Introduction

There are certainly countless solid propellant formulations that have been tried by amateur experimentalists over the years. Some have been very successful and have gained worldwide popularity, although undoubtedly most formulations have been simply downright failures, or at best, marginally successful. Surely anyone who has ever been involved in AER can cite formulations that they have tried without success, including myself. The very first propellants that I experimented with were zinc/sulphur as well as black powder. For whatever the reasons, I had no luck with either. Other experimentalists, however, have had good (or even great) success with these. The rocket propellant that provided great results for me in my early work was the potassium nitrate-sucrose formulation. Interestingly, certain other experimenters at that time had only limited success with it. Clearly, it can be said that many propellant formulations simply won't work (e.g. bad chemistry), some work, but are of limited value (due to cost, difficult to produce, safety concerns, lack reproducibility, etc.), and yet there are other formulations that will function very well -- *conditionally*. What exactly does this mean?

In hindsight, the reason that I did not have success with the zinc/sulphur or blackpowder propellants was certainly due to the methodology I employed in usage, not a fault with the propellants, per se. The key to success with any viable propellant is *knowledge of the propellant with regard to its particular properties and its usage*. For example, the exact ratio of constituents strongly affects how well a propellant will perform. "Perform" is meant in a broad sense, encompassing such parameters as specific impulse, burn rate, mechanical properties, castability (or formability), reproducibility, etc. Getting it right such that all these performance parameters are met, to a reasonable degree, is a daunting task. What adds to the challenge is that this is only part of the picture. There are other complicating factors that have a strong impact on whether a propellant will behave satisfactorily. For example, grain (particle) size of the oxidizer, or its purity, effective blending of the constituents, cure time, moisture content, and even the particular shape of the propellant grain may or may not be suited to a particular propellant. It can therefore be said that the key to consistent success with a formulation (that is known to work well historically) is to follow the correct methodology in preparation and appropriateness of usage. Meeting these conditions will greatly enhance the likelihood of success.

Solid Propellant Requirements for the Amateur Experimentalist

With amateur rocketry, unlike professional rocketry, the availability of materials, the facilities and processes by which rocket propellants and motors may be produced, as well as available financing, vary greatly. And clearly these pale in comparison. As such, a clear distinction must be made between the needs of the professional, and the needs of the amateur, with regard to requirements defining an ideal rocket propellant. More importantly, what works well for one person, may not work at all for another. Expanding on this thought, what is suitable for one person, may not be at all suitable for another. Therefore, the list that follows is not presented in any particular order, as the importance of each would vary by individual. The exception are the first two items, which must always be of primary importance.

1. **Safety of handling, storage, and usage**
2. **Toxicity of the constituents and products of combustion**
3. **Availability of the constituents**
4. **Predictability of performance**
5. **Consistency of performance**
6. **Adequacy of performance**

7. **Formability (or castability)**
8. **Cost**
9. **Practical burning characteristics**
10. **Ease of formulation**

Expanding on these ten requirements:

1. *Safety of handling, storage, and usage* -- These requirements apply to the individual constituents separately, as well as in combination. In combination, all the intermediate steps leading to the final prepared form of the propellant must be considered.
   Some of the factors to be considered for the individual constituents are sensitivity to ignition by friction, static charges, impact or shock. Chlorates should be avoided for this reason. Certain finely divided materials, such as magnesium and aluminum, require particular care in handling and storage due to possible "spontaneous combustion" and static charge sensitivity. High auto-ignition temperature is desirable for those propellants which are prepared at elevated temperature, as well as low melting point of the binder. A propellant should, *ideally*, not burn at atmospheric pressure, although nearly all do.
2. *Toxicity of the constituents and products of combustion* -- Ideally, the propellant constituents as well as the exhaust products should be non-toxic, non-carcinogenic, and non-corrosive. Certain composite propellants require a catalyst (or curing agent). Typically, these contain isocyanates which require special handling procedures. Polyester and epoxy, when utilized as a fuel, binder or inhibitor, also require care in handling (such as impervious gloves, proper ventilation, and eye protection) due to sensitivities that may develop due to prolonged exposure. Ammonium perchlorate based propellants produce corrosive hydrochloric acid as an exhaust product.
3. *Availability of the constituents* -- This requirement is probably the one that would differ the most amongst those involved in AER. A local source is preferable, especially for the oxidizers, as these have special shipping requirements and cannot be send through the regular post. Oxidizers such as potassium nitrate (KN) and ammonium nitrate (AN) are likely the most readily available, as both are commonly used as fertilizers, and have many other commercial uses as well. For example, my local drugstore sells both of these in the form of pharmaceutical products.
4. *Predictability of performance* -- In order to investigate the performance characteristics of a rocket motor, and therefore be able to predict how high and fast a rocket will go, it is desirable to be able to study the theoretical performance that a propellant will deliver. As such, it is necessary to know the chemical makeup of the constituents in order to perform a combustion analysis, or to examine the effects of changing the proportions of the constituents (e.g. O/F ratio). Some materials are a complex mixture of chemicals. Examples are asphalt and charcoal, which often vary significantly in chemical makeup from one source to another. Combustion analysis (using a software program such as PEP) allows the determination of ideal specific impulse and flame temperature, and exhaust gas properties. These parameters are most useful in the design of motors. For example, knowing the flame temperature is important for choosing nozzle material. The gas properties aid in the design of the nozzle geometry. In addition to theoretical analysis, it is desirable to obtain empirical data on the propellant, such a pressure and temperature influence on burn rate.
5. *Consistency of performance* -- Firing a rocket motor repeatedly with identical grains should yield similar, or consistent, performance results, time and again. This goal can be difficult to meet , for example, with powdered or compressed grain propellants (or those using evaporative binders) as reproducibility is hard to achieve, at least for the amateur, without specialized equipment. Heat cast propellants offer excellent reproducibility, due to the inherent simplicity of the method. Composite propellants also have the potential to generate consistent performance, although particular care must be exercised in the preparation, as a

greater number of steps and ingredients are involved.

6. *Adequacy of performance* -- Although there is a natural tendency to want to employ high performance propellants in a rocket motor, this is not always a good approach. With relatively small rocket motors (say, size M or under) that amateurs typically produce, there is arguably little benefit in using a high performance propellant. This is especially true if the complexities in producing the propellant, cost or tradeoffs such are reliability are introduced. If a more powerful motor is required, it is simple enough to scale up a motor that utilizes a lower impulse propellant. For motors of appreciably larger size, however, use of higher impulse propellants become imperative. Scaling up low impulse motors eventually leads to diminishing returns, whereby the mass of the propellant (and therefore takeoff mass of the rocket) becomes so great that it imposes a severe limitation on altitude goals or payload potential.
7. *Formability (or castability)* -- Casting a propellant grain is the most common and is arguably the best method of producing a reliable grain. If a propellant has a high percentage of solids, casting by means of pouring or scooping is not possible, as the mixture is dough-like. Packing may be successfully employed, although great care is necessary to prevent the inclusion of *voids* due to trapped air or a result of inadequate packing pressure. The same holds true for cast mixtures, but the likelihood of voids is less due to the greater fluidity of the material.
8. *Cost* -- Cost is a particularly important consideration for most amateur experimentalists. Since the money comes out of our own pockets, is not recovered, and is generally quite limited, the choice of which propellant we employ for our projects is often based largely on cost of ingredients. This is especially true considering that *all* expenses incurred in a project, not only for propellant, must be borne ourselves. Fortunately, there are a number of propellant formulations that are low in cost, and do not impose a burden on our pocketbooks.
9. *Practical burning characteristics* -- In order for a rocket propellant to be practical, it must have acceptable combustion characteristics when burned in a rocket motor. Successful solid propellants burn at a greater rate when combustion occurs under pressure, as experienced inside an operating rocket motor. However, there are bounds within which the rate should increase. Not too little, and not too much. If the burn rate does not increase sufficiently, the pressure within the motor may not develop to a level as to produce useful thrust. On the other hand, if the propellant burn rate is too sensitive to pressure, severe fluctuations in operating pressure could result, or worse, the motor may overpressurize too easily. The physical parameter that is used to measure a burn rate sensitivity to pressure, of a given propellant, is called the *pressure exponent*. The pressure exponent is determined through experimental measurement, and for most practical propellants the value lies between 0.2 and 0.7.
10. *Ease of formulation* -- The preparation of a particular propellant may be as uncomplicated as the blending of two chemicals together, then packing into a motor. For example, this is the simplest means of preparing zinc/sulphur propellant. On the other hand, certain composite propellant formulations require multiple steps to be carried out. For example, careful grinding of the oxidizer to a predetermined particle sizes before blending. As the number of constituents may total eight or more, each of which has to be precisely weighed (or measured), then mixed meticulously for a certain time period. A curative may then be added, then blended, before packing into moulds before the mixture sets. Just how important the "ease of formulation" is, is very much up to the individual experimenter to decide. Generally speaking, the novice experimenter should aim for simplicity in formulation until enough experience in propellant and motor making has been accumulated to be confident enough to attempt more complicated formulations.

Compendium of Solid Propellants

The following is a partial list of solid rocket propellants that have been used successfully by amateur experimentalists. Note that there are are certainly other formulations that I am not presently familiar with:

1. Potassium Nitrate/Sucrose (or KN/SU)
2. Potassium Nitrate/Sorbitol (or KN/SO)
3. Potassium Nitrate/Dextrose (or KN/DX)
4. Zinc/Sulphur (or Micrograin)
5. Blackpowder (KN/Charcoal/Sulphur)
6. Ammonium Nitrate/HTPB polymer /Magnesium (or AN/HTPB/Mg)
7. Ammonium Nitrate/Urethane (or AN/UR)
8. Ammonium Perchlorate/Silicone II
9. Ammonium Perchlorate/PBAN polymer/Epoxy
10. Ammonium Perchlorate/PBAN polymer/Epoxy/Aluminum
11. Ammonium Perchlorate/HTPB polymer/Aluminum
12. Ammonium Perchlorate/PVC (or AP/PVC)
13. Potassium Perchlorate/Sucrose (or PP/SU)
14. Potassium Perchlorate/Epoxy
15. Potassium Perchlorate/Asphalt

Notes on these propellants:

1-3 These three propellants are those which I have direct experience with. KN/SU is the "classic" formulation, KN/SO was developed in the early 1980's, and KN/DX is a recently developed formulation. This web site provides extensive information on these "sugar" propellants.

4 Zinc/Sulphur was a popular propellant during the 50's and 60's. Due to it's low impulse and rapid and uncontrollable burning rate, it has limited contemporary appeal. A typical ratio is 67.1% Zinc and 32.9% Sulphur. The "Photuris B" rockets described in C.L.Stong's *The Amateur Scientist* utilized a 75% Zinc/ 25% Sulphur mixture. More information may be found in Brinley's *Rocket Manual for Amateurs* or Bill Colburn's *The Micrograin Rocket*.

5 Pyrotechnic "skyrockets" as well as Estes type of model rocket engines use blackpowder as a propellant. The latter has propellant in the form of a highly compressed pellet comprised of 71.8% KN, 13.45% Sulphur, 13.8% Charcoal, and 0.95% Dextrin.

6 *CP Technologies* has developed a composite propellant that is comprised of 20% HTPB (R45HT), 20% Magnesium (260#) and 60 PSAN (phase-stabilized Ammonium Nitrate). By most accounts, this seems to be a good propellant that is reasonably simple to produce and gives good performance. A drawback is with the use of magnesium powder, which requires particular care in handling, and is quite expensive. As well, the AN is very hygroscopic, necessitating proper storage of the AN and finished grains.

7 Of the polymers, polyurethane has one of the highest heating values. According to one source, a ratio in the range of 85-90% AN and 10-15% Polyurethane works well.

8 The use of GE Silicon II (GE280) as a fuel/binder with AP as an oxidizer is discussed in the paper *Silicone II -- a New Fuel and Binder for Fireworks* by Ken Burdick. See also the Journal of Pyrotechnics #8 (1998). Silicone has a no-stick property, like Teflon, which makes this formulation a interesting contender for grains with complex core shapes with large surface areas, such as star or cruciform.

9-10 These are two basic composite formulations. The addition of aluminum results in an increased specific impulse, as the reaction of aluminum with an oxidizer is very exothermic. The drawback with the use of PBAN is the requirement that curing occur at an elevated temperature (140^{o}F) for several days. Detailed information on this propellant may be found in Terry McCreary's book *Experimental Composite Propellant*.

11 Another basic composite formulation. HTPB has the advantage over PBAN of curing at room temperature. The uncured mixture is typically doughlike, and packs nicely into a mould. Trapped air can be a problem, creating voids in the grains. Likewise, voids and bubbles can result from gases given off during curing (as a result of moisture absorption). Drawbacks also include the limited pot life once the curative has been added to the mixture. Quite a few ingredients are required (binder, plasticizer, Tepanol, cross-linking agent, curative and surfactant). The curative is an isocyanate, which requires stringent handling procedures, due to its toxic nature.
It is worth noting that the composite formulations (both PBAN and HTPB based) result in propellants that deliver excellent performance, have good mechanical properties, and offer potentially long burn times. Composite propellants burn with a brilliant hot flame, and it is really spectacular to watch a rocket take to the sky powered by a composite motor.

12 I have been made aware of a successful composite propellant which utilizes powdered PVC (polyvinychloride) as the fuel/binder, and AP as the oxidizer.

13 An early "sugar" formulation, this propellant apparently delivers good performance, but has a very high burn rate. The high pressure exponent of PP based propellants dictates the motor design, necessitating a nearly neutral grain configuration.

14 This formulation was developed by the *Aurora Project Group* for their sounding rocket project.

15 The "GALCIT" propellant used this formulation, with a 75%PP and 25% asphalt ratio. Brinley's book describes an advanced amateur rocket (being built at the time) that utilized 100 lbs. of this propellant.