ESTES INDUSTRIES TECHNICAL NOTE

TN-2

MODEL ROCKET ENGINE PERFORMANCE

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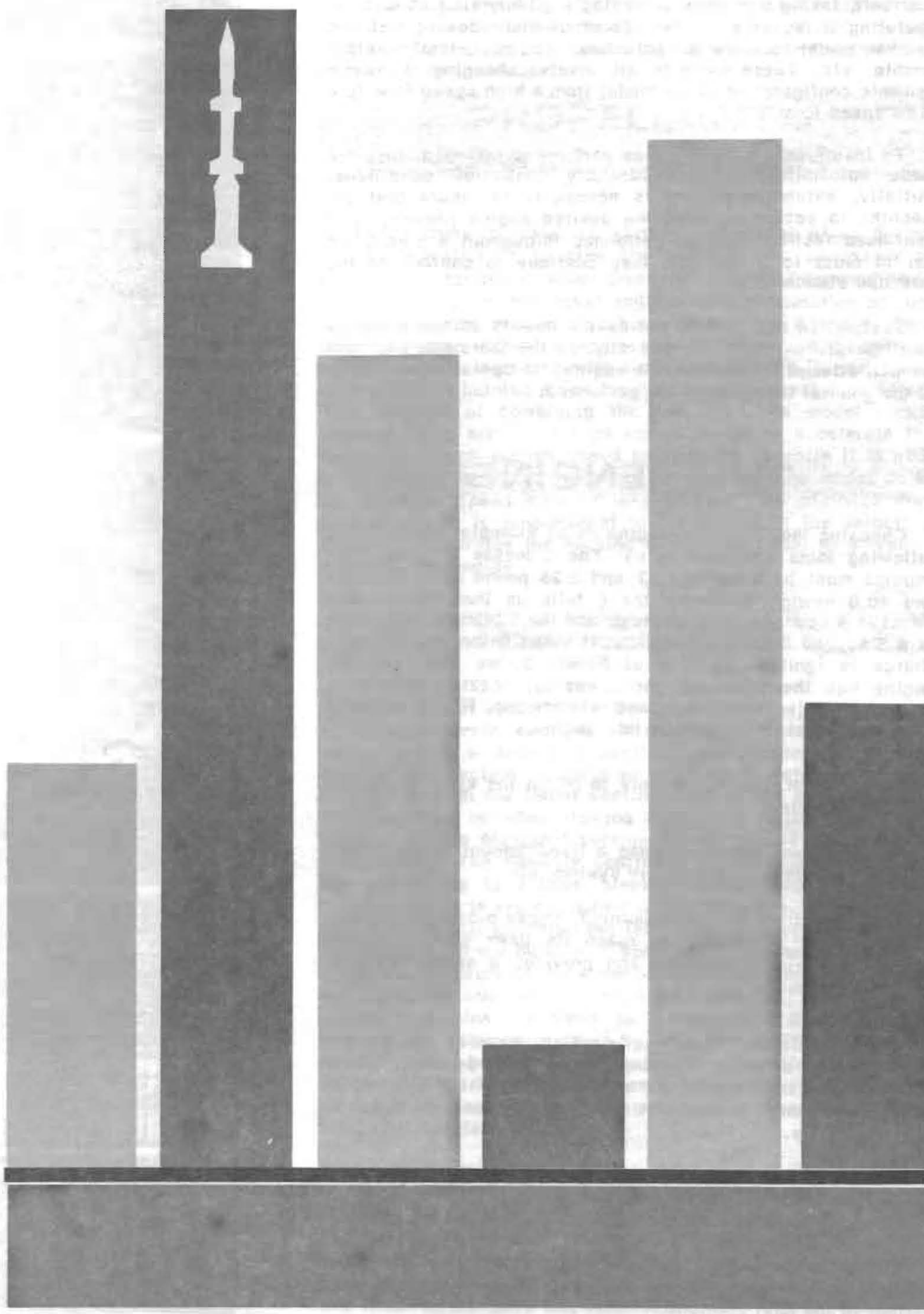


INTRODUCTION

A model rocket engine is scientifically designed to produce a relatively precise amount of force for a predetermined length of time. This means that each engine will produce a certain total impulse; total impulse being equal to the average force produced multiplied by the time during which the force is generated. The units used to measure total impulse are most often pound-seconds or newton-seconds. Total impulse can be illustrated as the area under a thrust-time trace. Figures 1A and 1B show some thrust-time traces.

When a model rocket engine finishes producing force, which we will refer to as thrust, it may be used to ignite another engine automatically (staging), or the engine may be made with a delay train which ignites an ejection charge at a predetermined length of time after thrust has ceased being produced. This charge provides a quantity of gas which is used to operate various secondary devices (activating or de-activating a circuit, taking a picture, releasing a glider, etc.) as well as operating a recovery system. Some of the recovery methods used in model rocketry are parachute, streamer, featherweight tumble, etc. These methods all involve changing the aerodynamic configuration of the model from a high speed form to a slow speed form.

To insure that Estes engines perform as intended, they are made automatically under carefully controlled conditions. Initially, extensive testing is necessary to insure that the machine is set up to make the desired engine properly, and continued testing must be performed throughout a production run in order to insure that they continue to conform to the intended standards.

Testing, in itself, does not assure quality unless we know what we are checking for and why. In the following sections we will attempt to describe the engine, its operation and some of the general tests which are performed.

THE ENGINE

Choosing the C6-5 type engine as an example, we have the following facts available to us: The C means that the total impulse must be between 1.13 and 2.25 pound seconds (5.01 and 10.0 newton seconds); the 6 tells us that the average thrust is 6 newtons (1.35 pounds); and the 5 tells us that there is a 5 second delay after the thrust stops before the ejection charge is ignited. Looking at Figure 2, we see that this engine has the following parts: casing; nozzle; propellant; delay train; ejection charge; and retainer cap. Figure 3 shows a typical thrust-time trace for this engine.

The retainer cap serves only to retain the ejection charge until it is ignited.

The ejection charge provides a fixed amount of gas which is used to activate the recovery system, etc.

The delay train is a slow burning, smoke producing mixture which allows the rocket to reach its peak altitude before igniting the ejection charge and provides a smoke trail for tracking purposes.

The propellant is a composite which produces the reaction products by a self-sustaining combustion process. These allow us to take advantage of Newton's Third Law, "For every action there is an equal and opposing reaction," making our rockets fly.

The De Laval nozzle converts the pressure (thermal) energy of the reaction products into velocity (motion) energy of reaction products at the nozzle exit.

Since the propellant and the nozzle determine the major portion of the engine's performance, we will discuss them further in the next sections.

Fig. 1A

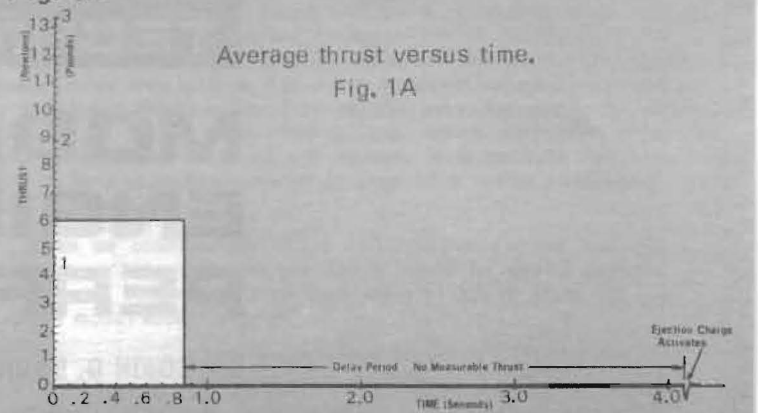


Fig. 2

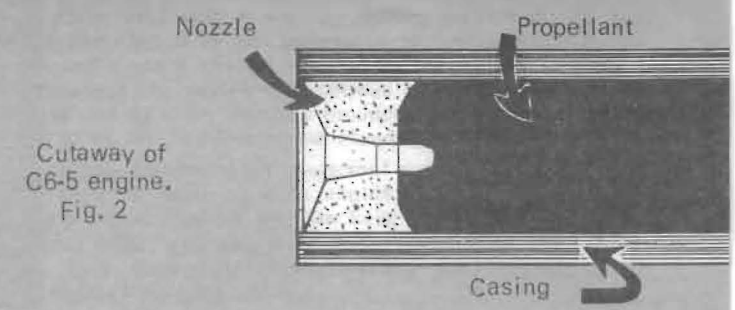


Fig. 3

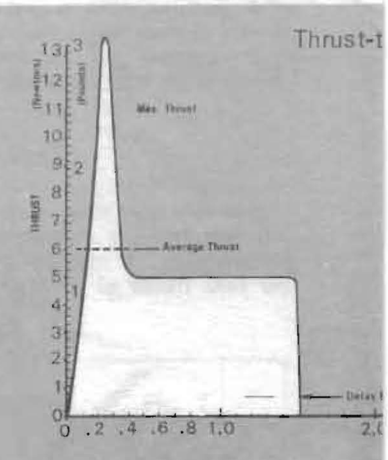


Fig. 4

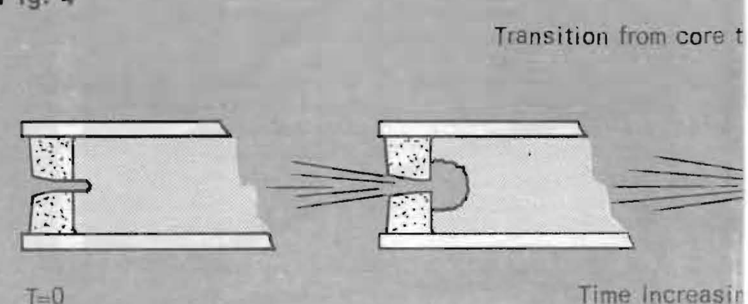
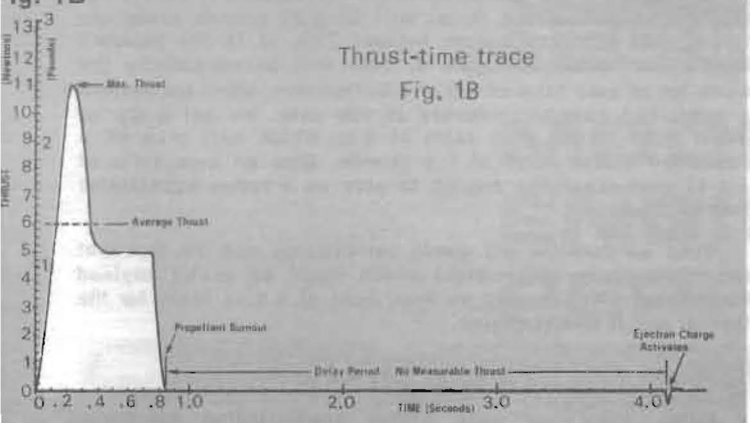
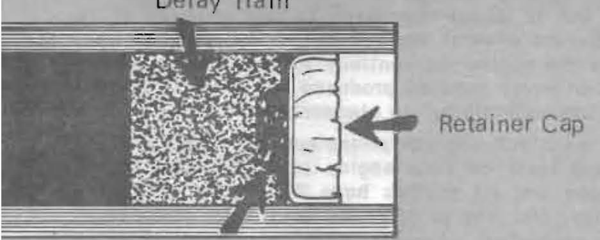


Fig. 1B

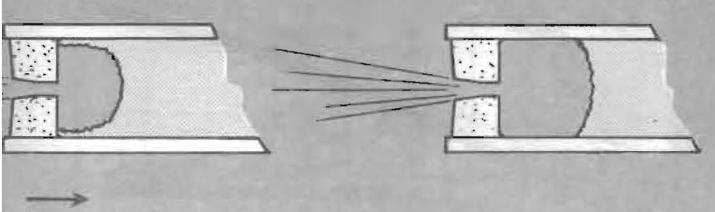


Thrust-time trace
Fig. 1B



ne trace (average) for C6-5.
Fig. 3

end burning Fig. 4



PROPELLANT CHARACTERISTICS

One of the most important characteristics of a propellant is its burning rate. The volume of gas that a given propellant can produce is limited by how fast it burns and the area of the burning surface. This is complicated somewhat by the fact that the burning rate is not a constant. It not only increases as chamber pressure increases, but also increases as the propellant's preignition temperature is raised. It also varies with the propellant composition and the oxidizer particle size within that composition.

Other important characteristics of a propellant are: specific impulse; density; characteristic exhaust velocity; specific heat ratio; temperature of combustion; pressure and temperature requirements for ignition; composition of reaction products; resistance to damage due to handling or storage, and possible toxicity. We will define specific impulse as the total impulse we would measure if we fired an engine which contained one pound of propellant. We will bypass the other characteristics in this report on the assumption that it is sufficient to know that it is not a simple subject.

PROPELLANT GRAIN DESIGN

The primary purpose of varying propellant grain design (grain geometry) is to give the burning area necessary to produce the desired chamber pressure. The most common grain design found in model rocket engines is a combination of core burning and end burning as shown in Figures 2 and 4. Core burning is also known as progressive burning since the burning area obviously increases with time. End burning is sometimes called neutral burning since the burning area remains constant. The purpose of combining the two types in model rocket engines is to provide a high initial thrust to accelerate the rocket to a high enough speed to stabilize it while it is still being guided by the launch rod, and to bring the model up to its maximum speed more or less gradually to minimize drag buildup. (Drag is proportional to the square of the velocity.) Figure 4 illustrates the burning of the propellant in a typical model rocket engine.

THE NOZZLE

Model rocket engines use De Laval nozzles; these consist of three separate sections: a convergent section; a throat section; and a divergent section. The convergent section causes the reaction products to increase in velocity in order to pass through the throat section much in the same way that water speeds up when flowing through a narrow part of its channel. In the divergent section things become slightly more complicated. The velocity continues to increase because we are exhausting to a lower pressure region and the gaseous reaction products are expanding to this pressure. This idea can be illustrated by watching the launching of a weather balloon. At ground level the balloon is somewhat loose and slack; as it rises, the pressure of the atmosphere surrounding it decreases and the balloon visibly expands. However, the internal pressure remains the same as the external pressure; if it exceeds the external pressure by more than the strength of the balloon, the balloon ruptures. Figure 5 illustrates what happens to the velocity, pressure and specific volume (volume occupied by a unit of mass) of gaseous reaction products in a De Laval nozzle.

Once grain design and propellant composition are fixed, then the nozzle and its design become the controlling factors in model rocket engine performance. By varying its design and size, we can vary chamber pressure, specific impulse, thrust levels, engine efficiency, etc., etc. The following equations and illustrations make this relatively clear.

$$F = C_F P_c A_t \quad \text{eq. 1}$$

$$c = I_{sp} g \quad \text{eq. 2}$$

$$c^* = c/C_F \quad \text{eq. 3}$$

$$I_{sp} = F/\dot{W} \quad \text{eq. 4}$$

F = Thrust (pounds)

C_F = Thrust Coefficient (a dimensionless, relative measure of nozzle efficiency).

P_c = Chamber pressure (Pounds per square inch absolute).

A_t = Nozzle throat area (square inches).

c = Effective exhaust velocity (feet per second).

I_{sp} = Specific Impulse (seconds) A measure of propellant efficiency.

g = Acceleration due to gravity (32.17 feet per second^2).

c* = Characteristic exhaust velocity (feet per second).

$\dot{W}$ = Weight flow rate (pounds per second).

I_t = Total impulse = mc = $\frac{W_p c}{g}$

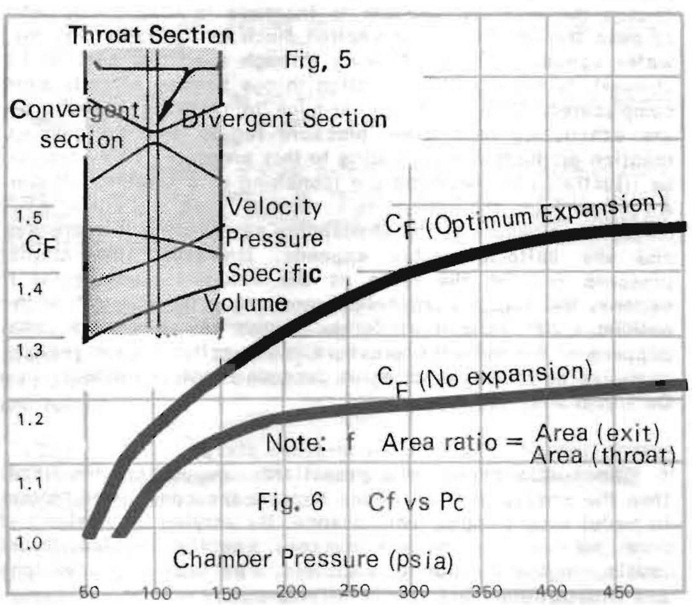
Obviously the equations above can be rearranged into many different forms to find the value of various terms.

The Estes model rocket engines use an area ratio of 2.0 in their nozzles. By area ratio we mean the nozzle exit area divided by the nozzle throat area. If you look at figure 7, you will see why this is done. At peak thrust we have a chamber pressure of about 225 pounds per square inch*. This drops to about 100 pounds per square inch during sustained thrust. With an area ratio of 2.0 we will not lose 5% of potential thrust until chamber pressure drops to around 60 psia. This gives us a good thrust coefficient at both our peak chamber pressure and at our sustained chamber pressure. With an area ratio of 4.0 there would be a loss of more than 5% until a chamber pressure of 160 psia is reached. A few simple calculations should show this more clearly.

Using equation 1 as a basic thrust equation we can determine the thrust an engine design will produce:

$$F = C_F P_c A_t$$

*(abbreviated psia).



If we assume a peak chamber pressure of 225 psia, then refer to figure 6 and choose a conservative value of 1.3 for our C_F, we know that our thrust will be 3.22 pounds since our throat area is 0.011 square inches. This is in the ballpark that we indicated in Figure 3. This will be essentially the same for an area ratio of 2.0 or 4.0. However, when we assume a sustained chamber pressure of 100 psia, we get a C_F of about 1.12 for an area ratio of 2.0, which will give us a sustained thrust level of 1.3 pounds. Now an area ratio of 4.0 is over-expanding enough to give us a rather substantial loss of thrust.

When we consider our above calculations and the fact that a larger nozzle adds weight which could be useful payload weight, we can see why an area ratio of 2.0 is ideal for the typical model rocket engine.

TESTING

Estes Industries uses highly sophisticated electronic equipment to test engines for proper thrust levels and total impulse. The continuing goal is to not only meet the standards set forth by the NAR, but to meet and exceed our own standards, which are somewhat more stringent.

As we set up to manufacture a certain type of engine, we may need to test only 5 engines before we are within our specification, but it is not uncommon to test upwards of 20 engines and discard several hundred before we are satisfied. As we produce the engine we continue to test; approximately 3 engines out of every hundred produced are static tested to insure that we are maintaining our standards.

Our engine manufacturing equipment automatically performs various physical tests on each engine as it is made. These tests help insure that all engines have the correct amount of propellant, delay, etc. The proof of the validity of these tests is that very consistent characteristics are maintained as sample engines are static tested.

Since quality is essential to us and to America's rocketeers, our testing also includes random testing of older engines. This is necessary to insure that aging and other factors do not appreciably change the performance of the engines. Test launchings and many more checks are performed on a random basis.

NOTE TO READER

Due to its brevity, this paper suffers much from over simplification. If you have further questions, we suggest that you write to Estes Industries. We will attempt to answer your questions at that time with the attention to detail that the questions deserve.