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A Primer for University-Level Solid Rocket Motor Research and Development

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The recent addition of multiple intercollegiate rocket competitions has prompted the increased use of custom rocket propulsion systems by numerous universities. Collegiate rocket and research teams starting the development of solid propellant rocket motors often encounter problems throughout the entirety of design and testing phases. Specifically, there exists a discrepancy between standardized university textbooks on the subject and current hobbyist literature. Daedalus Astronautics at Arizona State University began research on solid rocket motors in 2006 and has since developed numerous successful motors. These motors have progressed from simple propellant formulations into high regression rate propellants utilizing multiple burn rate catalysts. The evolution of Daedalus' motor mixing methodology and other key information pertinent to solid rocket motor design and manufacture is included in this paper. A number of significant steps are outlined including safety and regulatory concerns, basic formula compositions, propellant characterization methodology, manufacturing processes and motor testing. The intended use of this paper is to act as a primer for the quick start-up and development of reliable solid rocket motor designs suitable for use in high powered sounding rockets.

Nomenclature

AP	=	ammonium perchlorate
APCP	=	ammonium perchlorate composite propellant
DAQ	=	data acquisition
LEUP	=	low explosives users permit
LEMP	=	low explosives manufacturers permit
BATFE	=	Bureau of Alcohol, Tobacco, Firearms and Explosives
ProPEP	=	propellant performance evaluation program
SRM	=	solid rocket motor
D	=	Bates grain outside diameter
d_o	=	Bates grain initial inside diameter
L	=	grain length
a	=	burn rate coefficient
n	=	burn rate exponent
P_c	=	stagnation pressure
P_2	=	nozzle exit pressure
P_3	=	ambient pressure
γ	=	ratio of specific heats
A_b	=	propellant burning area
A_t	=	nozzle throat area
c^*	=	characteristic velocity
ρ_b	=	propellant density

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I. Introduction

Daedalus Astronautics, the rocket group at Arizona State University, has been involved in the design, manufacture, testing and flight of various solid rocket motor systems since early 2006. The experience for our student members has proven very fruitful. It has not only allowed for an enhanced understanding of the rocket propulsion concepts taught in the classroom setting, but also a fantastic opportunity to troubleshoot true engineering problems. The program created at Arizona State University has not been without its share of setback however and this primer intends to pass these lessons learned on to other universities interested in pursuing SRM research programs. The example set by Daedalus Astronautics is simply that, an example. No grand claims are made that this is the only viable method for a successful SRM research and development program. Information presented in the following sections is a compilation of some of the lessons learned and knowledge gained over the past few years. This paper will be an evolving primer in the future and is certainly not a complete guide to the SRM by any means. The reader is cautioned that the development and testing of SRMs can be a dangerous and costly task if approached poorly. We are not responsible for the results of the use or misuse of the information in this paper.

II. Solid Rocket Motor Development

The startup time associated with SRM development is somewhat long and arduous due to a lack of cohesive information regarding the process. On one had there exists a wealth of analytical information in numerous rocket propulsion textbooks which are used throughout academia. On the other hand the hobby rocketry community is a fantastic resource regarding real world application of SRMs. The average hobbyist does not have the knowhow to perform the mathematical modeling and predictions that are taught at the university level. For the most part, the average undergraduate does not have the hands on knowhow to successfully develop a working SRM. The information gap between these two groups is unfortunate to say the least. This paper hopes to diminish that information gap by presenting both the analytics involved and the experimental techniques required to start and maintain a successful SRM program.

III. Propellant Formulation

The five main constituents of a SRM are: oxidizer, fuel, binder, additives and curative. Any good standard rocket propulsion book, such as “Rocket Propulsion Elements” by Sutton and Biblarz or “Space Propulsion Analysis and Design” by Humble, Henry and Larson, will list the functions of each component. However a general overview is provided below for each constituent. This section also serves to show more details about specific types of each constituent. The combination of these constituents can be studied through the use of ProPEP or one of the GUI based derivatives of ProPEP such as GUIPEP. ProPEP provides necessary parameters for a basic evaluation of propellant performance but it is not always user friendly enough to provide the intricacies of additives and other small changes. For these considerations experimental testing is still the only viable research method and the only method for determining key ballistic parameters.

A. Oxidizer

SRMs are unique in that they contain all of the necessary combustion components in the combustion chamber unlike a hybrid or liquid which requires pumps or pressurized systems to deliver the combustion components during the burn. The largest percentage of a SRM is made up of oxidizer. The oxidizer provides the oxygen necessary to initiate and sustain combustion. The most common choice of oxidizer is ammonium perchlorate, but ammonium nitrate, potassium perchlorate and potassium nitrate among others are also used.

B. Fuel

Fuel for a SRM is typically a fine metal powder. While the binder will serve as sufficient fuel to sustain combustion, metallic fuel increases the performance of the system by increasing the stagnation temperature. There is an optimum percentage of fuel at which performance no longer benefits from increasing the fuel percentage. In the case of aluminum, one of the most common fuels, this tends to be around 6-8% in small to medium sized motors. Larger motors have longer combustion stay times and can fully combust larger percentages of fuel on the order of 10-15%. Magnesium, titanium and aluminum are relatively common while steel, brass, and zinc are also used to a limited extent. The combination of oxidizer and fuel is known as the “solids loading,” or percentage of the total propellant that is solid. For an easily packable beginners propellant 80% solids loading works very well. Performance increases can be realized by increasing the solids loading but certain additives are required to ease propellant processing.

Metallic fuel poses the largest hurdle for SRM design and manufacture, that hurdle is mostly due to federal regulation. It has becoming increasingly challenging to acquire aluminum and other metals in a fine powdered form. In order to get around the one pound of fuel per year restriction you have to increase the particle size to a point at which insufficient combustion will occur inside the combustion chamber. Unused fuel will be expelled from the motor resulting in decreased efficiency. There are still a couple vendors who have not been hit by federal injunctions yet, but that may not last very long. In the event that the pool of unregulated vendors dries up it will be necessary to attain a Low Explosives Manufacturers Permit, LEMP, from the Bureau of Alcohol, Tobacco, Firearms and Explosives, BATFE. A LEMP will allow the permit holder to buy whatever fuel is required; however; the process of attaining the permit is rather involved.

C. Binder

A binder acts in a literal manner; it binds the solid portions of the SRM propellant. Hydroxyl-terminated polybutadiene (HTPB), Carboxyl-terminated polybutadiene (CTPB), and PBAN are common binders. HTPB is the most common binder in the hobby realm as well as the university level groups and is our binder choice as well. The binder provides more fuel to combine with the metallic fuel and combust with the oxidizer. Typical binder percentages are around 15-20%, with the higher percentages being much easier to manufacture.

D. Additives

Propellant additives include burn rate modifiers, plasticizers, stabilizers and numerous other categories. Burn rate modifiers include iron oxide, copper oxide, strontium nitrate and countless others. These modifiers serve to modify the regression rate of the propellant by changing the burn rate coefficient, a, exponent, n, or both. These changes to the regression rate are still not able to be determined analytically so experimentation is required. The use of burn rate modifiers is not something to be taken lightly; percentages must be kept low, 0.05 to 0.5%, until a solid understanding of the interaction is established. A plasticizer such as dioctyl adipate, DOA, helps make the propellant easier to mix and helps ensure uniformity. Plasticizers are typically used at about 0.25 to 0.5%. In a low or no metals propellant carbon black is added at about 0.5% in order to increase the opacity of the propellant. A translucent propellant runs the risk of undesired radiative heating on the wall surface and thus inadvertent combustion of excess propellant likely resulting in over-pressurization. Cross linking agents, anti-oxidants and numerous other chemicals can be used to tailor the final propellant but these are not necessary for initial research endeavors.

E. Curatives

Curatives are the final major constituent of SRM propellant. Isonate 143L and Isophorone diisocyanate (IPDI) are two common curatives which are typically about 10-15% of the binder mass but may vary based on environmental parameters. The actual amount of curative is based on what is known as the “equivalent weight.” This is a property that is specific to the binder and other propellant constituents. The general rule of thumb of 10-15% works in most situations but small batch binder cure tests are always recommended. Too much binder will cause the propellant to not fully cure. Typically the center of the grains or test batch will remain sticky or even liquid if there is enough excess curative. Isonate 143L is a great room temperature curative requiring no additional equipment. The downfall however is that the working time, or “pot life,” of the propellant is only 30-45 minutes. IPDI on the other hand has an almost infinite pot life until it is heated. IPDI requires up to 2 days at 140° F to fully cure. This property allows for long packing and processing times but does require that a heat box is constructed.

F. Additional required items

Electric matches are extremely useful for both SRM testing and general rocketry but are challenging to purchase. A LEUP is required to purchase electric matches prohibiting most people from using them. A short search on the internet will turn up numerous homemade methods to make electric matches and other ignition systems. SRM ignition charges are another challenge for most people starting in SRM design. One method that has proven very reliable uses 50 caliber pyrodex reloading pellets and any type of ignition system, electric match or other homemade solution. In larger motors it is acceptable to use a full pellet, whereas smaller motors can get by with a half pellet. A 1/16” or 1/8” dowel can be used to hold the igniter at the top of the motor. If the igniter is not placed at the top of the motor there is a significant risk of what is known as a hang-fire. This occurs when the flame front from the motor is established near the nozzle trapping a pocket of air at the top end of the motor. The lower grains will burn until the flame front can propagate to the upper grains. The end result is a longer than predicted burn time and the chances of casing burn through at the aft end depending on the severity of the hang-fire. This phenomenon is unlikely to occur as long as you are careful to place the igniter near the forward end of the motor and secure it with either a dowel or similar retention system.

IV. Propellant Purchasing and Regulations

The degree of difficulty inherent in the purchase and storage of solid rocket motor material is certainly worth mentioning. One might think that it is impossible as a student group to be able to mix propellant on campus. What the pessimist might not realize are the type of inherently dangerous activities that other departments are performing, often times no more than one wall away from a classroom or office. When the Daedalus rocketry group broached the subject of mixing propellant at ASU, the safety department official laughed and stated that another department was using quantities of TNT for some of their own research. Other on-campus labs were worse. The fact of the matter is that the safety department is used to these kinds of requests. It is the job of the researcher to convince them that the group is capable of following a strict set of rules and adhering to all manners of safety stipulations. It is difficult to illustrate the level to which the sponsoring department and safety officials will take this matter seriously. They will want to be involved and the safety officials will write up specific sets of rules just for the mixing and storing activities. They WILL check on the group's progress often and it is therefore very important to be transparent during safety audits. This sort of supervision is normal, and in the end you'll be very thankful for their diligence and concern for your safety.

Indeed propellant mixing can be quite unexciting (as it should be!) but it is important to follow all rules religiously. Of course cautions should be taken to avoid open flame and other heat sources, as with any oxidizer or fuel source. One important purchase that should be made prior to purchasing propellant or chemicals is a fire cabinet. In fact, at least two should be purchased to keep the oxidizers away from the fuels. Vendors for chemicals include firefox-fx.com and skylighter.com among others listed in Section X. Be sure to check with the company prior to placing an order to verify if you are legally allowed to make the purchase. Until recently ammonium perchlorate composite propellant (APCP), which we are discussing in this primer, was regulated by the Bureau of Alcohol Tobacco Firearms and Explosives (BATFE). Thanks to a member funded effort the Tripoli Rocketry Association and the National Association of Rocketry filed and won a lawsuit against the BATFE. The BATFE had deemed APCP an explosive despite evidence to the contrary. Unless APCP is cast into a closed vessel it deflagrates, or burns aggressively, making it a fire hazard but in no way an explosive. Regulations are constantly in a state of flux however, so please be mindful of the current state of regulation for any of the chemicals in your inventory.

V. Grain Design

Thrust histograms, commonly known as thrust curves, for SRMs are directly dependent on the grain geometry. Depending on the core shape, grain length and surface inhibition a SRM can be tailored to yield any thrust histogram desired to meet a given design mission. SRM thrust histograms fall into a few categories; progressive, neutral and regressive. Dual thrust motors are gaining popularity but are not recommended for initial research efforts. Depending on the grain configuration these categories can be achieved. All rocket motors, despite which category they fall in, adhere to the same total impulse equation shown below as Equation 1.

$$I_t = \int F \, dt \tag{1}$$

In the hobby realm total impulse is used to determine classifications for not only SRMs but other rocket motors as well. This classification system is based around the alphabet. An "A" class motor has an I_t between 1.26-2.50 N·s and each subsequent letter designation has twice the I_t of the one before it. For example a "B" motor has a max I_t of 5.0 N·s while a "C" motor has a max of 10 N·s. This is a system of convenience which is seldom seen in industry, but is useful when working with hobbyist groups and the national rocketry organizations.

The three categories of SRM thrust histograms are shown in Figure 1. Some sample grain geometries are shown in Figure 2.

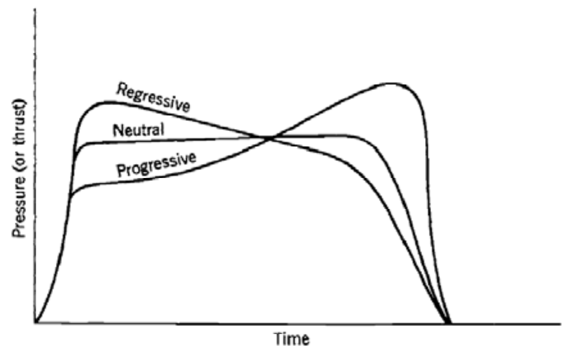

Figure 1. Categories for SRM thrust hitograms.[1]

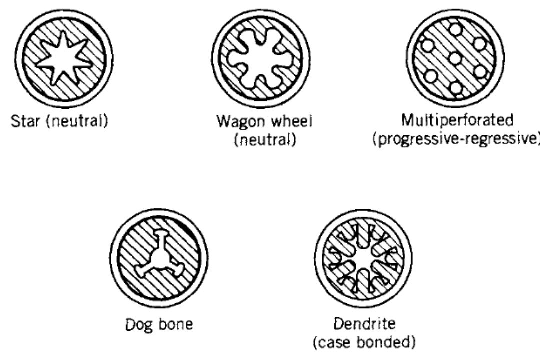

Figure 2. Sample grain geometries.[1]

Progressive burning motors are desirable when initial g-loading is a concern, especially in the case of sensitive payloads and they are also one of the most simple grain designs to manufacture. The most common progressive motor is a single long circular port. Other possibilities include multi-port designs but more often than not a multi-port grain will be progressive then regressive as the burn progresses. Progressive motors can be any grain design that exposes more burning surface as time increases. Regressive motors are exactly the opposite of progressive motors. They include dendrite and certain variations of the star, wagon wheel and tube and fin (finocyl) geometries. These motors are useful for situations when high initial thrust is required with a lower thrust sustained burn.

Neutral burning motors are the most commonly used in the hobby realm due to cost savings measures by SRM manufacturers. Manufacturers typically use multiple Bates grains for all of their motors because the grain itself is neutral. Therefore it is very easy to add or subtract one or two grains from a motor, change the nozzle throat and have a "new" motor to put on the market. A Bates grain is one of the most important SRM grain designs for the beginning and even experienced rocket group. It provides a test bed for new propellants and hardware because of the relatively predictable behavior. The ratio of core and outside diameter to grain length is what makes a Bates grain special. Bates grain length is shown in Equation 2 where D is the grain outside diameter and d_o is the initial core diameter.

$$L = \frac{1}{3}(3D - d_o) \tag{2}$$

This relationship allows individual grains to be designed as neutral and thus an entire motor comprised of multiple Bates grains to also be neutral. This is a quality which will become very important when propellant characterization and small scale testing is discussed later. Other neutral burning grain geometries include the wagon wheel, star and end-burner. These motors require that at any time during the burn the same amount of surface area is burning.

An important SRM design parameter which is rarely seen in university texts is the Kn value, also known as the K value in literature. This is the ratio of the burning surface area, A_b, to the nozzle throat area, A_t. The Kn value allows for a back of the envelope estimation of chamber pressure with a given grain and nozzle geometry. Typically Kn values between 180 and 280 are workable especially in small scale (38mm) test motors. These types of Kn values will yield chamber pressures in the range of 500 to 1000 psi which is acceptable for most 38mm motor casings (Be sure to check for factors of safety before assuming that any motor casing can handle a given pressure). If the results of small scale testing are favorable then the Kn value becomes a scaling parameter. A motor made with a given propellant formula will operate with the same chamber pressure regardless of actual size if it operates at the same Kn value. This allows for the reliable scaling SRMs without exact characterization of a propellant formula, which is an extremely valuable ability given the limited funds and time often afforded to university level rocket groups.

VI. Computational Ballistic Modeling

Commercial software options are available for the ballistic modeling of solid rocket motors. Burnsim is the most widely used of these software packages. It was developed by Greg Deputy and is available for a small fee that funds the continued development of the software package. Information on obtaining the software is included in Section X. The second option is to create a simulation program through the use of MATLAB, C++ or any other coding language capable of iterative solutions. This is even possible through the use of spreadsheet based software.

The modeling of solid rocket motor performance can be accomplished through the implementation of an iterative solution. The process used to determine performance is based on a few key concept and fundamental equations. This process requires knowledge of the burn rate coefficient, exponent, density, characteristic velocity and specific gas constant for the propellant under analysis. Also required are the general parameters of the combustion chamber, nozzle and ambient operating conditions. These parameters are used to determine propellant burn area, chamber pressure and thrust as a function of time.

The process starts with a determination of initial values for burn area, chamber pressure and burn rate. With these initial conditions the iteration is initiated, with "i" denoting the current time step and "i-1" denoting the previous time step. The first step is to determine the burn area for the desired grain geometry. The grain geometry directly impacts the thrust profile of the final motor so selection is key to both the modeling method as well as the desired final performance. Refer to Section V for more information on geometry selection. In order to determine burning area, all surfaces that are not inhibited must be accounted for, where the equations for two possible geometries are discussed below.

The iteration initiates at a second time step, i = 2, since the first time step is the initial conditions. The ratio of initial burn area to throat area, sometimes referred to as the Kn value or in literature just as K, is shown in Equation 3.

$$K_{i-1} = \frac{A_{b_{i-1}}}{A_t} \tag{3}$$

From this ratio as well as the propellant burn rate coefficient, pressure exponent, propellant density and characteristic velocity the chamber pressure can be determined at the previous time step using Equation 4.

$$P_{c_{i-1}} = (K_{i-1} a \rho_b c^*)^{\frac{1}{1-n}} \tag{4}$$

The chamber pressure is used in conjunction with the burn rate coefficient and exponent to determine the regression rate at the current time step using Equation 5.

$$\dot{r}_i = a {P_{c_{i-1}}}^n \tag{5}$$

The regression rate allows for the burning surface to be determined at the next time step. At this point differentiation must occur depending on the chosen grain geometry.

The methodology used for finding the burn area as a function of time alters the coding scheme due to physical break points such as reaching the combustion chamber wall. The first geometry investigated is the common Bates grain discussed in Section V and shown below in Figure 3. Burning occurs at the core and on both ends for this grain configuration. Equation 6 shows the burning area for the Bates Grain at the current time step.

$$A_{b_i} = 2\pi r_i L_i + 2\pi {r_i}^2 \tag{6}$$

where,

$$R_i = R_{i-1} + \dot{r}_{i-1} dt$$
$$L_i = L_{i-1} - 2\dot{r}_{i-1} dt$$
$$R_i < R_{chamber}$$

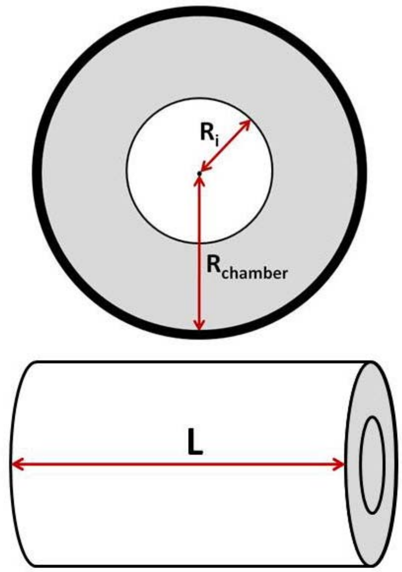

Figure 3. Bates grain characteristic parameters.

This burning area is used along with Equations 3-5 in a computational loop until the core radius reaches the combustion chamber radius, at which point there is no propellant left to burn.

A second geometry investigated here is a full length grain with an x-shaped core. In this case the ends are inhibited so the only burning surface is on the core. There are two distinct burn phases: the first phase is the burning of the x until the combustion chamber wall is reached by the widest portion of the x-shape (dimension c), this is shown in Equation 7 and Figure 4.

$$A_{b_i} = 4a_i L_i + 8b \tag{7}$$

where,

$$a_i = a_{i-1} + 2\dot{r}_{i-1}dt$$
$$c_i < 2R_{chamber}$$

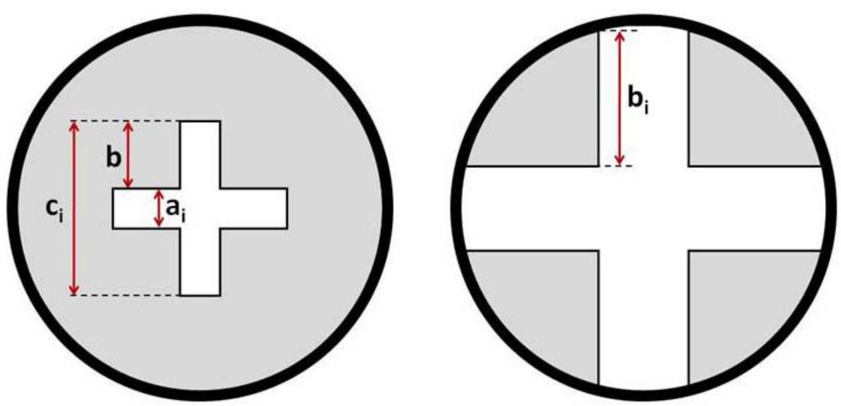

Figure 4. X-core characteristic parameters phase 1 (left) phase 2(right).

The second phase of the burn is initiated when the widest part of the x (dimension c) reaches the combustion chamber wall diameter. This phase continues until dimension b goes to zero and is governed by Equation 8 and shown in Figure 4.

$$A_{b_i} = 8b_i \tag{8}$$

where,

$$b_i = b_{i-1} - \dot{r}_{i-1}dt$$
$$b_i > 0$$

Any complex geometry can be modeled with a unique set of equations for characteristic dimensions. Trouble shooting will be required for more complex geometries due to certain areas of the grain being consumed. A paper study into the characteristic shapes in the grain (rectangles, triangles, circles, etc.) during the full burn duration is always recommended prior to writing a formal code. This allows for a sanity check on the code results.

In conjunction with the above calculations a few other performance parameters can be determined. The first of these is the propellant mass flow rate. The burning area is used with the regression rate and propellant density to find the mass flow rate of the propellant as shown in Equation 9.

$$\dot{m}_i = \dot{r}_i A_{b_i} \rho_b \tag{9}$$

Equation 9 is essentially a volume of propellant multiplied by its density thus giving the total mass of propellant converted from solid to gas. Conservation of mass states that the mass flow rate from the propellant must be equal to the mass flow rate out of the nozzle. The thrust of the motor can then be determined given the dimensions for the nozzle and the ratio of specific heats of the propellant. Equation 10 calculates the exhaust velocity as a function of the chamber pressure, exit pressure, chamber temperature, specific gas constant and ratio of specific heats.

$$v_{2_i} = \sqrt{\frac{2\gamma}{\gamma-1} R T_c \left[1 - \left(\frac{P_2}{P_{c_i}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{10}$$

With the exit velocity determined and the known ambient pressure the thrust is calculated as shown in Equation 11.

$$F = \dot{m}_i v_{2_i} + (P_2 - P_3) A_2 \tag{11}$$

A second method which is somewhat less susceptible to coding errors involves the use of a thrust coefficient which accounts for the increase in performance due to the expansion of the nozzle. Typical values for the thrust coefficient are 1.2-1.4. The thrust coefficient can be found using Equation 12.

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1 - \left(\frac{P_2}{P_{c_i}}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \left(\frac{P_2}{P_{c_i}} - \frac{P_3}{P_{c_i}}\right)\frac{A_2}{A_t} \tag{12}$$

With the thrust coefficient the thrust can be determined using Equation 13 and the nozzle throat area.

$$F = A_t P_{c_i} C_F \tag{13}$$

Once the ballistic simulation is complete the total impulse can be determined by integrating the entire thrust curve. The specific impulse can then be found with the known propellant mass. These two parameters are shown in Equations 14 and 15.

$$I = \int_0^{t_b} F\, dt \tag{14}$$

$$I_{sp} = \frac{I}{m_p} \tag{15}$$

The specific impulse can be thought of as the fuel efficiency for a propulsion system. It represents how much useful work you get out of a given amount of propellant. Large scale SRMs can achieve specific impulses upwards of 250 seconds. In the small scale motors we typically test, the theoretical specific impulse will be significantly higher than the actual specific impulse from testing. Typically we have seen our small scale motors perform in the 180-200 seconds range.

These are general methods for solid rocket motor ballistic modeling and simulation. More advanced methods are available but for the university level engineer this methodology works well and can be a valuable tool as well as a great learning experience. A word of warning, the time step, dt, in this method must be small in order to achieve accuracy. Typical values used range from 0.01 seconds on small motors to 0.1 seconds on larger motors. This time sensitivity is due to the nature of the solution. The solution calculates ballistic parameters based on the geometry at the current time step. If the time step is short the characteristic dimensions do not change significantly during the time step. If the time step is large however the increase in burning area can be quite steep and will cause undesirable results. This warning is more applicable to non-neutral burning motors since in theory a motor with a neutral burn can be approximated using the starting and ending conditions. In reality a "neutral" Bates grain does have similar starting and ending parameters but a slight hump occurs in the middle of the burn.

VII. Propellant Mixing

The following section outlines how to mix SRM propellant. It does not specify any propellant quantity amounts. First, there is some essential equipment that any group interested in SRM manufacture will need to acquire. This is not a complete list but is a good starting point for a new operation.

1) An orbital stand mixer preferably 4 of 5 quart capacity. This mixer can NEVER be used for anything but propellant again.
2) Two scales: 0.1 gram sensitivity; 300-500 grams capacity and a less sensitive scale with at least a 5 kg capacity.
3) Vinyl/Neoprene gloves – These need to be worn at all times when measuring or mixing uncured propellant or chemicals.
4) Dixie cups and disposable bowls, spoons, spatulas – We prefer "Spongebob Squarepants" themed cups because they are hard to miss and must be disposed of in the burn box not the normal trash.
5) Burn box – Everything that cannot be cleaned goes in the burn box, including the cleaning towels.
6) Motor casing, casting tubes, liners, end caps – commercially available.
7) Dowel rods – 0.5 to 0.75 inches in diameter, keep at least a couple of sizes on hand for packing.

Assuming that you were given a list of ingredients and quantities, the following steps shown in Table 1 outline the SRM mixing process. Information about the grain geometry and propellant formula will impact the quantities mixed when you reach the point of mixing your own motors. (See image numbers associated with each step)

Table 1. Mixing procedure used at Arizona State University.

Description of Steps	Associated Figures
1) Binder a) Place the mixer bowl onto your large scale, zero the scale and add the full binder amount. (#1)	
2) Fuel b) Slowly add the full amount of fuel to a bowl. Be aware of "dusting," airborne metallic fuel particles are a flash explosion hazard. c) Slowly pour the fuel into the mixer bowl and mix by hand until no dry fuel is present. (#2) d) Place the mixer bowl in the mixer and mix at medium speed for 5 minutes. e) Scrape the bottom of the mixing bowl and mixer paddle with a spatula at least 3 times during mixing to ensure proper incorporation.	

3) Additives and Plasticizer
   a) Measure additives and plasticizers into separate Dixie cups on your small scale and add to the mixer bowl one at a time. (#3)
   b) Mix by hand until the propellant is entirely wet then mix at low to medium speed for 5 minutes. (#4)
   c) Scrape the bottom of the mixing bowl and paddle with a spatula at least 3 times during mixing to ensure proper incorporation.

4) Oxidizer
   a) Measure no more than 300 grams of oxidizer into a bowl and mix into the propellant by hand until mostly incorporated. Mixing with a hard plastic spatula will be necessary near the end of the process. (#5)
   b) Mix at low speed for 5-10 minutes until the propellant returns to a uniform appearance.
   c) Repeat the process until all oxidizer is incorporated. More hand mixing will be necessary near the end as the propellant will become dense and hard to mix after each oxidizer addition. (#6)
   d) Scrape the bottom of the mixing bowl and paddle with a spatula at least 3 times during mixing to ensure proper incorporation.

5) Curative
   a) Measure the curative into a Dixie cup and add to the propellant.
   b) Mix by hand until the curative is well distributed then mix on low to medium speed for 5 minutes. Higher ambient temperatures will shorten cure time, but at least 5 minutes of mixing is necessary.
   c) Scrape the bottom of the mixing bowl and paddle with a spatula at least 3 times during mixing to ensure proper incorporation.

6) Casting the Grains
   a) Roll a 1 inch ball of propellant and drop into the casting tubes for small motors with no core rod and make “donuts” on larger motors to drop in around the core rod. (#7)
   b) Use dowel rods to pack the propellant into the corners of the casting tube being careful not to allow air bubbles in the propellant. (#8)

VIII. Propellant Casting and Curing

In order to improve propellant quality and reduce voids in the final propellant a vacuum system can be used. This is certainly not a requirement as we have made numerous large scale solid rocket motors without the benefits of vacuum processing with a great deal of success. The objective is to expand any air bubbles in the propellant to the point of popping by applying a vacuum to the mixer bowl. Ideally this would be done with the mixer running to enhance the effect by exposing more surface area and allowing more bubbles to escape. Unfortunately a vacuum box large enough to fit the mixer inside is somewhat more challenging and expensive to construct. As an alternative, a vacuum setup can be created that attaches to the top of the mixer bowl.

This type of system only requires a single piece of polycarbonate sheet about a half inch thick and large enough to rest on the top of the mixer bowl (12”x12”) to create the vacuum chamber since it uses the bowl itself as the majority of the chamber. The other components needed are a vacuum pump, a length of hose, a relief valve and some hose fittings. The complete system is shown in figure 5.

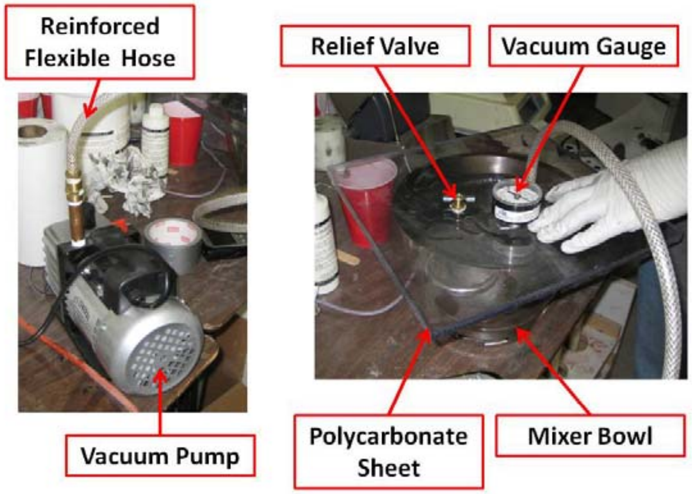

Figure 5. Vacuum system components.

Vacuum pumps can be found in numerous places online or for a cheap and slightly less reliable option at your local Harbor Freight tool store. These pumps are typically used for pulling vacuum on air conditioning systems prior to recharging them with refrigerant. The Harbor Freight pump is certainly not ideal but for the budget minded university group it is a good starting point. A word of caution, do not try to remove the hose fitting installed on the pump, try to adapt off of it. There is a screen and filter that will break if you remove the fitting allowing pump oil to be sucked into the vacuum hose. Once you have your pump and polycarbonate sheet you need to drill and tap holes in the sheet to accept your hose fitting as well as your relieve valve. Lastly, connect the hose to the pump and sheet and you are ready to pull a vacuum. A vacuum gauge can be added to the sheet as well to see how strong of a vacuum is being created but this is not necessary. Some form of gasket may be needed to give a good initial seal between the bowl and sheet, black electrical tape on the lip of the bowl has proven to work well, once the vacuum is started the sheet will hold on tight to the bowl.

As mentioned in the discussion of curatives above IPDI is a high temperature curative for HTPB allowing for increased working and processing time. In order to achieve the required 140° F a heat box needs to be created. A simple wooden box that is large enough to hold the grains you are trying to cure as well as the heat sources is all that is required. Some extra area for circulation is also advisable as is some form of additional insulation if your ambient temperature is low. The simplest and safest heat source for this situation is normal incandescent light bulbs; they offer a sealed system with no exposed heating elements. Two 200 Watt light bulbs in a two foot cube heat box maintains 150° F very well. Wall mount light sockets and two conductor wiring can be found at your local hardware store and assembled with a little bit of engineering knowhow or advice from someone with experience. Optionally, a dimmer can be wired into the circuit to allow more precise temperature control. Temperature measurement can be performed using a simple probe style meat thermometer. Drill a hole just large enough for the probe on the lid of the box and you can easily monitor the temperature. A word of caution, do not leave this heat box in a location where faulty wiring can cause a fire that would damage more than the box itself. The best location to leave the heated box would be outside with no combustible materials either nearby or above the box. The likelihood of a fire from a wooden box at such a low temperature is very low but since the wiring is not professionally done precautions should be taken.

IX. Testing

A very necessary step in motor production is testing. The intent of this section is to familiarize the reader with several SRM testing methods that are currently in use at Arizona State University. Three such methods have been used to date: strand (Crawford) burner, small-scale testing and full-scale testing. Inherent in each method is the necessity for proper instrumentation. Examples of data that can be gathered include temperature, pressure and thrust all as a function of time. Of these, pressure and thrust data are the most essential. From these values, the all-important "a" and "n" values for St. Robert's Law, shown as Equation 16, can be easily determined.

$$\dot{r} = aP_c^n \tag{16}$$

Small and large scale testing has the potential to be either relatively affordable or prohibitively expensive depending on the approach taken. The largest potential cost associated with ballistic testing is the data acquisition system, DAQ.

A. DAQ Systems for Ballistic Testing

A relatively low cost DAQ system can be put assembled *LabVIEW*™ programs can be written to store the information and assist in the necessary calibration of the input voltages from load cells and pressure transducers. A pressure transducer (*Omega Engineering*™ PX309-2KG5V) can be directly attached to this DAQ as the resolution of the DAQ is of sufficient quality to resolve the voltage output. A variable DC voltage power supply is used to supply the excitation voltage. Special consideration is required for the load cell. Typical load cells require excitation voltages of around 10volts, but will output voltages of the order of millivolts (either 2 or 3 mV/V typically). This is simply too low for a low cost DAQ to resolve. To alleviate this problem use of an operational amplifier (op-amp) is required to increase the magnitude of the output voltage. One such op-amp was built by Daedalus personnel for an approximate cost of $40. The op-amp shown in Figure 6 is a low-price homemade solution to the low output voltages from the load cells, more information can be found at the website listed in Section X.

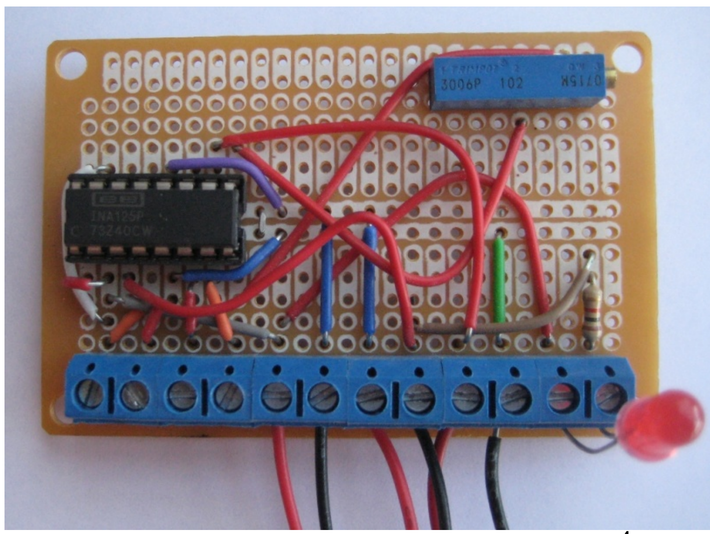

Figure 6. Op-amp used to amplify load cell output.[4]

This op-amp is powered by two 9 volt batteries and works reasonably well with fresh batteries. The gain is adjustable through the use of a potentiometer mounted to the board. This adjustability also provides a source of error though. Load cell calibration must be performed every time the op-amp is used since variations in battery voltage and gain setting will skew results. A commercially available option also exists from Aerocon Systems (link available in Section X). This option has the benefit of being commercially tested and proven but still has a number of disadvantages that must be overcome for reliable operation.

Large improvements in data acquisition can be made through the use of higher quality DAQ hardware. Unfortunately these improvements come at a steep price. The DATAQ DI-718B DAQ is a very versatile and easy to use piece of hardware. It has the capability to accept almost any type of sensor through the use of signal conditioning modules. These modules include built in op-amps and excitation voltages where necessary and make instrumentation very simple to set up. The DI-718B costs around $800 for the unit and around $100 for each instrument module. This DAQ allows connectivity with a computer through local area network allowing a standard CAT-5 crossover cable to be used for remote monitoring and recording. The people at DATAQ also offer an educational discount and are very eager to help students. When testing becomes critical enough to warrant the extra cost this is one of the best options available for ease of use and reliability.

B. Instrumentation Considerations

As mentioned above, the specific type of instrument in use directly impacts what you need in order to be able to reliably and accurately record meaningful data. The DATQ system allows for any number of instruments to be used simultaneously with the appropriate signal conditioning module. This includes pressure transducers, load cell, thermocouples, accelerometers and many others. The low cost DAQ from *National Instruments*™ is not as user friendly in the case of thermocouples and other instruments.

The majority of the instrumentation used at Arizona State University for rocket propulsion research comes from Omega engineering with a few from Futek. Omega is a great source for load cells, pressure transducers, thermocouples and associated accessories. Table 2 shows the instrumentation that has been used at Arizona State University with success.

Table 2. Instrumentation used for ballistic testing.

Instrument	Model
Load Cell	Omega LCGB series (Small motors, 0-500lb) Futek QLA154 series (Large motors, 0-2000lb)
Pressure Transducer	Omega PX-303 series (0-1500psig) Omega PX-309 series (0-2000psig)

When selecting the appropriate measurement range for instruments your future testing must be taken into consideration. If you plan to move to large scale motors down the road you need to look at whether or not a single load cell can serve both your large and small scale needs. It may be that you need two load cells in order to be able to get meaningful data in both cases. A general rule of thumb is to aim for a full scale pressure or load rating of around 150% of your expected values. This allows for system failure with a higher possibility of salvaging instrumentation. In the event of a motor over-pressurization or the ejection of a nozzle or forward closure during a burn the instrumentation will experience higher than expected loads. If your instrument is only rated to 10% above what you expect then that instrument will be overloaded and possibly ruined in the event of a failure. When selecting instrumentation be sure to note the input and output voltage. Depending on your choice of DAQ you will either have to provide that with a DC power supply or from the signal conditioning modules. Often instruments are available in both millivolt and volt output versions. If you are using the lower cost DAQ then the voltage output will make your life much easier since you will not need to amplify the signal. With the DATAQ system the extra cost of the volt output instruments is not incurred since the signal conditioning module takes care of the amplification.

Pressure transducers require some special consideration from the system design standpoint. When designing the sensing port on a solid rocket motor it should be considered that the direct impingement of hot propellant gases on the sensing diaphragm in the pressure transducer may cause the pressure transducer to produce erroneous pressure measurements during the initial transient of motor operation. This cause has been attributed to the transient thermal nonequilibrium[2] and has been revealed to exist in Daedalus motor hot-fire tests, even on tests where a pressure snubber is used. It is therefore good practice to pack the inside of the acoustic cavity with high temperature silicon grease, such as *Dow Corning*™ 111 Valve Lubricant and Sealant. This will help mitigate the problem by blocking the direct impingement of the hot propellant gases. Other options include the extension of the pressure sensing port to allow the gases to cool before the contact the pressure transducer or specialty high temperature pressure transducers.

C. Strand Burning (Crawford Burner)

One viable method for measuring the regression rate of a propellant makes use of an apparatus called a “strand burner” or “Crawford burner.” The purpose of such a device is to burn a strand of propellant no larger than a normal drinking straw in a high pressure vessel. This vessel is meant to mimic the operating pressure inside of a typical SRM, approximately $300psi < P_c < 1{,}200psi$. The advantage to using a Crawford burner is that a new propellant combination can be rapidly tested at differing operating pressures. The regression rate coefficient and exponent can then be extrapolated and used towards the design of larger motors.

One Daedalus member recently built and operated such a device[3]. The current Crawford strand burner consists of a high pressure tank that serves as the combustion bomb. A length of iron pipe is used to support the propellant strand and the required sensing and ignition wires. This pipe has a quick disconnect fitting and valve on the other end allowing for pressurization and venting. The strand of propellant is assembled onto the support structure, the break wires are connected to the sensing leads and the igniter is installed in one of the strand. The strand is then placed into the tank and the pipe threaded in with Teflon tape providing a pressure seal. Through the use of a *LabVIEW*™ virtual instrument the timing initiates when the first break wire is burned through and ends when the second break wire is burned through. Data for tank pressure and burn time is recorded at multiple tank pressures. The results of this testing are used to determine the ballistic parameters of the propellant as shown in Figure 7.

Validation of the Crawford burner agrees quite well with small-scale testing, though there is an approximate 15% error associated with the use of the Crawford burner, as shown in Figure 7. Both sets of data correlate well to existing data for composite AP/Al motors. However, there is also a known discrepancy between small-scale tests and full scale motors of 4 to 12% due to scaling factors[1]. As such, though the Crawford burner provides a reasonably good match of propellant characteristics ("a" and "n" values), it is not a complete substitute for full-scale test fires prior to a high powered rocket launch.

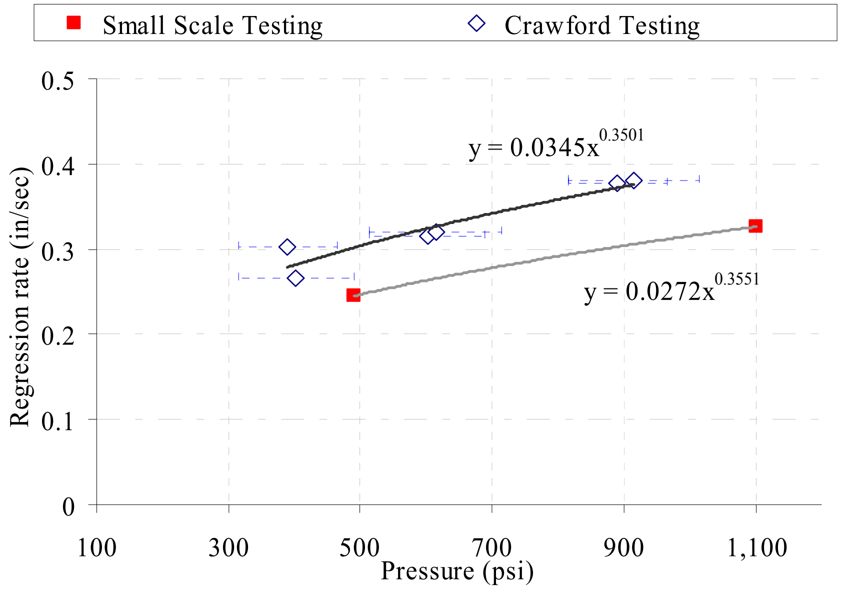

Figure 7. Results from Crawford strand burner testing.[3]

D. Small-scale Testing

In this context the definition of small-scale testing is approximately an "H" impulse motor, or approximately 250 N-sec. For some applications this might constitute an actual flight motor if a small rocket is used. There are slight discrepancies between full-scale and small-scale SRMs based on scaling effects. This means that performance will not be directly scalable between small scale tests and full scale flight motors. However the low cost and rapid prototyping advantages make them an obvious choice when trying to characterize propellants or investigate new technologies. The goal is to test a motor in its full configuration (nozzle, forward closure, actual grain geometries), but at a small-scale. In this manner, we can easily extrapolate the empirical burn rate coefficient and exponent that characterize the propellant. An example follows of two 38mm diameter "H" class impulse motors.

Two small-scale motors were designed to have neutral thrust curves, through the use of the Bates grain configuration, and two different Kn values to allow for the determination of the burn rate coefficient and exponent. The first motor consisted of four 2" long grains with 0.5" cores and utilized a 0.375" nozzle throat diameter. This configuration resulted in a Kn of 198. A second SRM consisted of four 2.1" long grains with 0.375" cores and utilized a 0.2968" nozzle throat diameter yielding a Kn value of 281. The components of the small scale test motors are shown in Figure 8. These two motors were instrumented with a pressure transducer and a load cell as shown in Figure 9. The test stand used for small scale testing was designed and built by Daedalus members and is shown in Figure 10 during one of the small scale tests. The resulting pressure and thrust data for motors 1 and 2 are shown in Figure 11.

Figure 8. Small scale motor components prior to assembly.

The motors were tested and data was recorded through the use of a load cell and pressure transducer. The pressure transducer was adapted to interface with the forward closure of the motor through a custom made adapter. This adapter was made from a piece of one inch square bar stock three inches long. One end of the stock was tapped to accept a ¼-20 bolt thread and the other end was tapped to accept the pressure transducer, ¼ NPT thread. A through hole was created to allow pressure sensing. To attach the adapter to the forward closure a vented bolt was purchased from McMaster-Carr (Part number 93235A542). The head was cut off of the bolt and a nut was used to bind the bolt against the adapter. The other end of the bolt was threaded into the ¼-20 hole in the forward closure after 1/16" sensing hole was drilled into the combustion chamber. This is the low cost solution for chamber pressure measurement in these small scale motors. A custom forward closure could also be machined if the resources are available to do so.

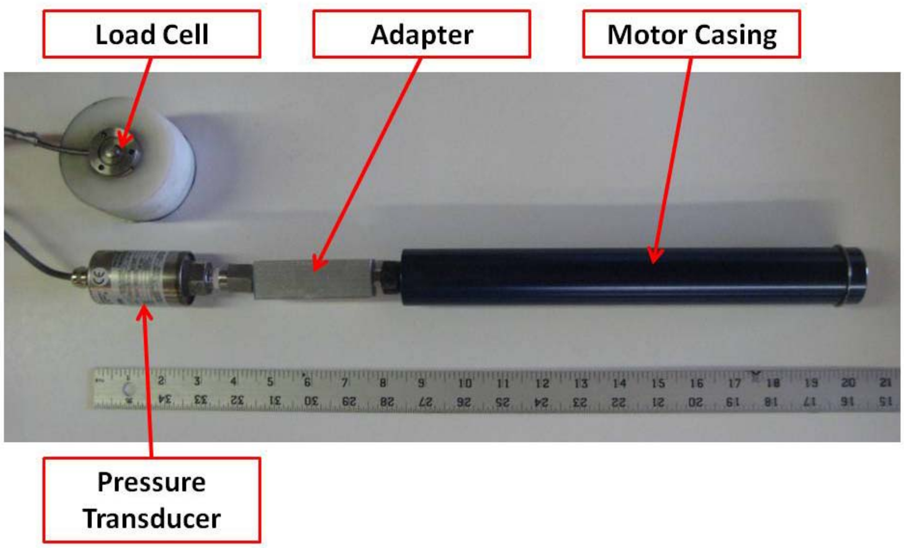

Figure 9. Small scale motor with instrumentation.

Figure 10. Horizontal test stand in use during a small scale motor test.

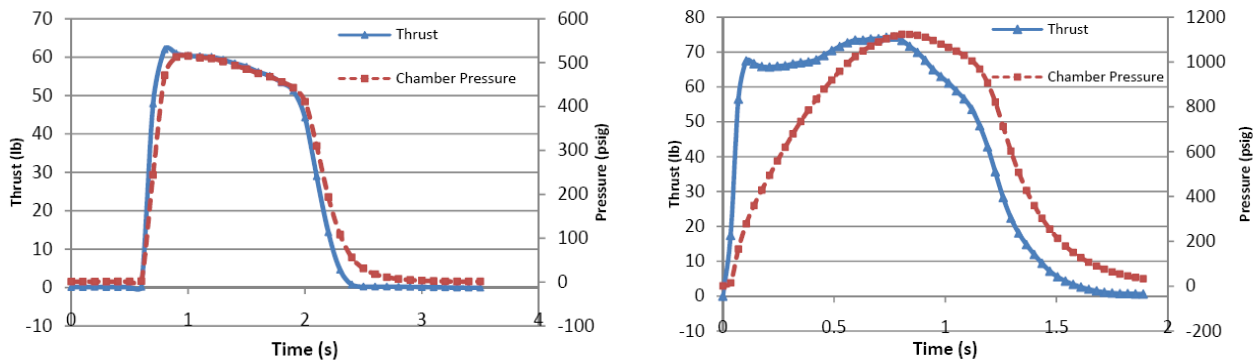

Figure 11. Test data from two small scale test motors.

The burn rate coefficient “a” and exponent “n” are easily determined using the chamber pressure, burn time, and grain dimensions. The method for determining the burn rate coefficient and exponent first involve determining the burn rate by dividing the web thickness by the burn time. With this parameter and the average stagnation chamber pressure, P_c, from the data above St. Robert’s law was used to determine the burn rate exponent using a root finding method. Alternatively, a power fit trend line in any standard spreadsheet can be used to arrive at the same results as shown in Figure 7.

When established, the empirical burn rate coefficient and exponent are the empirical numbers used to characterize that specific propellant combination. Any small changes in the formula will result in a change, even a drastic change, in the “a” and “n” values. Other factors that contribute include the method and consistency of the motor mixing, temperature variations, and a change in propellant constituent particle sizes, amongst others.

E. Full-scale Testing

Despite all of the knowledge that can be gained from small scale testing there is still great value in full-scale testing. As mentioned above, the regression rate can vary when proceeding from small-scale to full-scale SRMs. Therefore, the only way to have an accurate description of your thrust curve, and thus total impulse, is to do full scale tests. On that note, it is never recommended to proceed to full-scale testing on the first try, especially when impulses are of the range of an “M” motor (~6,000 N-sec) or larger. A catastrophic failure is not only dangerous, but very expensive. A commercial case and nozzle of that size regime cost upwards of $300. As such it is best to have your custom propellant fully characterized prior to full scale firing.

Full-scale testing practices differ from small-scale testing practices in one major way: thrust. The increased thrust of the motor must be properly managed. Whereas a horizontally directed thrust stand is adequate for smaller motors, it may not be sufficient for full-scale tests, a lesson learned the hard way (see Figure 12).

Figure 12. Results of a large scale motor test on the horizontal test stand.

Motors with thrust on the order of 500 or more pounds simply cannot be tested on a mobile test stand without permanent test stand mounting. In the case above the test stand was being held into the ground with six pieces of rebar driven 2 feet into the ground. These supports were pulled out of the ground with ease during testing. For more powerful motors, Daedalus now employs a custom vertical thrust stand set utilizing a 2,000lb donut load cell with a thru-hole (*Futek*™ QLA154). This thru-hole provides room for a pressure transducer to be attached to the forward closure of the motor. The line of action of the thrust through the donut load cell is therefore not directed onto the pressure transducer in any way. The vertical thrust stand uses the ground as a backstop preventing the test stand from moving during the burn even when testing high thrust motors. A CAD model of the vertical test stand and a picture from a hybrid rocket motor firing are shown in Figure 13.


Figure 13. Vertical test stand in CAD form (left) and in use (right).

F. Remote Launch Control System

In order to safely and reliably ignite solid rocket motors a launch control system is necessary. This system can be as simple as a 12 volt car battery and a two conductor wire (such as speaker wire). Connect one end of the wire to the igniter and the other end of the wire is the "controller." When ready to ignite the motor or launch a rocket, simply touch the two ends of the wire to the positive and negative terminals on the car battery. This is by far the cheapest solution to the problem but it lacks professionalism and safety features.

A more elegant system makes use of an automotive relay to prevent the full 12 volts from traveling all the way from the test stand or launch pad to the launch controller. The relay is triggered by the closing of the launch circuit at the controller allowing the full 12 volts to pass through the igniter. This keeps the voltage source near the point of usage and prevents any losses due to long cable runs. The system used at Arizona State University is adapted from plans created by Carl Tulanko, see Section X for a link to the plans. The system has a built in power switch and other useful features in both the pad box and launch controller. Some trouble shooting is necessary to make the system work with your components but the final result has proven very reliable. The general schematic is shown in Figure 14.

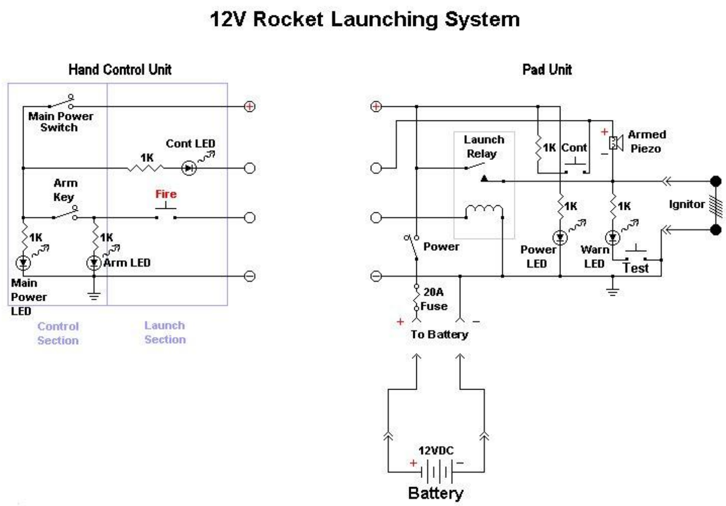

Figure 14. Launch controller designed by Carl Tulanko.

The system was adapted to have three channels in the most recent iteration. The pad box, built into a cheap toolbox is shown in Figure 15. The hand unit, built into a typical electronics project box is shown in Figure 16.

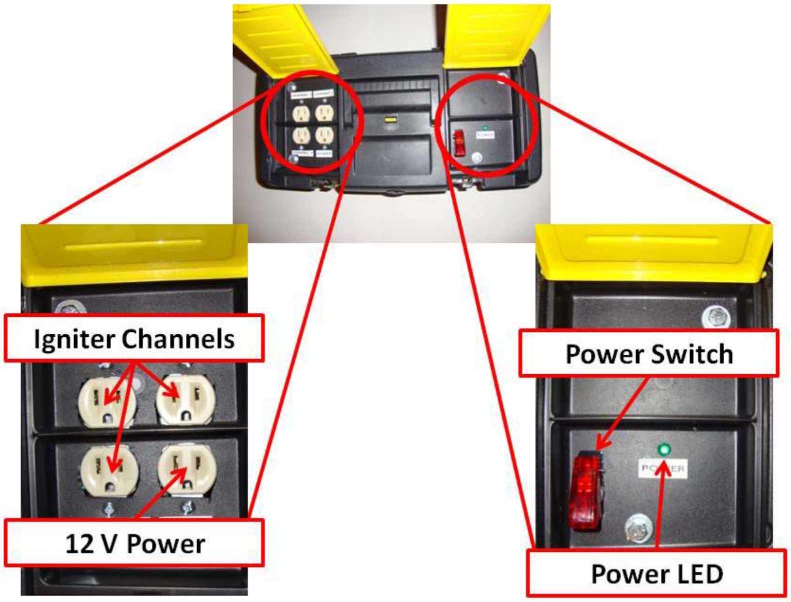

Figure 15. Launch controller pad unit component view.

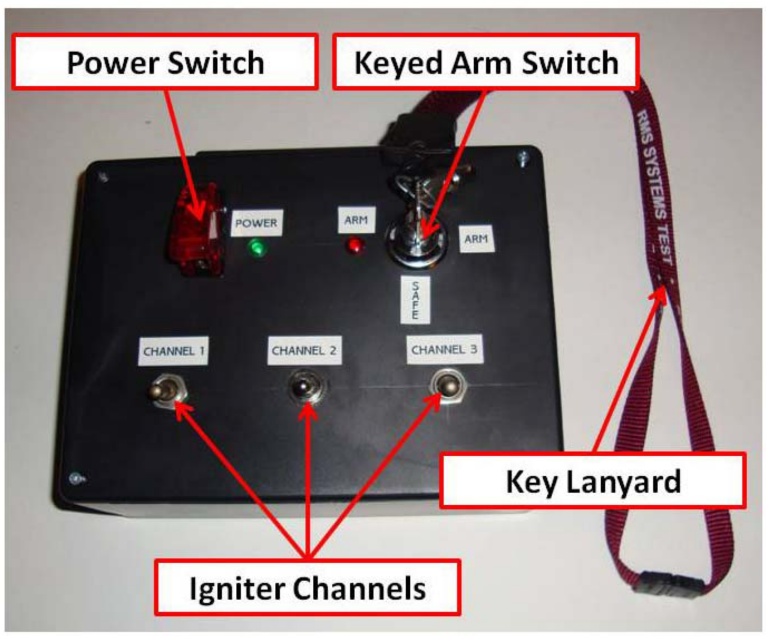

Figure 16. Launch controller hand unit component view.

The power switches all have safety covers preventing the power from being turned on accidentally. The key switch on the hand unit only allows the key to be removed in the off position so that the system cannot be left in the armed position. The keys themselves are also attached to a lanyard making them both harder to lose and more obvious if left in the armed position. The igniter channels are momentary normally off switches so that they cannot be left in the on position. The relays used are 12V 30A automotive relays from RadioShack (Part Number 275-226) and the majority of the switches and LED's are also available there. The key switch is a specialty item that a local electronics supplier will be able to find for you. To connect the hand and pad unit a CAT-5 cable can be used. This allows the cable to be bought in bulk and ends crimped by hand or a pre-made cables can be purchased. Networking wall outlets can be used for the connections at the pad unit and hand unit. The igniter connections are made through 15 foot indoor extension cords. These are available for about three dollars and come ready to plug into the standard outlets used for the igniter channels. The female end of the cord is cut off and alligator clips are attached. The same process is followed with the power cable but automotive battery clips are used in place of alligator clips. This is just one option that can be created to fulfill the launch controller requirement, though countless other options are available and a little research will yield the best solution for a given application.

X. Resources and Recommended Reading

General information that will prove useful to anyone starting a solid rocket motor development program is presented in this section. This includes reference texts that serve as extremely valuable resources during the design phase as well as vendors and information sources discussed in the preceding sections.

Required Reading:

"Experimental Composite Propellant" by Terry McCreary – A fantastic starting place for anyone interested in SRM design and manufacture.

Reference books:

"Rocket Propulsion Elements" by George P Sutton and Oscar Biblarz
"Space Propulsion Analysis and Design" by Ronald W. Humble

Vendors and Information

High quality data acquisition hardware – www.dataq.com
Op-amp information - http://www.jamesyawn.com/electronicstand/amp/index.html
Instrumentation – www.omega.com
Instrumentation – www.futek.com
Motor casings and casting supplies – www.lokiresearch.com
Chemicals – www.firefox-fx.com
Chemicals – www.skylighter.com
General motor information - http://www.nakka-rocketry.net/
Tripoli Rocketry Association (National Organization) – www.tripoli.org
Load cells/pressure transducers – www.omegaengineering.com
General hardware and materials – www.mcmaster.com
Metal stock – Local metal supplies (Industrial Metal Supply, Metal Supermarket, etc)
Vacuum pump – http://www.harborfreight.com/cpi/ctaf/displayitem.taf?Itemnumber=98076
Launch Controller by Carl Tulanko – http://www.rocketreviews.com/reviews/all/scratch_micromaxx_mega_pad.shtml

XI. Conclusion

The methods and information presented in this paper are offered as a template from which any university can have a solid knowledge base in preparation for starting a productive SRM research program. The authors do not claim to be experts in the subject at hand but simply wish to pass along the lessons learned and associated research that has been performed by Daedalus Astronautics at ASU over the past four years. The information presented in this paper is constantly being updated and refined as more experience is gained and more advanced research is performed. Ideally other universities will be able to benefit from the included information by reducing the start up time which plagues university level SRM design. We invite any comments and suggestions that readers of this paper may have.

Acknowledgments

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