Simple Core Design for Neutral Burn Composite Rocket Motors

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ABSTRACT

Two simple techniques for improving small amateur-type rocket motors are discussed. The first uses a simple, post-cure technique to produce neutral thrust profiles using a simple machinist's tap. The second uses a small Black Powder pellet to improve reliability and ignition of composite rocket motors.

Keywords: rocket motor, composite propellant, thrust profile, neutral burn, neutral thrust characteristic

In the design of solid rocket motors many variables must be balanced to optimize performance. One of the most challenging is the thrust profile. As the propellant grain burns, the burning surface area usually changes while the nozzle throat area remains relatively constant. This has the effect of changing the chamber pressure, thereby changing the thrust, the propellant burn rate, and the burn time of the motor. As a result, the motor design is complicated and undesirable performance characteristics may be introduced. Additionally, a rocket is heaviest just prior to launch before any propellant has been consumed. This is also when higher thrust levels are desired to attain stable flight speed quickly, when the rocket is still being stabilized by the launch platform.

In general, thrust curves are given three basic designations depending on the thrust as a function of time. *Progressive* indicates that the thrust increases as burning continues, *Neutral* indicates relatively constant thrust throughout the burn and *Regressive* indicates the thrust decreases as the burn progresses. These three thrust profiles are shown notionally in Figure 1. While thrust characteristics of commercially available motors vary, a neutral or mildly regressive characteristic is often desired.

Generically, solid rocket motors are of two basic types, end-burning and core-burning. As the name implies, end-burning motors are ignited at one end and the propellant generally burns in a linear fashion, propagating along the length of the grain. This maintains a relatively constant combustion area for cylindrical propellant grains. Thus, end-burning motors naturally have a neutral thrust characteristic. On the other hand, core-burning motors have a hollow core or hole down the length of the propellant grain. As the motor functions the flame propagates from the inside to the outside of the grain. Since

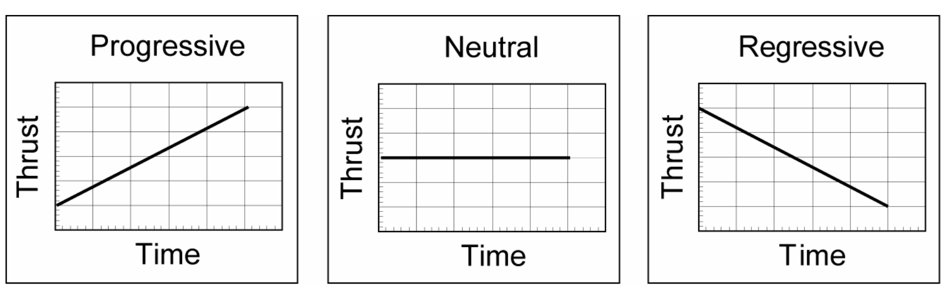

Figure 1. Illustration of three thrust profile types.

the combustion surface area increases with the radius of the burning core, core-burning motors with circular symmetry are naturally progressive in nature.

Since end-burning motors are naturally neutral, it is reasonable to ask "Why not just use this type of motor and forget about core-burning designs altogether?" Some manufacturers of hobby rocket motors provide end-burning motors for just this reason. Often, a small core, extending a short distance into the propellant grain, is used to aid in ignition and provide suitable ignition area or even a slightly larger thrust at ignition. However, end-burners are most useful when either low thrust is desired, or the propellant burns rapidly under the conditions present in the combustion chamber. A consequence of this geometry is a relatively low value of the parameter K_n, which is simply the ratio of the burning surface area to the nozzle throat cross sectional area. Modern, high-performance propellants, such as ammonium perchlorate composites, require a high K_n (typically >100). This forces the motor designer to use large diameters for end-burning motors to achieve the high thrust levels desired for amateur rockets. Core-burning motors, however, have very large burn surface areas and thereby high K_n, generating high thrust in more practical diameter motors.

Since core-burning motors have this progressive tendency, more complex designs for motors have been designed to make the thrust characteristic neutral. For example, various non-cylindrical cross-section core shapes have been used to increase the initial burning surface area to produce a neutral thrust profile. Multipoint stars have been used successfully as have multi-core geometries. Additionally, by allowing surfaces other than the core to burn, an overall neutral thrust characteristic may be obtained. In one popular design, the propellant grain is divided into cylindrical segments. Each segment is designed to allow ignition not only along the core but on each end as well. When this method is applied carefully, the decreasing end area and the shortening segments compensates for the increasing core area. A ratio of *core-diameter: grain-diameter:grain-segment length* of 1:3:5 produces a neutral thrust profile. All these designs make an attempt, some more successfully than others, to maintain constant burning surface area during the functioning of the motor to produce constant thrust.

Complex core geometries require that special mandrels and forms be used, which complicates the extraction process and may add additional hazards for the manufacturer. Other geometries such as off-center cores, sometime referred to as a "moon burners", and multiple cores may require complex tooling used during the casting of the grain and do not produce a very neutral profile. Allowing surfaces other than the core to burn may expose the motor casing (or the inhibitor) to the flame during operation. A technique developed by James D. Horswell uses a simple

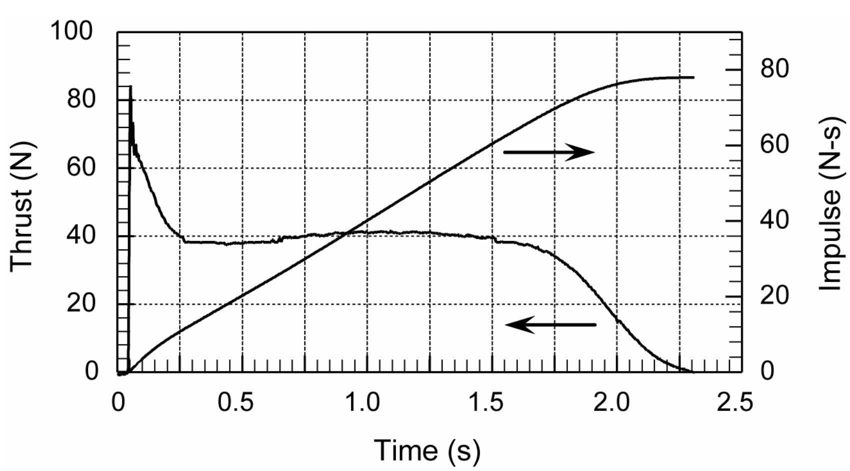

Figure 2. Thrust curve for F model rocket motor using a threaded core to produce a neutral thrust profile.

threaded core geometry to achieve neutral thrust. While this sounds somewhat complicated, the threads may be cut at low speed into the cured grain with a simple machinist's tap. This technique has produced grains with a very flat thrust characteristic. Figure 2 shows the typical thrust and impulse curves for a motor with a threaded core. As is clearly seen, the thrust profile is flat.

Threading also enhances ignitability of composites. Poor ignitability is in part due to the binder coating the particles of oxidizer. The threads cut through the cured composite exposing uncoated oxidizer surfaces. In addition, the many fine surface features increase the initial burn surface area and hence initial thrust. Low initial thrust can be caused by ignition at some mid point in the core. Since the motor K_n is computed using the entire core burn surface area, any reduction in burn surface area produces lower thrust. To ensure ignition of the entire core, a small pellet of handmade Black Powder is inserted into the top of the motor. These two design elements provide increased thrust during the first moments after ignition when rapidly achieving aerodynamic stability is paramount.

Many of these motors were made and tested and all repeatedly showed this thrust characteristic. Indeed, these motors were successfully used in several model rockets that attained altitudes in excess of 5000 feet above ground level. Further, the hand-mixed Black Powder pellet never failed to fully ignite the grain, thus providing for reliable ignition of the motor. Figure 3 shows a drawing of a motor in cross-section.

Since the basic method to produce a neutral thrust profile is to maintain constant burning area, it is natural to ask what constraints this technique places on the design of the motor and what are the adjustable parameters. At constant diameter, the only way to vary the surface area of a threaded hole is to change the root angle of the thread itself. The root angle is the angle formed by the helical surfaces of the thread itself and is illustrated at the bottom of Figure 3. Figure 4 illustrates how threading increases the initial surface area of the cylindrical grain as a function of the thread root angle. Changing the pitch (threads per inch or mm)—and thereby the depth of the thread—has relatively little affect on surface area. An excessively fine pitch thread creates a burn surface that would quickly erode away, producing unacceptably varying thrust. Moreover, the soft polyurethane binders used are not capable of capturing the small details of fine pitch threads.

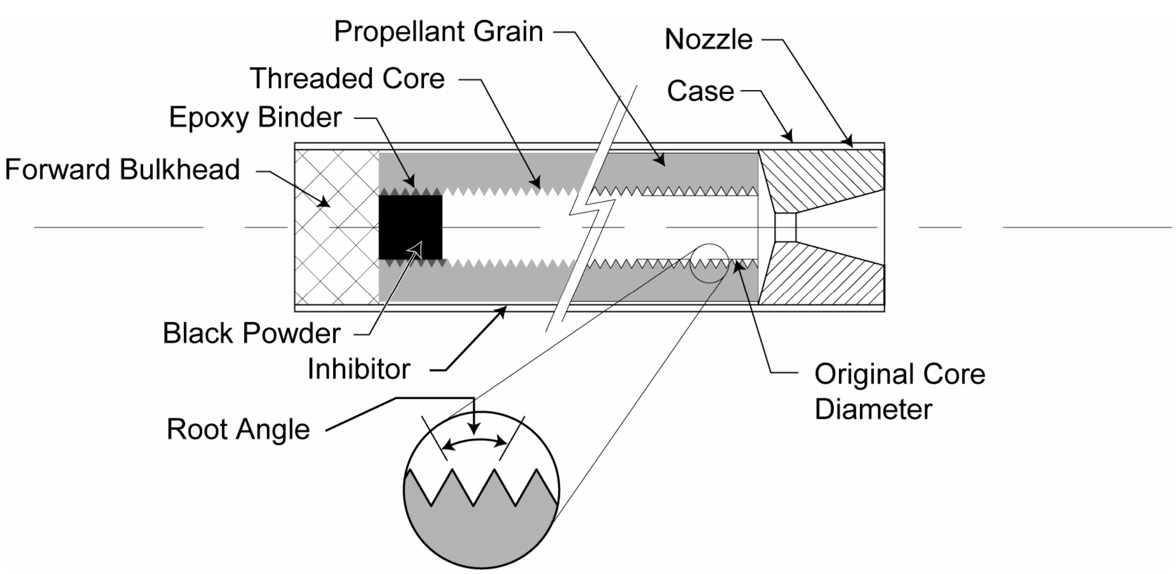

Figure 3. Cross-section of threaded rocket motor grain.

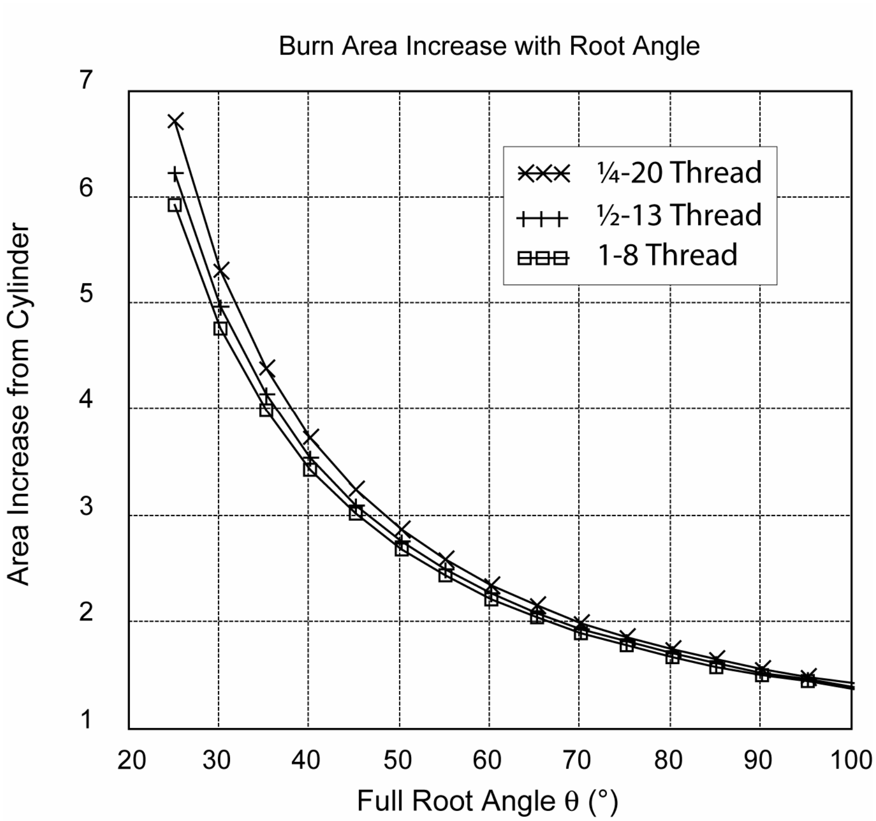

Figure 4. Graph showing the core surface area increase due to threading as a function of root angle for ¼-20, ½-13 and 1-8 US NC threads.

For simplicity, a tap from the National Course (NC) series was used to produce the thrust profile shown in Figure 2. Tap size was selected based on the initial core diameter of the grain. Because the standard US NC tap series is based on a 60-degree root angle, the increase in initial burn surface area of the core is increased by approximately a factor of two. Thus these threads produce a neutral burn for a grain design where the outside diameter of the grain is twice the unthreaded core diameter. As was shown, threading the grain in this manner produced a neutral thrust characteristic during the entire burn, excluding the intentional initial thrust spike.

These curves were generated using the formula presented below, which includes the effect of radius on area increase. Derivation of this formula is presented in the appendix in the discussion on the ringed-cylinder model.

$$A_{inc}(\theta) = \left[\frac{1 + \frac{0.25}{R}\cot\left(\frac{\theta}{2}\right)}{\sin\left(\frac{1}{2}\theta\right)} \right] \quad (1)$$

Other tap variations are readily available, such as pipe taps, which have a tapered thread. Moreover, the relatively soft nature of the urethane-based composites does not require hardened tool steel to cut acceptable threads. This leaves the designer, who has some skill and access to a lathe, freedom to explore other root angles and thread pitches using taps made from aluminum or brass. While this technique may not have application to production-class motors, it is the easiest method this author has used to produce very reliable motors with neutral thrust profiles. Further, by selection of tap and initial to final K_n, many thrust profiles are available from progressive to regressive.

In conclusion, two simple techniques to improve the performance of amateur rocket motors have been demonstrated. A simple hand-mixed Black Powder pellet, included at the top of the grain, improved ignition. Threading the propellant core using readily available, inexpensive machinist's taps, produced a neutral burn in simple core-burning motors. These two techniques, when combined, also produced an ignition thrust spike improving launch reliability.

Appendix
Simplified Formula to Compute the Increase in Surface Area Due To Threading

The computation used to produce Figure 4, for surface area increase, includes the effect of core radius. However, this level of precision is not always needed, especially when designing a new motor. In these instances a less accurate, rule-of-thumb formula, may be more appropriate and is presented below. In this equation, θ is the root angle and R is the core radius expressed in threads. (For example, a ¼-20 thread has an R = 0.125 inch × 20 threads per inch = 2.5.)

This formula assumes the core radius is large compared to the thread spacing (spacing = 1 per thread-pitch, e.g., ¼-20 thread spacing is 0.05"). Figure 5 shows the geometry used for this analysis.

Unit area of cylindrical core (Eq. 2):

$$A_{core} = 2\pi \cdot R \cdot 1_{thread} \tag{2}$$

Unit area of threaded core (Eq. 3)

$$A_{thread} = 2\pi \cdot R \frac{1_{thread}}{\sin\left(\frac{\theta}{2}\right)} \tag{3}$$

Ratiometric increase in core area (Eq 4 = Eq. 3 ÷ Eq. 2)

$$A_{increase} = \frac{1}{\sin\left(\frac{\theta}{2}\right)} \tag{4}$$

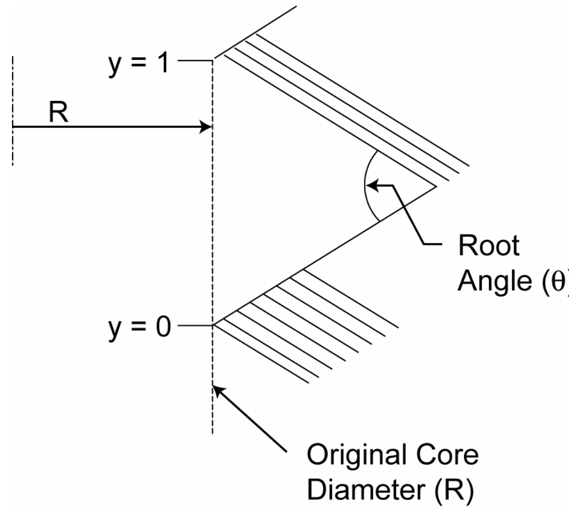

Figure 5. Simplified thread geometry.

Ringed-Cylinder Model

A ringed-cylinder model provides greater accuracy than the simplified version above. Figure 6 shows the detailed geometry used in this analysis. This formula neglects the small increase in area due to the thread being a helix and not a series of triangular shaped rings, but this error is quite small and considered third order for this approach.

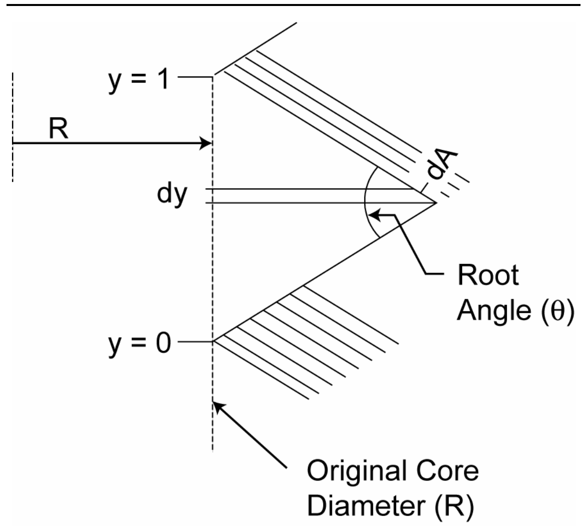

Figure 6. Detailed thread geometry.

Actual unit area of thread (Eq. 5)

$$A_{thread}(\theta) = \frac{2\pi}{\sin\left(\frac{\theta}{2}\right)} \times 2 \times \int_{0.0}^{0.5} R + y\cot\left(\frac{\theta}{2}\right)\mathrm{dy} \qquad (5)$$

Integrating Eq. 4 yields (Eq. 6)

$$A_{thread}(\theta) = \frac{2\pi R}{\sin\left(\frac{1}{2}\theta\right)} \times \left(1 + \frac{0.25}{R}\cot\left(\frac{\theta}{2}\right)\right) \qquad (6)$$

Ratiometric increase in core area (Eq. 1 = Eq. 6 ÷ Eq. 2)

$$A_{inc}(\theta) = \left[\frac{1 + \frac{0.25}{R}\cot\left(\frac{\theta}{2}\right)}{\sin\left(\frac{1}{2}\theta\right)}\right] \qquad (1)$$