencies which have helped him carry on his research at Clark University, Auburn and Fort Devens, Massachusetts, and eventually at Roswell, New Mexico, and describes in general terms the problems towards whose solution he worked and the methods he employed. His first experiments were with combustion chambers and nozzles for liquid propellants, and later with complete rockets of various types to test stabilization methods. He employed several systems for fuel injection, including pumps, and pressure from both liquified and compressed nitrogen. To secure stabilization he employed first the so-called "nose-drive" construction, then a pendulum device, and finally small gyroscopes actuating vanes in the exhaust jet of the motor. This last method he concludes is the only effective one, and this is the method he employed in the shots during recent years. Dr. Goddard bases his stabilizing requirement on the assumption of a rocket so heavily loaded with propellants that its acceleration, and consequently its velocities during the first part of the trajectory, are very low. The ultimate superiority of this regime for operating altitude rockets may be questioned on the grounds that the velocity-ratio efficiency during the first part of the flight is so low, and consequently the average efficiency is so reduced, that the benefit of the excess fuel is cancelled. Dr. Goddard plans to devote his next period of research to the problem of weight reduction. His paper is more in the nature of a general description of his work than a technical report and leaves the reader eager for more specific information of an engineering or mechanical nature. It comprises ten pages of text and is illustrated by eighteen photographs showing several rockets, the launching tower, observation dugouts, sighting instruments, etc., and by frames from the motion pictures taken of two test flights. — P. v. D.

Rockets through Space, by P. E. Cleator, Simon & Schuster, 227 pages, $2.50.

Beyond question here is a book which may do much indeed for the cause of rocketry. It is written with that rare combination — enthusiasm and judgment. Have you a friend or acquaintance whom you would convert to a reasonable view upon the possibilities of space travel? This book will do it, for it is written for the layman. Step by step each item of the theory and counter-theory, pro and con, is made plain. Insofar as the reviewer can judge there are no gaps in the chain of argument.

The history of the conception of the rocket as the medium par excellence for spatial motion is given with verve and zeal. Generous praise is accorded the American Rocket Society which, if the book attains the circulation which is its just due, should materially aid the Society in its efforts to stimulate popular interest. The illustrations, many of them, have appeared in various issues of *Astronautics.*

In addition to all, Mr. Cleator has imagination. His discussion of the basic problem—fuel—sends its tentative feelers into some out-of-the-way crevices of science. The "pace" of the writing is rapid and as a result one reads the book at a sitting and gains the impression that here is the first chapter of one of mankind's most thrilling adventures. The sections on the planets and possible courses to be laid thereto thru space are particularly engrossing. Yet thruout, there is no nonesense or phantasy. The scientific background is unimpeachable. One might perhaps wish that the author had devoted a trifle more attention to the immediately feasible uses of the rocket, for example in high altitude meteorology—but one cannot fairly criticize him on these grounds since his book is intended as a statement of ultimate possibilities.

In such a book, the omission of experimental data (such as exists) is only to be expected. Very few positive positions are taken, and a statement of immediate problems in precise terms is avoided. But perhaps it is just as well, for by so doing the author has gained his major point without risks of contradiction.—L.M.

Propulsion by Reaction, edited and published by the reaction division of the Military Science Committee of the Ossoaviakhim, USSR. Moscow, 1935.

This volume is a symposium of papers by several authors, each paper dealing with a special phase of the theory of the rocket. The subjects treated in each section, and the authors, are as follows:

1. "Ways of development of aviation and transit by reaction" — W. A. Davidoff.
2. "The Vertical Movement of Rockets"—Prof. W. P. Wetschinkin.
3 "The Stability of the Rocket in Flight" — M. K. Tichonrawoff.
4. "The Construction of the Trajectory of Reaction Engines Having an Initial Velocity"- I. A. Merkouloff
5. "Eddy Motions and Flow around Bodies in Parallel Rectilinear Streams at Velocities Greater than the Velocity of Sound" — F. Frankl.
6. "A Few Problems in the Dynamics of the Reaction Airplane" — W. P. Wetschinkin.
7. "The Application of Oxygen Reaction Motors to the Airplane" — E. S. Tshtetinkoff.
8. "The Calculation of the start of an Airplane using Starting Rockets" — W. I. Dudakoff.
9. "The Calculation of Airplane Braking after Landing by Means of

(concluded on page 20)

A SIMPLIFIED EXPRESSION FOR JET REACTION

A Communication from a California Reader

In the October, 1934, issue of *Astronautics*, an important equation of rocketry was developed by John Shesta. Much of its significance was probably lost to many, because of its cumbersome form. This article is an attempt to simplify the formula and relate it to old formulas and test data.

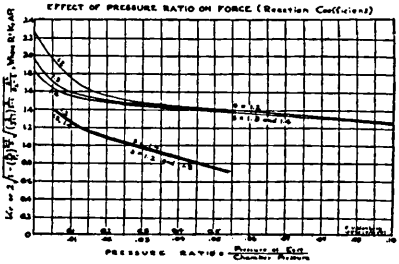
The formula was

$$R = 2\,A\,P_1 \sqrt{1 - \left\{\frac{P_2}{P_1}\right\}^{\frac{s-1}{s}}} \sqrt{\left\{\frac{2}{s+1}\right\}^{\frac{2}{s-1}} \frac{s^2}{s^2-1}}$$

This can be written $R = K_r\,A\,P_1$, where K_r is a function of the pressure ratio, $\frac{P_1}{P_2}$ and of s. But s varies considerably with temperature and with different gases; and in the rocket combustion and expansion processes several gases are involved, over a wide temperature range. What value of s is to be used?

The most probable values are between 1.2 and 1.3, extending somewhat on each side. For CO_2 at 3500-5000° F, s is 1.16, while at 70° F it is 1.28. Superheated steam runs about 1.30. CO and O_2 which are present if the combustion is incomplete, vary between 1.25 and 1.4, depending on the temperature.

Fortunately, upon further investigation, the dilemma disappears; no assumption need be made, and no laborious procedure need be followed. In plotting the values of K_r against P_2/P_1, for several values of s, the lines are found to nearly coincide. The value of K_r is nearly independent of the value of s! The accuracy of the curve shown is ± 1% down to .06, and within ± 2% down to .025. At 0.0 the range is from 1.8 (s = 1.4) to 2.24 (s = 1.2).



Low pressure, inefficient rockets may have values of the pressure ratio between .2 and .3 but the tests made by the Society show lower values.

No attempts have been made yet to measure P_2, but the values of K_r can be computed from the instantaneous values of P_1 and R given in the June, 1935, and October, 1935, issues of *Astronautics*, thus working backward.

In the first series of tests, the value of K_r is usually 1.3 (it jumps to 1.7 at one place) for the short nozzles. The value is between .7 and 1.1 for the long nozzles—the results with the long nozzles are puzzling, in what ever way they are considered.

In the second run of tests, the

value of K_r is consistently between 1.3 and 1.6, with a number of values at about 1.5. This corresponds to a pressure ratio range of from .015 to .085, with the majority at .025.

Supposedly, the absolute lower limit of these motors discharging into the atmosphere would be

$$\frac{15 \text{ lb/sq.in.}}{190 \text{ lb/sq.in.}}$$

or 0.08. (190 is about average chamber pressure). There is therefore not yet close agreement between theory and experiment, but when the experiments are complete enough to have consistent results, perhaps the theory can be modified to fit.

In the meantime, we have achieved one important result. The old, and very simple, formula that $R = A P_1$* is found to be true when expressed as $R = K_r A P_1$, where K_r has been experimentally determined as about 1.5.

— **Robert Uddenberg** Berkeley, Calif.

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*See, for example, Astronautics, January, 1933.

Rocket Motor Tests of Oct. 20, 1935

(concluded from page 13)

rangement, in which the propellants were injected through a pair of tangential orifices in a small pre-mixing chamber, failed to give satisfactory effect.

These results indicated that improvements are necessary in both the proving stand itself (to permit more accurate metering of propellants and controlled pressure conditions) and of course in the motors and nozzles. A new proving stand has been designed and is now under construction; its specifications will appear in the next issue of *Astronautics*. Members of the Experimental Committee are also preparing designs for motors with refractory linings and other modifications.

Present at these last tests of the season were Dr. George V. Slottman, of the Applied Engineering Department of the Air Reduction Sales Company, Major Lester D. Gardner, Secretary of the Institute of the Aeronautical Sciences, and Professor Alexander Klemin, head of the Guggenheim School of Aeronautics of New York University.

The personnel of the 1935 Experimental Committee was: John Shesta, Chairman (designer and builder of most of the apparatus), G. Edward Pendray (in charge of liquid oxygen and proving field arrangements), Carl Ahrens and Peter van Dresser (camera recordings), Nathan Carver (general assistant), and Alfred Africano (technical observer and recorder). Liquid oxygen was supplied through the courtesy of the Air Reduction Sales Company.

Books

(concluded from page 18)

Rockets" — W. I. Dudakoff.

All the papers are illustrated by means of diagrams, graphs, and tables. The editor's foreword promises early publication of another volume dealing with practical engineering problems in rocketry, as distinct from the purely theoretical questions of rocket dynamics dealt with in this book.

— G. D.