Prof. Terry McCreary's

EXPERIMENTAL COMPOSITE PROPELLANT

An Introduction To Properties And Preparation Of Composite Propellants: Design, Construction, Testing, and Characteristics Of Small Rocket Motors.

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Experimental Composite Propellant

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FOREWORD AND ACKNOWLEDGMENTS

"If I see farther than others, it is because I have stood on the shoulders of giants" – Sir Isaac Newton

Why write a book on a dangerous subject such as propellant making and rocket motor construction? Lots of reasons.

---Because its time has come. The number of born-again rocketeers (BARs) increases daily. TRA has swelled from a few dozen participants nationwide in its first few years to several thousand worldwide. NAR has changed from model-rocketry-only to model and high-power rocketry, and recently has instituted a Level 3 certification program.

In other words, there are people out there who want to make rockets. They want to fly rockets. And many want to advance. This book is intended to be a step in a logical progression for the intelligent, aware, experienced, safety-conscious rocketeer.

---Because more education is almost always a good thing. This book provides information that many hobbyists would like to know, that would help them understand the nature of rocket propulsion that is used in their hobby. All too many model and high-power rocketeers simply don't understand much about the motor and propellant. They don't know why that delay grain is too long, or why the propellant comes in slugs, or why this motor is progressive and this one regressive. This book is intended in part to correct that lack.

---Because as one who has spent over half of his life dedicated to higher education, I can no more refuse to educate than I can refuse to breathe.

---Because it may spur research on an area that is in dire need of it -- experimental rocketry for the individual. I *WANT* someone -- or many people -- to say, "The statement on page XX is absolutely wrong!" And I want them to back up their view with carefully obtained, reproducible data and results. There's a good journal out there (*Journal of Pyrotechnics*) for articles in this vein. I'd like to see experimenters write up their results for everyone to see, so that others can benefit from THOSE results, and so the process (it's called "science") can continue.

---Because most of the books I've seen on this subject have been largely how-to. In this book I've attempted to provide at least some of the "why". Again, I'm hoping that others will chip in and provide more.

There are those who will say that this book will contribute to the demise of model rocketry, that it will increase regulation, laws will be passed, etc. I think this unlikely. There have been such books before: Brinley, Wickman, Campbell, Teleflite, two by Colburn, and others. I hope this book inspires more such publications. Again, more information and more education is almost always better than less.

Thanks are due to:

-all the guys and gals on the Arocket and Chemroc electronic mailing lists, for the stimulating questions, answers, and discussions. Keep reaching for the stars, folks; they're within your grasp. Special thanks to the moderators of those lists, Ray Calkins and Jim Lanier, who put a great deal of unpaid, unrewarded time and effort into them, and to those who have provided information on the lists from their own extensive experience, including (but not limited to!) Bill Colburn, Troy Prideaux, and Larry Teebken.

-the folks at Skylighter, Firefox Enterprises, Iowa Pyro Supply, KSI, Prodyne; and to all those other rugged individualists who brave the difficulties of running pyrotechnic-chemicals companies in today's I'm-stupid-so-I'm-not-responsible-for-my-actions society. You folks do a big part in keeping the rocket experimenters going, we know it, and we appreciate it.

-my chairman who has been quite understanding when it comes to a faculty member making mixtures that are a bit more reactive than most.

- my very generous friend John Horton, who supplied a computer for data acquisition, gratis, when mine went down the tubes. He made the "thrust stand" section of this book possible.

-Art Lekstutis, for his work in creating GUIPEP, which changed the Propep program from an annoyance into a useful and fun tool.

-Tom Peregrin, whose "Introductory Practical Pyrotechnics" was part of the inspiration for this book.

-Jim Lanier, who offered a number of constructive suggestions during preparation, and whose book "Designing Rocket Motors" provided inspiration for part of the Propel notebook.

-Mike 'n' Curtis 'n' Tim 'n' Jim 'n' Mike 'n' Wiley 'n' Mike 'n' Chuck 'n' Colby 'n' all those other guys I fly with.

A very special thanks to the Cap'n, who gave generously and unstintingly of his years of hard-won experience in composite propellant formulation, testing, motor construction, sources of materials, etc., etc. As far as I'm concerned, the Cap'n is one of those giants of whom Sir Isaac Newton spoke.

And as always, to my three best girls -- Corinne, Yvette, and of course Geniece. Why they put up with this stuff (and with me) is beyond me...

INTRODUCTION

One of the most common -- and to many, the most annoying -- question on rocketry is "how do I make my own engines safely?" Model rocketry was built on the development of the model rocket engine, so that kids would be less tempted to work with dangerous chemicals and dangerous procedures.

But the lure of experimental rocketry is still there for many. And it's even condoned and admired by a large portion of the model rocketry community. Orville Carlisle, the inventor of the model rocket engine, was an outstanding amateur pyrotechnician first, a model rocketeer second. G. Harry Stine, revered by many as the individual who was most instrumental in promoting safe model rocketry, worked closely with Carlisle during development of the model rocket engine. In fact, some activities reported by Stine in various magazines undoubtedly would be classified as "amateur rocketry" today. Many modern manufacturers of rocket motors began in amateur rocketry. Homer Hickam of "October Sky" fame is hailed by many as a success story in rocketry; by his own account, he began as an untutored -- and in many ways unsafe -- amateur rocketeer.

Like those who practice it, model rocketry has grown up in the forty years since its conception. And a great deal has been learned about rocket motor technology, chemical handling, and other aspects of motor construction. The Homer Hickams of today, and the model rocket motor manufacturers of tomorrow, need not be uninformed. Some outstanding literature on the subject is listed in the bibliography of this book.

Unfortunately for the beginning experimenter, most of the books available generally fall into one of two categories: construction techniques that lack background; and general references (often at university level) with little experimental information. This book was written to bridge the gap between these two types of references, to provide background information as well as nuts-and-bolts preparation and construction information. It was written to educate, in an area that is sorely lacking in education. However, this book is neither the first word nor the last in experimental rocketry. And the answers are not all here. Others will come and (hopefully?) do a better job than I.

Question: "How can rocket motors safely be made?" Answer: they cannot. However, the danger level can be reduced by education. Read "Safety First!" and "Safety Rant" for more information. And while you're at it, read the section on "Making Motors to Save Money". Then decide if you wish to proceed further. In fact, it would be a really good idea to read the entire book before you try messing with propellant ingredients. Patience is a virtue in experimental rocketry.

If you do proceed, when finished with this book you should have at least one well-characterized propellant. You should be able to modify that propellant to have the properties (burn rate, specific impulse, pourability) you want. You should be able to design and construct rocket motors from (roughly) E-impulse to J/K impulse. And you should understand something of propellant chemistry so that design of a propellant is less of a "hit-or-miss" affair.

Be aware.

SAFETY FIRST!

About forty years ago, a few people got together and built an industry that has been the hallmark of safety -- the model rocket industry. Safety in this industry hinged on the introduction of the model rocket engine -- a simple, reliable package that did not require the user to handle rocket propellant or chemicals.

To discourage kids from attempting to make rocket propellant, 'basement bomber' leaflets were circulated among the youth by some of the model rocket companies. Graphic, horrific examples of injury and death were described in gruesome detail. And in many workers' minds -- mine included, at the time -- this was a justifiable action.

Over the last forty years we've learned a lot. There's a fair bit of literature on rockets and propellant, and this book is just the latest addition. Now we know that you simply *DON'T* use potassium chlorate or any other chlorate in rocket propellant, you *DON'T* stuff match heads into empty CO_2 cartridges, you *DON'T* mix chemicals haphazardly just to see what will happen.

Outside of a small group of people who make their own reliable rocket motors *and* are aware of the nature of their actions, there seems to be two common and diametrically opposed views to the subject of propellant preparation and motor construction:

"You idiot! You'll kill yourself!!!"
and "Geez, it's perfectly safe! The ones who don't do it are a bunch of wimps!!"

As with most diametrically opposed viewpoints, neither is correct, as those who already "roll their own" know.

Regarding the second point of view: no propellant is "safe". Potential energy is dangerous. The chemical potential energy in one ounce of composite rocket propellant is enough to lift the propellant, its surrounding motor, and another two ounces of rocket over half a mile into the air. Friends, that isn't safe, no matter how many exclamation points you put after the word.

However, some propellants are less dangerous than others. Composite propellant made with ammonium perchlorate is generally considered to present a modest danger as compared to many other substances. From "Propellants Manufacture, Hazards, and Testing", Advances in Chemistry Series 88, ACS, Washington 1969, pp 58-59 [the bold italics are my emphasis not the book's]:

> "PVC plastisol [n.b.: type of composite] propellants are quite safe to work with. Binder ingredients are nonexplosive and nontoxic. Ammonium perchlorate, the principal oxidizer, is...handled in quantity safely, ***common-sense attention being given*** to its segregation from organic materials and explosives and to the avoidance of (1) static buildup, (2) accumulation of ammonium perchlorate dust in work areas and on machinery and equipment, (3) introduction of organic matter into the perchlorate, and (4) subjecting perchlorate to overheating caused by

> sliding friction or otherwise. The powdered metals, often used as high energy ingredients, can also be handled safely ***with due regard to the usual precautions taken with combustible dusts***...
> Nevertheless...***propellants are high energy materials and should not be handled frivolously***."

The danger of cured composite propellant is sufficiently low that the NAR (National Association of Rocketry) and TRA (Tripoli Rocketry Association) both certify reloadable motors, in which the rocketeer handles finished composite propellant. The major danger, of course, arises in handling the propellant *ingredients*, as is implied by the quote above.

That danger can be minimized with proper care. It ***CANNOT*** be eliminated.

To those who would say "You'll kill yourself!!"...well, that is quite possible. However... as of this writing I have heard ten (presumably reliable) accounts of accidents involving experimental propellant and motor making. In EACH CASE the accident arose from a clear violation of reasonable safety guidelines. The accidents included:

-use of a chlorate compound in propellant
-smoking near propellant
-trying a new, unknown formulation in other-than-tiny quantities
-standing near propellant scraps that were being ignited
-mixing incompatible ingredients while dry
-failure to use safety equipment
-drilling an inappropriately sensitive composition.
-failure to test launch system properly

Negative evidence isn't necessarily evidence. But I await a report of an experimental rocketeer (1) making a standard ammonium perchlorate propellant; (2) involved in an accident in which the propellant was the major cause (3) in which reasonable safety guidelines WERE followed rigorously. I haven't heard of one yet. That doesn't mean that this is safe, of course.

Reducing the danger in any operation requires education. I was not trained professionally in propellant preparation. I can't tell you all of the dangers to be minimized, because I don't know all those dangers myself. Every individual who goes into experimental rocketry will assume risks, as I have done. I don't assume risks for you; you assume the risks yourself when you elect to prepare propellant and make motors.

Some guidelines for propellant safety are available online at http://www.ioc.army.mil/dm/dmsweb/4145/ch16.html. These guidelines are devised for commercial-scale operations. I'm cynical; I doubt that most experimenters will follow these guidelines strictly. When corners are cut, you introduce additional risk. How much risk I don't know. I can't tell you whether (for example) using a non-explosion-proof mixer increases your risk by two times or two hundred times.

In fact, since there aren't really that many experimenters making motors, the data doesn't appear to be out there. To put it bluntly: you're taking your life into your hands. It's your life, though.

The following is a suggested Safety Code for Experimental Propellant/Motor Making. It is not exhaustive, and it isn't meant to be. Following this code doesn't mean you'll be safe, though it should limit the degree of danger. NOT following it means you WILL be UNSAFE.

SAFETY CODE FOR EXPERIMENTAL PROPELLANT/MOTOR MAKING

1. Overall safety: All my actions will have safety foremost in mind. I will never become complacent, and will always be prepared for an accident. I will recognize that a mixture can ignite at any time, and act accordingly.

2. Work location: My work location for compounding of low-sensitivity propellant will be a minimum of 75 feet from any inhabited building, with distance to increase appropriately depending on the amount and type of material being used. All materials will be locked in proper storage facilities when not actually being used. Finished propellant/motors will be stored in a proper magazine.

3. Neatness: I will keep such area where propellant is being prepared and motors being constructed clean and neat at all times. Oxidizers, powdered metals, and other ignition hazards will be treated with appropriate care to minimize the danger of accidental ignition, with special care taken to avoid "dusting" of fine material. I never will have more than one open container of chemical within this area at any time.

4. Chemicals: I will become familiar with the associated literature, including MSDS for each chemical used. I will not use "makeshift" chemicals, but instead will obtain technical-grade or appropriate/equivalent purity for propellant compounding. I will learn about chemical incompatibilities and avoid them (examples: ammonium compounds with chlorate compounds; aluminum and any nitrate). I will never make substitutions simply to see "if this works", but instead will engineer mixtures to meet the preselected criteria.

5. Training: The initial phases of my work will be performed under supervision of a knowledgeable person, one who has been properly trained in that which I am doing. My initial work will involve mixtures that have been well-characterized by others and have found to be minimally sensitive. I will study regularly to learn more about the nature of my propellant and motor work.

6. Amounts: I will work with small amounts of materials. For well-characterized minimal-hazard mixtures I will make no more than can be used within a reasonable length of time. Uncharacterized experimental mixtures will be made initially in quantity not to exceed one gram, until the mixture has been properly characterized as to sensitivity and other hazard.

7. Safety equipment: I will use proper safety equipment, including eye protection,

respirator, and flame-resistant clothing, at all times. A water-type fire extinguisher of appropriate size will always be at hand, excepting for mixtures for which water would create a greater hazard than ignition.

8. Legal: I will work in compliance with federal, state, and local laws. The local authorities having jurisdiction will be aware of my activities.

9. Testing: I will test the (impact and friction) sensitivity of mixtures using the smallest practical amounts of the mixture. I will carefully note and avoid any mixtures that are unduly sensitive. I will test any motor design at least three times, by proper static test, before committing that motor to flight. I will not be closer than 75 feet from any motor being tested, and the launch system will be tested properly so that a motor under test will not ignite inadvertently.

10. Motors: rocket motors will be constructed of materials properly selected and engineered. I will not use makeshift materials. Each rocket motor will be designed so that its failure mode is longitudinal, and testing of such motors will be performed in a vertical mode until the propellant has been properly characterized. The motor will be designed to endure a minimum of 1.5 times the maximum expected stress.

11. Waste: I will dispose of scrap material and flammable waste from my operations properly, by remote ignition, on a daily basis or more often. Scrap and waste will not be allowed to accumulate.

12. I will carry out any other procedures needed to minimize properly the hazard to myself, to others, and to my surroundings.

Some other safety guidelines and hints that have been passed to me over the last few years:

--Dust and accumulation of scraps may be minimized by taping a large sheet of kraft paper to the work area. All work is performed and all chemicals handled within this area. At the end of the work session, the paper is carefully folded and burned by remote ignition.

--Temperature used for processing should not be excessive. Sensitivity of mixtures to friction and impact increases as temperature increases. About 60°C (140°F) is as high as is necessary for ordinary processing of typical composite propellant. At least one reference suggests that ammonium perchlorate can partially decompose at higher temperatures than this.

--Drilling, cutting, or machining of propellant grains should be performed in an area well removed from the propellant processing area, in case of accidental ignition. Tools used should be sharp.

--Clothes worn during propellant work should be washed separately from other clothes, using *soap* or *non-bleaching detergent*. Bleach has the potential for undesirable and unsafe side reactions. Never dry-clean clothing that has been worn during propellant work; the cleaning solvents may react violently with residual propellant or chemicals on the clothing. Heavy cotton clothing is preferred over synthetics; the latter can melt onto the skin.

--At least one reference has given the quantity of 500 grams as "laboratory scale". Limiting propellant batches to this size or smaller would be wise. Five hundred grams of propellant is quite a large batch, equal to half a dozen H-motors, a single J-motor, or a grain of an M-motor.

-- Keep fingernails trimmed short and filed smooth. This minimizes the problem of getting composition under the fingernails. It also minimizes the problem of fingernails cutting through thin plastic gloves.

--The cheap thin plastic or vinyl gloves are intended to prevent gross contact with a hazardous material. They are not intended to prevent a toxic substance from skin contact over an extended period. In short, if you have worries about toxicity of propellant chemicals, it would be wise to limit contact even through such gloves.

--A major hazard in propellant work is "dusting", in which fine powders are dispersed during ordinary operations. The finer the material being weighed or processed, the greater the hazard. When fine oxidizer dust is dispersed, it can get into all sorts of places, such as oil on moving parts, etc. There is a very real hazard of ignition in such a case. Thus, thorough precautions should be taken to avoid raising dust, to avoid dispersing the dust that *is* raised, to clean up dust properly, and to segregate "dust" areas from machinery, etc.

-- Powdered metal presents a similar hazard, especially relative to sparks or static discharge. It is very important that powdered metal used in propellant is "wetted" thoroughly with the liquid binder material before it is mixed; and the mixture should be mixed thoroughly before adding any oxidizer, to avoid possible contact of powdered metal and dry oxidizer in the mixing container.

-Commercial fireworks and pyrotechnics buildings usually incorporate a "blowout" wall that is thinly constructed so that the worker can crash through the wall if necessary to escape a conflagration. Some workers have a work building in which one wall is made of sheet insulating foam, for this purpose. Others use a (canvas! not nylon!) tent with open side(s).

IS THIS LEGAL?

It is legal for me to do what I do with propellants, to the best of my knowledge. I don't know if it's legal for you to do it. I'm not a lawyer.

It's up to you to become legal.

An outstanding essay on some aspects of legalities of commercial high power rocket motors is provided at: http://www.info-central.org/index_propulsion.html. Some of what has been written there is applicable to experimental motors as well.

It's worth noting that legal matters are fluid. As I write this there is a lawsuit pending that may determine whether composite propellant will continue to be classified as an explosive. So the situation can change dramatically.

REQUIREMENTS

1. Get a Federal Low Explosive User's Permit (LEUP) from the Bureau of Alcohol, Tobacco, and Firearms (BATF). You may or may not need one, it depends on your particular situation. But you'll have a better grip on that situation and possess more credibility if you have one. Imagine that you are testing rocket motors (in a remote location) and the sheriff pulls up and asks "Whatchoo doin, boy?" Being able to flip open your notebook and show your LEUP can have a significant effect.

2. Construct or buy a proper storage magazine. This is a requirement for the LEUP. And it's a requirement even if you *don't* have a LEUP. Motors and propellants *must* be stored safely whether or not you need a permit or license to make them. When you apply for your LEUP you will need to show the BATF agent where and how you're going to store your propellant and motors.

3. Never sell or give away propellant or motors. That changes the status from "user" to "manufacturer", which is a whole 'nother story.

4. Just because you are legal according to *Federal* law doesn't mean that you're legal. You must comply with *state* laws and *local* laws regarding your activities.

5. Be certain that the authorities having jurisdiction (AHJ) *know* of your activities. Generally speaking, rocketry activities can't be hidden. If the authorities know what you are doing, you may be less likely to be tossed in the pokey when they see you.

I know this all sounds vague. It has to be that way; laws differ so much from state to state, from county to county. A blanket statement about the legality of rocketry-related activities in the US is almost certain to have exceptions somewhere.

Now...with all of that having been said...

The BATF has reported in its own Explosives Newsletter that a Federal Manufacturer's License is *not* required to make explosives for your own personal use. Again, if you give them away or sell them it's a different matter. And you still have to store the material properly. And comply with state and local laws.

A LEUP is a federal permit, and generally is not required if you make and use motors within the same state. Again, there are good arguments for having one anyway.

The "destructive device" clause of the The Gun Control Act of 1968 is often quoted as restricting propellant mass to 62.5 grams. However, that act specifically refers to *explosive, incendiary* or *poison gas* rockets. It also specifically *exempts* a device that has not been designed or redesigned as a weapon. The following is an excerpt from that Act:

> (4) The term "destructive device" means -
>
> (A) any explosive, incendiary, or poison gas -
> (i) bomb,
> (ii) grenade,
> (iii) rocket having a propellant of more than four ounces.
> (iv) missile having an explosive charge of more than one quarter ounce.
> (v) mine or,
> (vi) device similar to any of the devices described in the proceeding clauses;
>
> (B) any type of weapon (other than a shotgun or shotgun shell which the Secretary finds is generally recognized as particularly suitable for sporting purposes) by whatever name known which will, or may be readily converted to, expel a projectile by action of an explosive or other propellant, and which has any barrel more than one-half inch in diameter; and
>
> (C) any combination of parts either designed or intended for use in converting any device into any destructive device described in subparagraph (A) or (B) and from which a destructive device may be readily assembled.
>
> The term "destructive device" shall not include any device which is neither designed nor redesigned for use as a weapon; any device, although originally designed for use as a weapon, which is redesigned for use as a signaling, pyrotechnic, line throwing, safety, or similar device; surplus ordnance sold, loaned, or given by the Secretary of the Army pursuant to the provisions of section 4684(2), 4685, or 4686 of title 10; or any other device which the Secretary of the Treasury finds is not likely to be used as a weapon, is an antique, or a rifle which the owner intends to use solely for sporting, recreational or cultural purposes.

So, to minimize problems, do not design or redesign your rockets to be weapons.

Legal or not...if you launch in the dry season and start a fire, or send a chunk of casing through someone's hand, or otherwise destroy property, etc., don't be surprised if you are tossed in jail. Use common sense.

WHAT IS COMPOSITE PROPELLANT?

Composite propellant (Figure 1) usually consists of an *oxidizer* (ammonium perchlorate preferred for many purposes) and a synthetic-rubber *binder* to hold the oxidizer grains together. It may contain other additives as well: metals to increase the *specific impulse*; plasticizers, catalysts, and crosslinkers to make the propellant stronger or easier to process; burn rate modifiers to make the propellant burn faster or slower, etc.

Some important characteristics of composite propellant include:

-It is much higher in specific impulse (power available per weight) than blackpowder (BP). The largest "standard" 18×70 mm BP motor is a "C" motor. The same physical size in composite propellant might be a full "D" or even a low "E"; twice the power for the size.

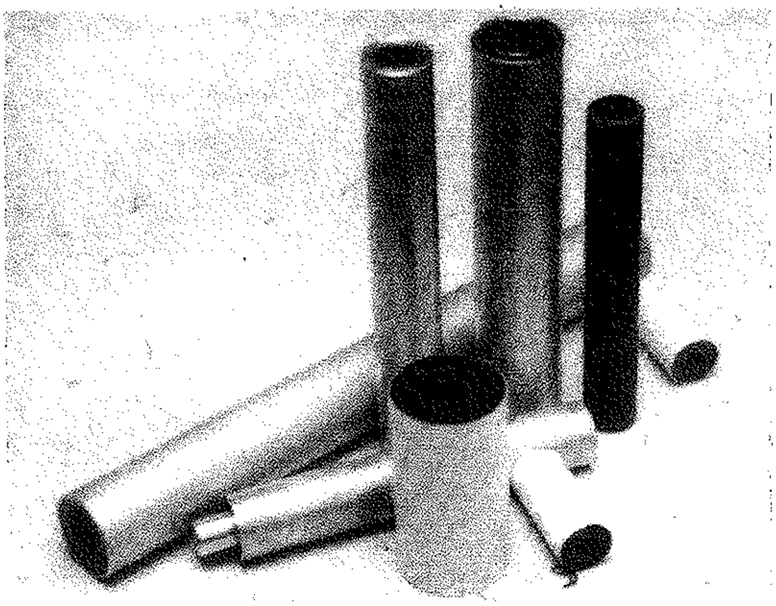

Figure 1: Composite propellant grains and motors made by the author.

-It is rubbery like an automobile tire, rather than brittle. Dropping a composite motor on the floor won't crack the propellant. Temperature changes don't affect it much either.

-It burns more slowly than BP, so there has to be more burning surface area. Most composite motors are some sort of *coreburning* motor (see "Grain Configurations") to provide that surface area. Most small BP motors are endburners.

-Motors using composite propellant often operate at higher chamber pressure (300-1000 psi) than BP motors (75-300 psi).

-It is more expensive per pound than BP. This isn't a serious issue for the typical experimental motor maker. Ten pounds of materials for composite propellant will cost about $50; a like amount of material for BP will run around $5-20, depending on the source. Ten pounds of composite propellant is about seventy G-impulse or a dozen J-motors...

-It is less sensitive to spark and flame than BP. Loose BP can be and has been set off by a single spark. By contrast, most high-power rocketeers know about the dreaded "chuff", wherein a composite motor ignites, then goes out after a moment. Point being: sometimes composite propellant can be annoyingly hard to ignite. Many workers consider making composite propellant less dangerous than making good BP.

-Its ingredients may be more toxic and/or hazardous than BP ingredients.

-It can be more complicated to make than BP (or possibly not...)

-Some workers find composite propellant to be more reproducible, from batch to batch, than BP.

-Since it's rubbery, composite propellant can be cut or molded into ingenious shapes for particular motor configurations.

-It can be altered to provide colored flame, white or black smoke, sparks, etc.

HOW DOES A COMPOSITE ROCKET MOTOR WORK?

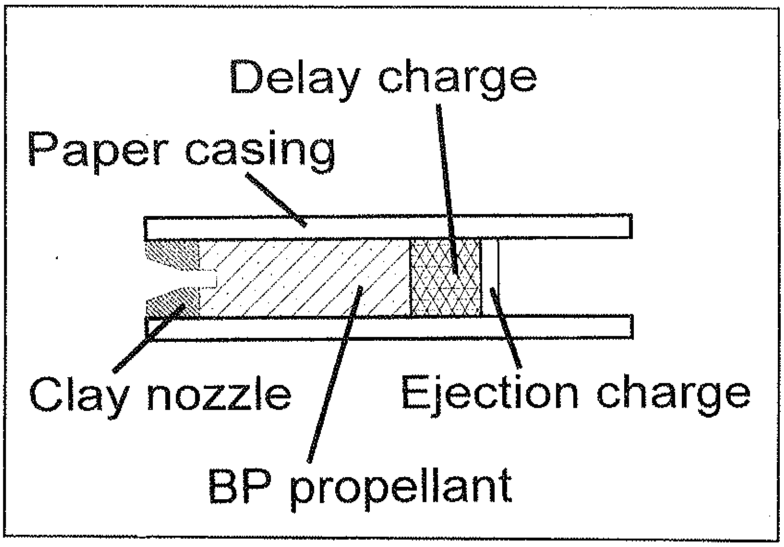

Figure 2: A typical blackpowder model rocket motor

There are some significant differences between a BP rocket motor (Figure 2) and a composite rocket motor (Figure 3).

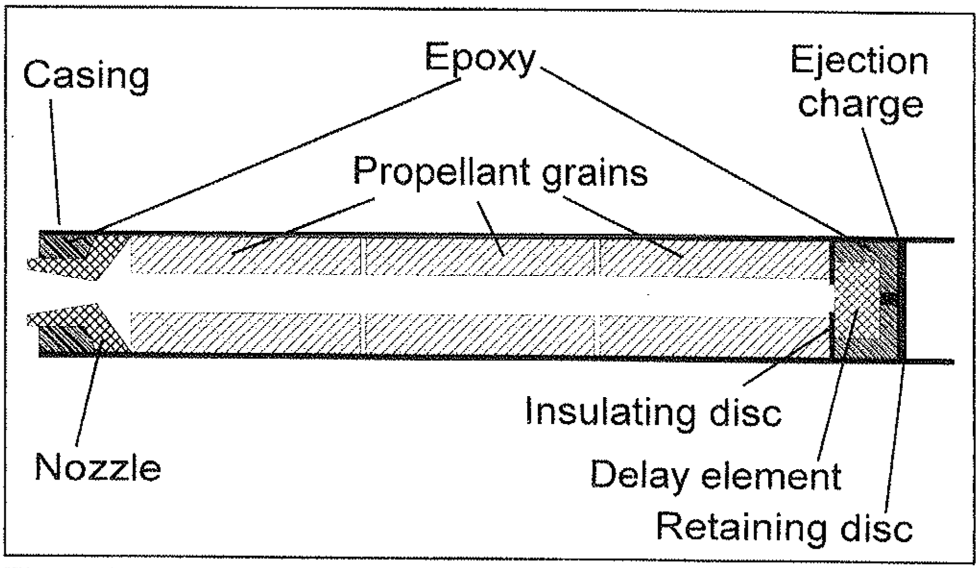

Figure 3: A typical composite rocket motor

The first major difference is, of course, the propellant. BP is a mixture of potassium nitrate, charcoal and sulfur. The BP is pressed into a paper casing under several thousand pounds of pressure. The resulting propellant *grain* (chunk of propellant) is rather brittle, as noted before.

It's not shown here but composite propellant for small motors usually is molded in thin-walled paper *casting tubes*. The propellant is pressed or poured into these tubes and allowed to harden (cure) by chemical reaction, like epoxy glue. High pressure is neither used nor needed to force the propellant into place.

A second major difference is (usually) the shape and configuration of the propellant. Most BP motors are *endburning* motors. The propellant burns from one end to the other, like a cigarette. The composite grains have a hole lengthwise through them. These are *coreburning* grains and burn from the inside out (see "Grain Configurations" for a more detailed discussion).

The BP motor has a clay nozzle which is hydraulically pressed in place (like the BP propellant). This nozzle works well at the "low" flame temperature of BP. A clay nozzle in a typical composite motor would rapidly increase in *throat diameter* as the propellant was burnt. This would change drastically the characteristics such as thrust and chamber pressure of the motor. So the nozzle for a composite propellant motor must be made of material which can handle the high temperatures. Most commonly used are *phenolic* or *graphite*. Phenolic is a hard, brittle plastic material that withstands high temperatures nicely for short times. Graphite is the same material used in pencil lead. In most single-use motors the nozzle is glued into place with epoxy and may include an o-ring to minimize gas leakage.

The casing for a BP motor is made of glued paper about an eighth of an inch thick or so (some large motors use aluminum or phenolic casings). The paper erodes slowly during the motor burn. Paper casings can be used for composite propellant but they need to be a good bit thicker than this. More commonly, phenolic, fiberglass, or aluminum is used, since the walls can be thinner for the same strength. A typical 29mm (1⅛") composite motor has a casing with 1/16" thick walls.

The delay for BP motors is similar to the propellant and is pressed, or cast and glued, into place. It usually burns slower than the rest of the propellant, but faster than ordinary composite propellant. Note that the delay charge in a composite motor is well-insulated from the casing.

Composite motors use a piece of composite propellant as the delay. Since the delay time is fairly long (up to 20 seconds), this bit of propellant must be insulated carefully or it will burn through the case. Surrounding the delay is a layer of epoxy or paper tube, to act as insulation.

In the BP motor the delay charge is ignited when the propellant is consumed. In the composite motor the delay charge is ignited at the same time as the rest of the propellant, so it will burn during the propellant combustion[1]. This causes problems (see "Delay Charges in Composite Motors" for more information).

The ejection charge is just plain granular BP for both types of motors.

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[1] Some experimenters leave out the delay charge entirely on composite motors, to avoid the attendant problems. Instead an electronic timer or similar is used to set off the ejection charge.

The disk included with this book has a program called "Motortut", written by Gary Crowell. It is an outstanding animation that shows the basic operation of several types of rocket motors. To run the program (it is a DOS program that will run under Windows) simply double-click on the file name.

One last point worth mentioning: the components of a BP motor are *pressed* into place, so it's feasible to make very small motors. But composite motors consist of a number of parts usually *assembled* into a motor. Very small composite motors (18 and 24 mm) often are *more difficult* for the experimenter to make than larger ones, in the same way that very small models can be harder to make accurately than large ones. That is one reason why this book focuses on 29, 38, and 54 mm motors rather than on smaller ones.

THAT "THEORY" STUFF

It should be noted at the outset that it is quite possible to make composite rocket motors without knowing all the theory stuff. But a proper understanding of rocket motor theory will reduce the danger level, will help you understand motor operation, will aid you in designing better and more reliable motors, and will help you to understand the tradeoffs to be made in design.

Let me also note that I'm not going to cover this theory in a great deal of detail, since that's been done elsewhere, and quite well. If you're sharp enough to read college textbooks, Sutton's *Rocket Propulsion Elements* should float your boat. If you need a more basic discussion with worked-out examples, try Lanier's *Designing Rocket Motors*. Don't expect to read and digest such books in a single sitting. A good technical book is consumed as one would an elephant. One bite at a time...

THRUST

Okay, we all know how a rocket motor works (I hope). The propellant burns. Hot gases are formed. They go out the nozzle.

Why does this produce thrust? Conservation of momentum. If you stand in a boat and throw rocks out the stern, the boat will move forward. In a rocket motor, the gases are the rocks. The harder they're thrown (i.e., the higher the gas velocity) the faster the rocket will move in the opposite direction. The more rocks you've got, the more motion you get. The thrust obtained from this phenomenon is sometimes called *momentum thrust.*

Consider a rocket motor that burns 1 lb of propellant each second. That means the motor is producing 1 lb of hot gas each second, which is dumped out the nozzle. Assume that the hot gases exit at 3000 ft/sec. The momentum thrust is:

Momentum thrust **= (propellant flow rate) × (exhaust velocity) / (32.2 ft/s^2)**
= (1 lb/s) × (3000 ft/s) / (32.2 ft/s^2)
= 93.2 lb
(The last term, 32.2 ft/s^2, is the acceleration of gravity)

Another consideration is that of *unbalanced pressure*. Let's assume that our rocket motor has a chamber pressure of 300 psi. Let's also imagine that, for an instant, the nozzle is plugged (Figure 4, left). That internal pressure is the same over the entire inner surface of the motor. So the forces are in balance. No motion.

Now you instantly open the nozzle (which is 1" diameter). Gas escapes out that hole. And the pressure at the hole is now nil; there's no plug there anymore, got it? So no pressure. On the opposite end of the combustion chamber is an area 1" diameter with 300 lb per square inch pushing against it. So the rocket moves in that direction; the unbalanced force against that round spot makes it move. That 1" diameter spot has an area of 0.785 square inches. This *pressure thrust* should be equal to:

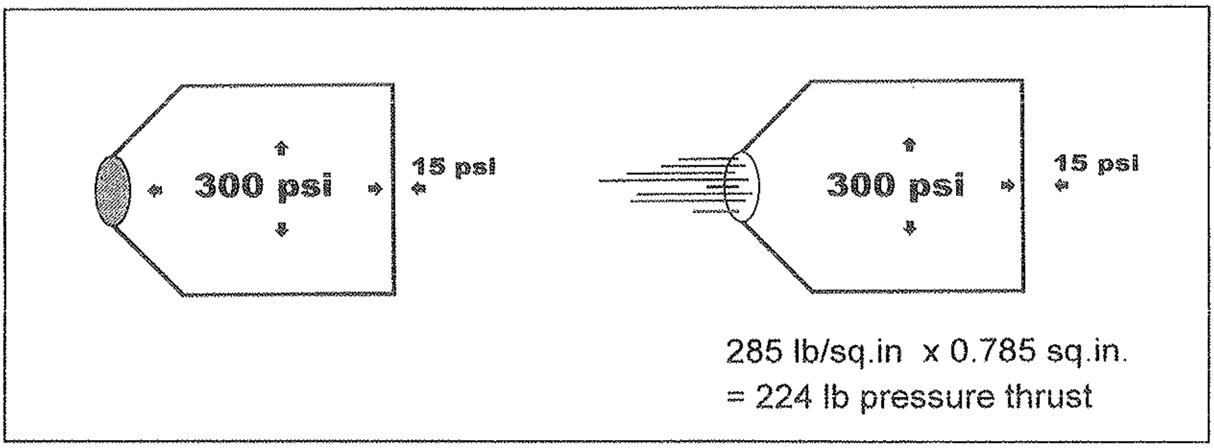

Figure 4: Left: chamber at 300 psi, with no opening. External pressure is 15 psi. Chamber is at equilibrium. Right: When a 1" dia hole is opened in the chamber, pressure is released. Pressure opposite this hole creates *pressure thrust* of 224 lb (see text)

$300\ \text{lb/in}^2 \times 0.785\ \text{in}^2 = 236\ \text{lb}$. **(NOT!)**

Whups! This is true only in vacuum. If the motor is at sea level there's pressure *outside* the rocket as well. Atmospheric pressure is about 15 lb/in^2. So the net pressure *difference* between chamber and outside is

Pressure difference $= 300 - 15 = 285\ \text{lb/in}^2$

and the pressure thrust is

Pressure thrust $= 285\ \text{lb/in}^2 \times 0.785\ \text{in}^2 = 224\ \text{lb}$.

The total thrust in this simple example is the momentum thrust plus the pressure thrust:

Total thrust $= 224 + 93.2 = 317\ \text{lb}$

Not that the actual numbers are all that critical in this example. Points to note here are (all other things being equal): the higher the propellant flow rate, the greater the momentum thrust; the higher the exhaust velocity the higher the thrust; a higher chamber pressure gives more thrust; and larger nozzle throat gives more area and therefore more thrust.

Of course this is rocket science, and so things can get complicated. Example: for a given motor, opening up the nozzle means that gases can escape more readily, so that the chamber pressure *drops*. To maintain chamber pressure with a larger nozzle, the propellant mass flow rate must be increased. That is, *more* propellant must be burned per second. In other words, all other things *aren't* equal. Also worth noting: a properly shaped and designed nozzle will actually increase the thrust, since the escaping gases can be made to do additional work as they expand from the nozzle throat. Not to worry, though; it will all come out in the end (pun intended).

SPECIFIC IMPULSE

This is probably one of the most misused terms in hobby rocketry, so take care that you learn what it means. That way you can correct your friends when they screw it up.

Specific impulse, I_{sp}, is the relationship between thrust (pounds) produced by burning a given amount (pounds) of propellant per time (second). That's:

I_{sp} = lb thrust / (lb propellant / s)

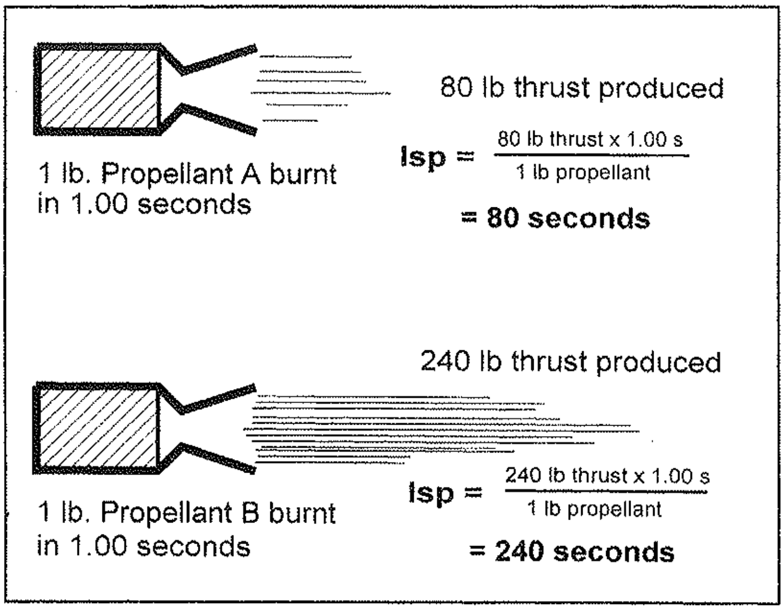

Figure 5: Performance of propellant with (A) I_{sp} =80 seconds and (B) I_{sp} =240 seconds. The higher the I_{sp}, the more thrust can be obtained from a given mass of propellant for a given burn time.

Mathematically, the "lb" are often canceled and the units become "seconds". The concept of specific impulse for two different propellants is illustrated in Figure 5. Typical composite propellant has I_{sp} of 150-260 seconds; the simple starter propellant described in this book has I_{sp}=238 s. Thus, one pound of this propellant burned in one second under the proper conditions can produce an average thrust of 238 lb.

Looking at the concept another way: a motor using propellant A from the figure could be designed to burn one pound of propellant and create one pound of thrust, for 80 seconds. A similar motor using propellant B would create one pound of thrust from one pound of propellant for 240 seconds -- three times as long.

Specific impulse depends on several factors. A major one is propellant makeup. Ammonium perchlorate (AP) oxidizer tends to produce higher I_{sp} in propellant than most other oxidizers. As noted above, the simple AP propellant described later in this book has I_{sp}=238 seconds. With either potassium perchlorate (KP) or ammonium nitrate (AN) as the oxidizer, the propellant would give I_{sp} = 205 seconds.

We now know that thrust depends on factors such as chamber pressure and outside (exhaust) pressure, and on the nozzle used. It follows logically that I_{sp} also depends on these factors. It's most common to quote a value of *standard* I_{sp}. Standard I_{sp} means specific impulse at 1000 psi chamber pressure, with a perfect nozzle, at normal atmospheric exhaust pressure of 14.7 psi.

Of these last three factors, I_{sp} is much more dependent on proper nozzle design than on chamber pressure. Table I shows what happens to the simple propellant when chamber pressure is changed.

Chamber pressure (psi)	I_{sp}, seconds
1000	238
700	232
500	225
300	213

Table I: Effect of chamber pressure on specific impulse for the simple propellant.

The values in Table I all assume a proper nozzle. Without a proper nozzle (with only a "hole" at the end of the motor), I_{sp} at 1000 psi drops to 188 seconds! Happily, a good nozzle isn't hard to come by.

Dependence of I_{sp} on atmospheric pressure is considerable. However, it isn't terribly important for the small experimental motors operated within the atmosphere. There just isn't much that the experimenter can do about changing the atmospheric pressure...

DELIVERED SPECIFIC IMPULSE

Since I_{sp} depends so much on motor design and other factors, it's common for manufacturers and certifying agencies to report *delivered* I_{sp}. That's the I_{sp} that is actually obtained for a particular motor. For example, consider a motor that contains 0.5 lb of propellant, and gives 40 lb thrust for 2 seconds. The delivered I_{sp} is

$$I_{sp} = 40 \text{ lb} \times 2 \text{ s} / 0.5 \text{ lb} = 160 \text{ seconds}$$

regardless of the I_{sp} that that particular propellant formulation is *supposed* to have at that pressure, etc. In small motors, delivered I_{sp} is often smaller than calculated or theoretical I_{sp}. There are several reasons for this, one of which is that small motors often aren't as efficient as larger ones.

TOTAL IMPULSE

Technically speaking, total impulse is thrust integrated over the burn time. A simpler definition is:

$$\text{total impulse} = \text{average thrust} \times \text{burn time}$$

Total impulse of several motors is illustrated in Figure 6. This figure illustrates two general points. First, while thrust and burn time can be varied by changing the configuration of the motor, for a given amount of propellant (of a given type), total impulse remains about the same. That is, a motor containing 50 grams of the simple starter propellant described here will produce about 100 N-s total impulse, whether designed as an endburner or as a coreburner. Also, total impulse can be changed by using a different type of propellant. For a motor of given size and amount of propellant, an increase in I_{sp} of the propellant will increase the total impulse.

A very important point: total impulse and specific impulse are, of course, related. But *burn rate* is *not* related directly either to specific impulse or to total impulse. A propellant of $I_{sp} = 240$ can be made to burn either very slowly or very rapidly, depending on how it is formulated. A "hot" or fast-burning propellant does not imply greater specific impulse, nor does it imply greater total impulse for a given mass of propellant.

To give a specific example, 60 grams of the simple starter propellant described in this book, used in a *BATES* grain configuration (to be described later) produces a G100 motor, roughly. When the propellant is made to burn faster by adding a burn rate catalyst, a 60-gram motor is a G160. But *both* motors produce just about 120 N-s total impulse. The faster propellant produces more thrust -- but for a shorter time.

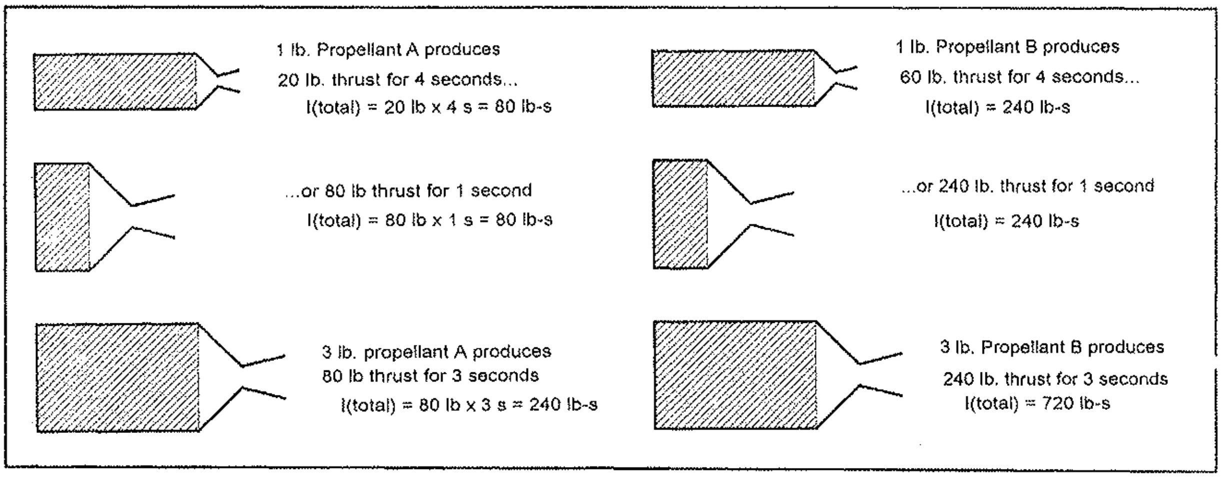

Figure 6: Total impulse for motors containing propellants with I_{sp}=80 s and I_{sp}=240 s. Note that thrust and burn time can be changed by varying the configuration of the propellant; however, to increase total impulse, the amount of propellant must be increased, or a propellant of higher I_{sp} must be used.

BURN RATE AND PRESSURE

Burn rate is (duh!) the distance a propellant will burn in one second. Consider a soda straw 6" long, packed with propellant. If one end is lit and the propellant takes 12 seconds to burn to the other end, it has a burn rate of 6 in/12 s = 0.5 in/s.

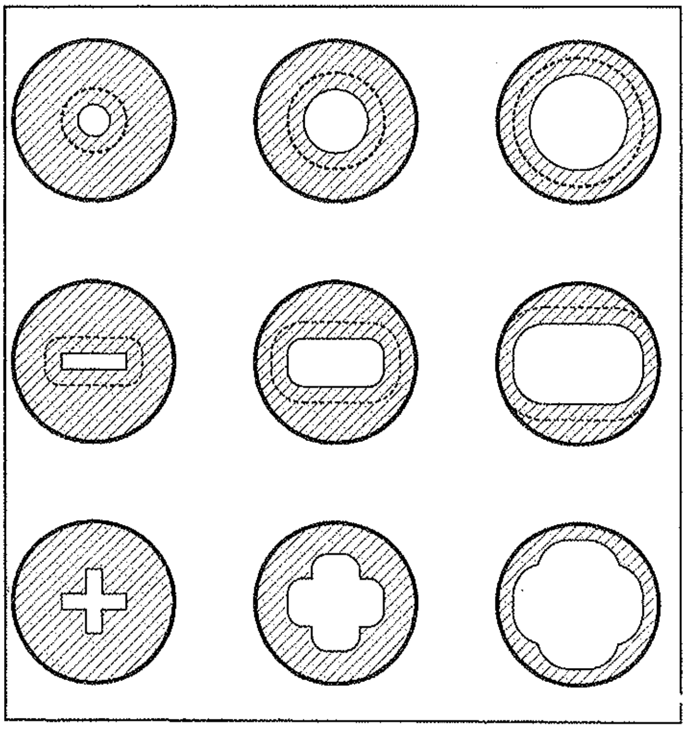

Figure 7: From left to right, burning in *parallel layers* causes change in the shape and surface of propellant during combustion. Note that outside sharp corners (of the core) "round off" during the burn. Inside corners remain sharp.

Propellant is said to burn in "parallel layers", as illustrated by the three grain shapes in Figure 6. Technically speaking, the propellant surface recedes perpendicular to the burning surface. Each figure on the left represents propellant before ignition, and the figures to the right show what the propellant will look like as it burns.

One of the most common and most important problems to be dealt with in motor design has to do with burn rate and pressure. The burn rate of most propellant changes as chamber pressure changes. The rule for this is called *Vielle's Law*:[2]

$$\text{burn rate} = a \times P_c^{\,n}$$

where "burn rate" is given typically in inches per second, P_c is the chamber pressure in psi, $\underline{a}$ is the *burn rate coefficient* and $\underline{n}$ is the *burn rate exponent.*

Burn rate and chamber pressure are pretty easy, but what exactly are burn rate "coefficient" and "exponent"? In chemical terms, the coefficient represents the "rate constant" and the exponent represents the "molecularity" of the rate-determining step(s). For those who don't understand that, don't worry about it. It's more important to understand how the coefficient and exponent govern the propellant burn.

Let's take a look at how burn rate is affected by $\underline{a}$ and $\underline{n}$. Consider two typical propellants:

A typical ammonium perchlorate propellant, for which a=0.03, n=0.4

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[2] Like so many other equations in this book and in other books, this equation is an approximation. At low (<50 psi) and high (>3000 psi), the equation takes a different form. The beginner should be cautious in applying a limited equation to every possible situation.

A typical potassium perchlorate propellant, for which a=0.005, n=0.7

At 300 psi, burn rate of the AP propellant is

$$\textbf{rate} = 0.03 \times 300^{0.4} = 0.293 \text{ in/s}$$

and that of the potassium perchlorate propellant is

$$\textbf{rate} = 0.005 \times 300^{0.7} = 0.271 \text{ in/s}$$

so the KP propellant actually burns a bit slower than the AP propellant at this pressure. But look at what happens as pressure goes up:

Pressure, psi	AP burn rate, in/s	KP burn rate, in/s
300	0.294	0.271
400	0.330	0.331
500	0.360	0.387
700	0.412	0.490
900	0.456	0.585
1200	0.511	0.715
2000	0.627	1.023

Table II: Burn rate of typical AP and typical KP propellant with increasing pressure.

At 400 psi the two burn rates are almost the same. Above this pressure, the burn rate of the KP propellant increases more rapidly than that of the AP propellant. This is caused by the high burn rate exponent of the KP propellant.

Several very important points about a and n:

1. They are characteristic of a given propellant, prepared in a particular fashion. The space shuttle SRB's propellant has a particular value of a and of n; the simple starter propellant in this book also has its own particular values of a and of n; these aren't the same as those for the space shuttle SRB.
2. Values of a and n ***CANNOT BE PREDICTED EXCEPT APPROXIMATELY***. They are *empirical* quantities; to find them, propellant must be prepared and tested (burned). In fact, a and n can depend on the individual's technique in making the propellant. So two people can make the "same" propellant, yet the two propellants may have somewhat different burn characteristics.
3. Generally, a low value for n (0.2-0.4) is desirable; low n means that the propellant's burn rate will be less sensitive to pressure changes. A large value of n means that the burn rate can jump dangerously with minor changes in pressure.
4. The approximate value of n is strongly dependant on the type of oxidizer. Ammonium perchlorate propellants usually have n around 0.2-0.5. Ammonium nitrate propellants have n around 0.4-0.6. Potassium perchlorate propellants have n around 0.7-0.9. This is an important reason why ammonium perchlorate is a preferred oxidizer for experimental (and commercial) work in propellants.
5. The value of a depends on particle size of the oxidizer and of any solid fuel (such as aluminum), among other factors. The finer the oxidizer and/or fuel, the larger

the value of a and the higher will be the burn rate at a given pressure. The value of a also depends on oxidizer type, though not to as great an extent as does the value of n.

6. Burn rate catalysts may increase either a or n, or both, depending on the type of catalyst. Generally, metals (aluminum, magnesium) increase a and decrease n.

NEUTRAL, PROGRESSIVE, AND REGRESSIVE BURNS

From the previous discussion it should be clear that burn rate and hence chamber pressure may vary during a burn. Since thrust depends on chamber pressure, it should be clear that thrust too can vary during a burn. A motor that is designed to have little variation in burn rate will produce nearly-constant thrust. This is referred to as a *neutral* burn (Figure 8, left). If thrust increases more-or-less constantly during the burn, the burn is referred to as *progressive* (center). A *regressive* burn means that thrust decreases during the burn (right).

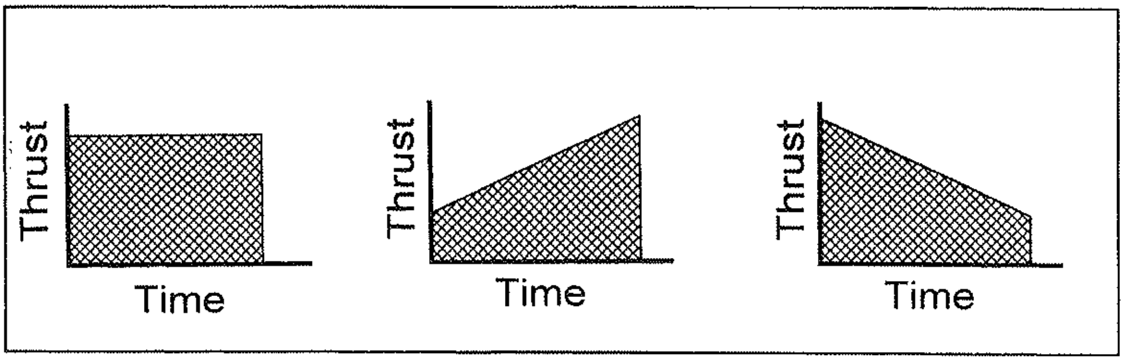

Figure 8: From left to right; neutral burn, progressive burn, regressive burn.

Real motors may be designed to produce some combination of these burns. For example, a so-called "bathtub" motor starts with a progressive burst, then a neutral portion, and ends with another progressive phase.

Generally speaking, a neutral-burning motor is quite efficient overall for routine experimental use, and is also fairly easy for the experimenter to design. A progressive motor must be constructed to handle the high chamber pressure at the end of the burn. That means that it is not operating as efficiently as it could be at the *beginning* of the burn. Likewise, a regressive motor is more efficient at the beginning, less so at the end of the burn. Thus, much of the discussion in this book will center on motors with neutral or nearly-neutral burn profiles.

AREA RATIO AND PRESSURE

So, how is a motor designed to be progressive, regressive, neutral, or some combination? Let's define a new term, the *area ratio* K_n:

$$K_n = \frac{\textbf{area of burning propellant surface}}{\textbf{area of nozzle throat}}$$

Example: A C 6-5 motor has a nozzle throat 0.1" in diameter. The propellant diameter is 0.5". The propellant burns from one end to the other, so the burning propellant surface is always a circle 0.5" in diameter.[3]

The radius of the nozzle throat is half its diameter, or 0.05". The radius of the propellant surface is 0.25"

Area of nozzle throat $= \pi r^2 = 3.14 \times (0.05)^2 = 0.00785$ **square inches**
Area of propellant $= \pi r^2 = 3.14 \times (0.25)^2 = 0.1962$ **square inches**

$K_n = 0.1962 / 0.00785 = 25$

A key characteristic of K_n is that the chamber pressure P_c is directly related to K_n by the equation:

$$P_c(\text{lb/in}^2) = K_n \times I_{sp}\ (\text{sec}) \times \text{propellant density}\ (\text{lb/in}^3) \times \text{burn rate}\ (\text{in/sec})$$

At a given pressure, specific impulse and burn rate are both virtually constant. Likewise, propellant density is a constant for a given propellant. Thus, from the equation, if K_n also is constant for a particular motor during the burn, the chamber pressure also will remain unchanged during the burn. Since thrust depends on chamber pressure, thrust should be constant, too.

On the other hand, if K_n increases during the burn, chamber pressure and thrust will increase; if K_n decreases; chamber pressure and thrust will decrease; if K_n first increases then decreases, chamber pressure and thrust will go up, then down.

The equation above makes K_n a very useful parameter in motor design. Since K_n is directly related to chamber pressure, this means that two motors (with the same propellant) ***operating at the same K_n have about the same chamber pressure*** -- REGARDLESS of the sizes of the motors[4]. This gives a fairly simple method of scaling a motor up or down. Once a working motor has been constructed, a larger or smaller motor (with the same propellant) may be designed to have (nearly) the same value of K_n,

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[3] The more sophisticated among you will know that this isn't quite true; the burning surface of these motors is dome-shaped. Those who aren't so sophisticated will learn that in a little bit. But as a first approximation it's a useful assumption. For an in-depth treatment of endburning rocket motors see Journal of Pyrotechnics #5, 1997

[4] You know-it-alls will know that there's much more to scaling up a motor than this. But within limits, it's a useful means of scaling.

with reasonable assurance that the new motor will produce about the same chamber pressure as will the smaller one.

As an example, consider that C6-5 motor mentioned earlier. We may not know what the chamber pressure is, but we do know that K_n =25 gives appropriate chamber pressure and thrust for the motor. To design a bigger motor with this propellant, determine motor dimensions that will give the same K_n as the smaller motor.[5]

To design a 1.5" id motor that will operate at the same pressure, using K_n = 25.

Area of burning propellant $= \pi r^2 = 3.14 \times (0.75)^2 = 1.767$ **square inches**
K_n = **area of burning propellant / area of nozzle throat,**
so: Area of nozzle throat = **area of burning propellant** $/K_n$
$= 1.767 / 25$
$= 0.07068$ **square inches**

Area of nozzle throat $= \pi r^2$, **so**

$r = \sqrt{(\text{area of nozzle throat} / \pi)}$

$r = \sqrt{(0.07068 / 3.14)} = 0.15"$

and the nozzle diameter would be

$0.15 \times 2 = 0.3"$ **(see Figure 9)**

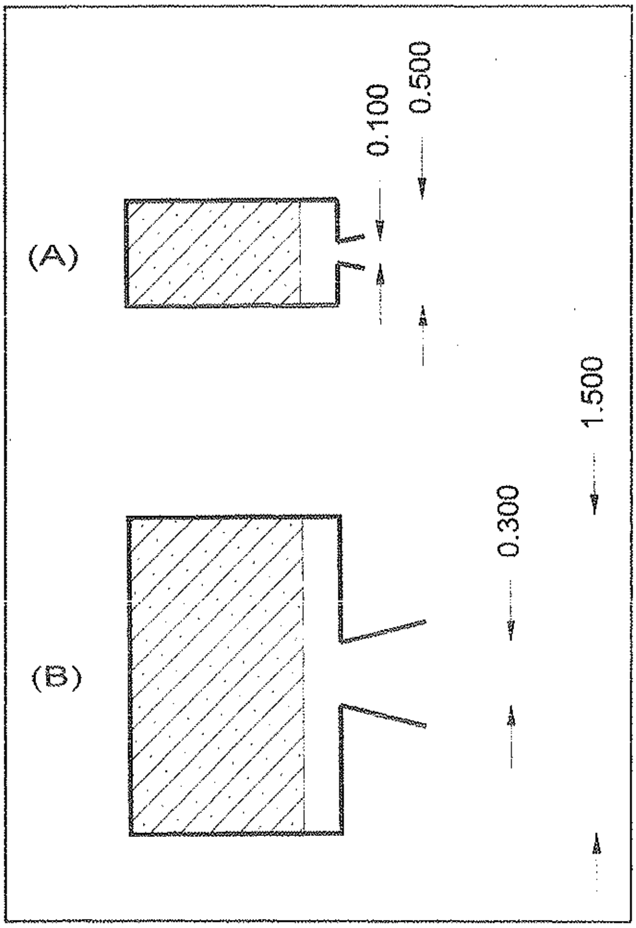

Figure 9: (A) ½" dia endburning motor operating at K_n =25. (B) A 1½" dia endburning motor designed also to operate at K_n =25 will produce about the same chamber pressure as the motor in A

The concept of area ratio helps to answer a number of questions. For example, how might a motor be made regressive? Answer: by designing so that the burn area, and K_n, decrease during the burn.

How might a motor be made neutral? Answer: by designing so that burn area and K_n are nearly constant during the burn.

Why are bubbles such a problem in propellant? Answer: when propellant burns and a bubble is exposed, the inside of the bubble suddenly becomes additional burning surface area. That increases K_n, and chamber pressure increases. If the bubble is large enough or if smaller bubbles are numerous enough, K_n can increase enough to

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[5] Calculating the area ratio for typical experimental motors isn't a whole lot of fun. But with this book you received software to help you do just that. We'll talk about that software later.

overpressurize the motor.

Why are some commercial motors that use phenolic nozzles regressive? Answer: in part, it is because the phenolic nozzle throat *erodes* (gets larger) during the burn. If the nozzle throat increases while burn area stays the same, K_n *decreases* (nozzle throat area is in the *denominator*). In turn, this causes a decrease in pressure and in thrust.

GRAIN CONFIGURATIONS

If you understand K_n, you should be able to grasp the idea behind different grain shapes. Simply put, a grain configuration is designed to give certain changes in the burn area during the burn. Burn area controls K_n; K_n controls chamber pressure; chamber pressure controls thrust. Thus, changes in burn area are reflected in the thrust-time curve.

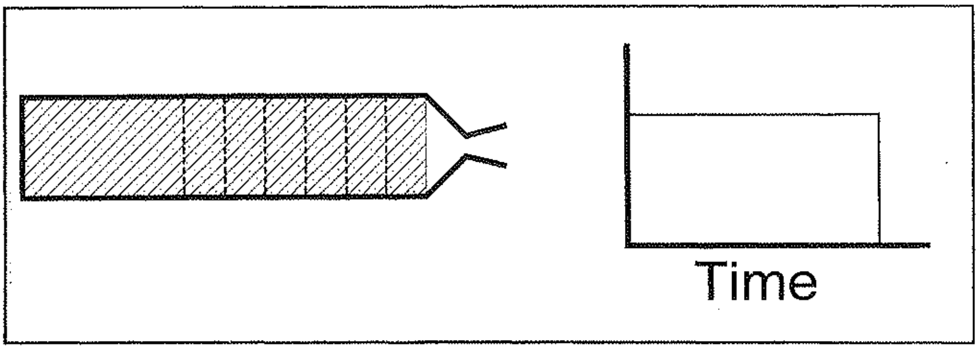

Figure 10: Endburning motor and representative thrust-time curve.

ENDBURNER

The simplest grain configuration is the *endburner* or cigarette-burn motor. In this configuration the propellant is a solid grain, and burns from one end to the other like a cigarette. If the entire end of the grain is ignited simultaneously and the nozzle size doesn't change (no erosion), the burn area (and K_n) remain constant during the burn. Thus such an endburner is perfectly neutral, as shown in Figure 10.

A disadvantage of the endburner is that the casing is exposed to hot gases near the nozzle end, for most of the burn. Insulation (a thick liner) is required to avoid burn-through, especially for aluminum casings and for longer burns.

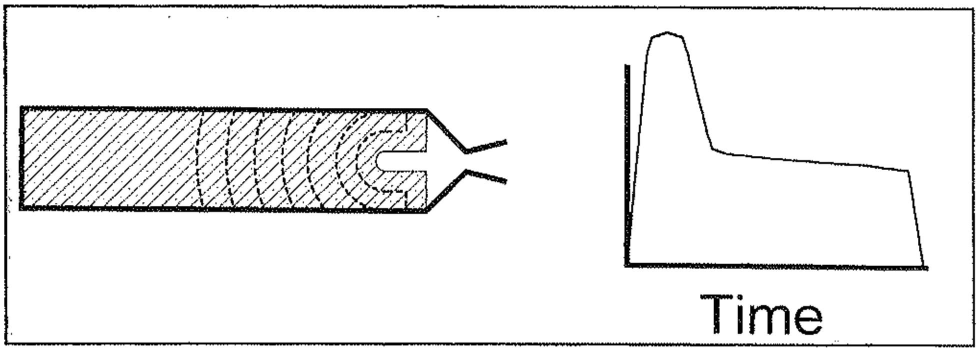

Figure 11: Cored endburner and representative thrust-time curve.

CORED ENDBURNER

Most blackpowder "endburners" used in model rockets are actually cored endburners (Figure 11). For best performance, a model needs a bit of a kick at the beginning, to get it off the ground quickly. So a short core is shaped at the nozzle end of the propellant grain. When the propellant is ignited, the burning surface area increases at first, up to the point where the flame reaches the wall. At this point the burning surface is roughly the shape of a hemisphere plus a cylinder (see the figure). After this, the surface is more like a hemisphere without the cylinder, so the burn area drops off and thrust decreases.

Look carefully at the figure, and you will see that the surface of the burning propellant becomes less curved as the flame progresses. This means that the burn area decreases slightly in the second portion of the burn. And *this* means that thrust drops slightly in the "neutral" part of the burn. But for all practical purposes the cored endburner gives a quick spike of thrust, and is neutral afterward.

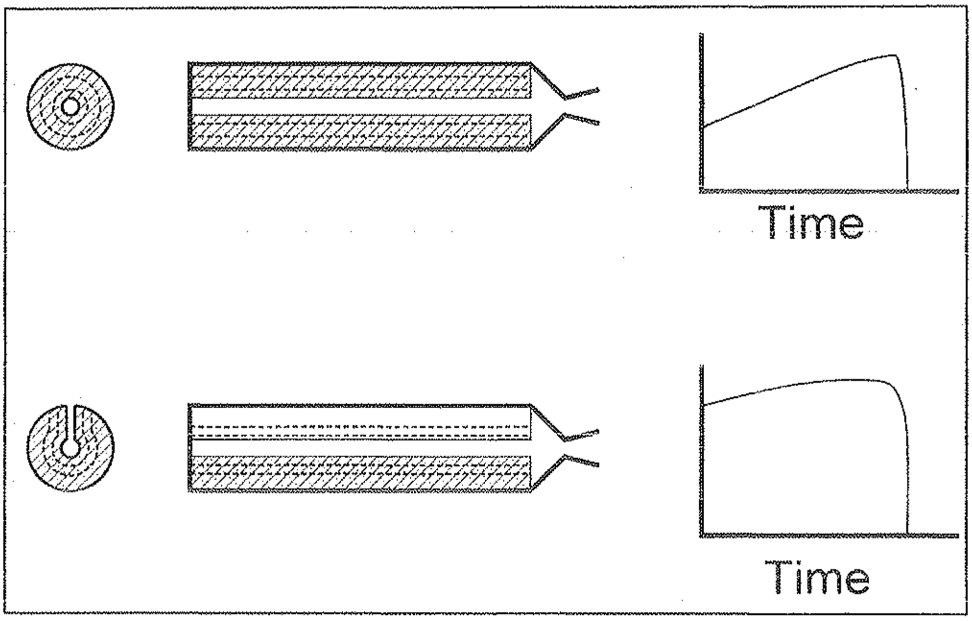

Figure 12: Top: simple coreburning motor and thrust-time curve. Bottom: slotted core and thrust-time curve.

COREBURNER AND SLOTTED CORE

The word *coreburner* (Figure 12) often refers to a grain with a central circular core[6]. A coreburner is progressive, since the core increases in diameter (and in area) during the burn. The progressive-ness can be reduced a bit by using *unrestricted* ends; i.e., the ends are exposed and will burn. If the propellant burns from the ends as well as in the center, the grain (and the core) becomes a little shorter during the burn. In addition, the burning ends themselves become smaller as the core diameter increases. Together, these two phenomena keep the area from increasing as much during the burn, and so make the burn a little less progressive.

One advantage of the coreburner is that the propellant itself acts as insulation during the burn. Most of the case is not exposed significantly to hot gases until the very end.

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[6] Some references use the word "coreburner" to describe any motor or grain with a hole running through it (i.e., as opposed to "endburner"). By the same token, the different grain configurations described in this book may be given different names or fall into different categories in other books.

As noted earlier, a simple coreburner with a circular central core isn't very efficient. The case has to be strong enough to handle the pressure at the end of the burn. This means that at the beginning of the burn, when pressure is lower, the case is actually stronger than it needs to be. One way to make the coreburner less progressive is to increase the core diameter. Of course, this means less propellant in the motor.[7] Tradeoffs...

Another way to make the simple coreburner almost neutral is to cut a long slot down the grain, from core to outside of propellant, as shown at the bottom of Figure 12. This is called a *slotted coreburner*. As the core diameter increases (progressive), the slot width also increases (regressive). The two factors offset one another to a great degree, giving a burn that is almost neutral. However, insulation will be required between the slot and the case, to avoid the flame burning through the case.

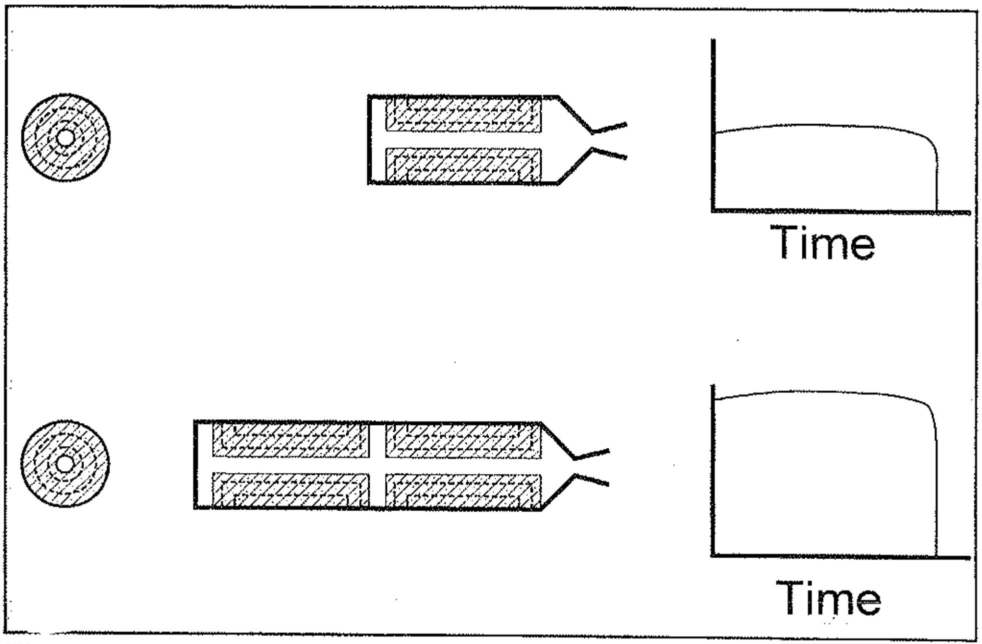

Figure 13: Top: Single BATES grain motor. The *unrestricted* ends burn, making the core shorter; the result is nearly neutral. Bottom: Two BATES grain motor operating at the same K_n as the single grain will give the same type of curve, but with twice the thrust.

BATES GRAIN

As noted earlier, a coreburning grain becomes less progressive if the ends are left unrestricted; as the ends burn, the core becomes shorter, increasing regression. It should be apparent, too, that as this coreburning grain is made shorter, the grain becomes less progressive. There is less core area, and so there is proportionately more "ends" surface area that regresses.

If such a grain is made about 1½ times as long as its diameter, with unrestricted ends,

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[7] *Volumetric loading* is the fraction or percentage of the space in a motor that is taken up by propellant. An endburner has a volumetric loading of 1; a coreburner's loading is less than one. A given coreburner with a larger diameter core has a lower volumetric loading than one with a smaller core.

something interesting happens. The progressive nature (increase in core diameter) is almost exactly balanced by the regressive nature (core becoming shorter and ends becoming smaller). So the burn is almost neutral, as shown at the top of Figure 13. The term BATES (*BA*llistic *T*est and *E*valuation *S*ystem) was coined to describe such a propellant grain.

Several BATES grains can be stacked in a motor, and all will burn on the ends and in the core, as shown at the bottom of Figure 13. The BATES grain is excellent for experimental work; it is simple to make, gives a burn that is neutral for all practical purposes, and a given total impulse can be obtained by stacking sufficient BATES grains.

BATES grain motors often use an insulating liner since the case will be exposed to hot gases at the junction between propellant grains. However, some workers have had success with omitting the liner in small motors, even those motors with aluminum cases. Notice in the figure that thrust increases slightly toward the middle of the burn, then drops off. This "hump" can be minimized if desired by using a larger core, or by cutting a "cone" into each end (rather than leaving the ends flat). Both of these actions (unfortunately) give lower volumetric loading. Tradeoffs again...

MOONBURNER OR OFFSET PORT

Generally, *offset port* is used to describe a coreburner in which the core is off-center. A *moonburner* is an offset port in which the core touches the outer wall of the propellant (Figure 14, top). It can be shown mathematically that the moonburner is regressive throughout its burn. An offset port will be progressive until the burning surface reaches the propellant wall; after this it will be regressive.

You can see that in both types of grain, the flame will reach the propellant wall before the burn is finished. This generally means that additional insulation will be needed on that side of the casing, to avoid damage or burn-through of the casing.

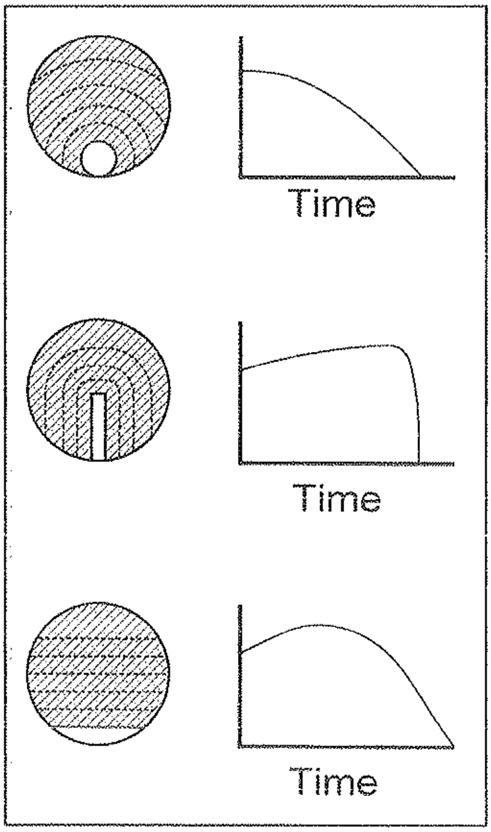

Figure 14: From top to bottom: moonburner, C-slot, D-slot.

C-SLOT

A c-slot has a narrow radial slot cut in the grain (Figure 14, center). Usually the slot is cut to the center of the grain as shown. This grain has a burn profile that is almost neutral (except near the very end of the burn). Like the moonburner, the c-slot requires additional insulation on the side of the case near the slot. However, since the slot is narrow (compared to the core of a moonburner) and reaches to the center of the grain, ordinarily there will be less heat directed onto the casing with the c-slot than with the moonburner.

Contrary to first impression, the c-slot is actually not difficult to make. A slow, sharp cutter similar to a circular saw blade is sometimes used to make the slot. Alternatively, the slot can be molded in place with a rectangular mandrel.

D-SLOT

The D-slot (Figure 14, bottom) is similar in burn characteristics to the moonburner, but is easier to make. A D-shaped piece of propellant is sliced off of the finished grain (this operation is illustrated later in Figure 33). Insulation will be required since the case will be exposed to the direct heat from the propellant from the beginning of the burn.

OTHER GRAIN CONFIGURATIONS

All the grains discussed so far are not terribly difficult for the experimenter to make in a home shop. There are several other propellant grain shapes that are not often encountered in experimental work. That's because the core in most of these types must be *molded* with a special mandrel. If the experimenter is willing to construct (not easy) or purchase (not cheap) the necessary mandrel, some of these grains give very good burn characteristics and volumetric loading.

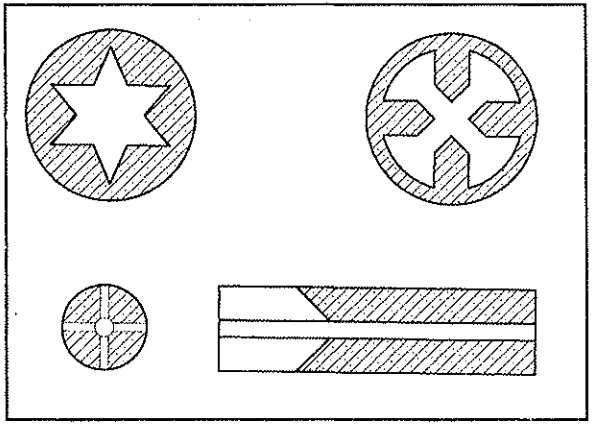

Figure 15: Top left: six-point star grain. Top right: cloverleaf. Bottom: end and side view of finocyl grain. All three can be made virtually neutral but also can be somewhat difficult to construct.

The *star* grain is commonly seen in commercial motors. Its major advantage is that it is almost perfectly neutral when designed properly. The outside points of the star give progression; the inside points give regression. For a neutral burn, the perimeter of the star should be equal to the circumference of the grain.

One problem with the star grain is that *slivers* of propellant are left over at the end of the burn, between the points of the star at the case wall. These occur because ammonium perchlorate composite propellant (usually) burns well only under pressure. Toward the end of the burn, the burn area drops, pressure drops, and the propellant may go out before all of it is burned.

The *cloverleaf* grain is similar in nature to the star grain, though it usually has a lower volumetric loading and may leave smaller slivers of unburned propellant.

The *finocyl* is a finned cylinder, hence the name. The slots shown in Figure 15 are cut partially up the sides of the grain. Regression/progression can be controlled by varying the length of the slots. It can be seen that insulation between the grain and the case will be needed near the bottom of the grain, where the slots are. However, the forward portion of the grain may be left uninsulated. One difficulty with the finocyl for the experimenter is cutting the narrow slots. A minimum width for such slots is about 1/16". If the slots are too wide, volumetric loading is reduced.

THE NOZZLE

A rocket motor that has nothing more than a hole at one end of the combustion chamber, for hot gases to escape (Figure 3) will work. However, such a motor will be less efficient than it could be. For most efficient operation, the hot gases from the combustion chamber must flow *smoothly* toward the nozzle throat. And the gases should be made to contribute as much as possible to the thrust of the motor. An optimum nozzle contributes to smooth gas flow, and also maximizes thrust.

THE ENTRANCE SECTION

In very small BP motors, the end of the nozzle that faces the propellant often is flat (Figure 16), for simplicity in construction. In larger motors it is desirable to funnel the hot gases smoothly from the combustion chamber to the nozzle throat. This is accomplished with an *entrance cone* of some sort. The simplest sort of entrance cone is a funnel-shape (Figure 16, center), used in many small motors. The length, angle, and shape of this section are something of a compromise. A very large angle is little better than no angle at all, and tends to cause turbulence. A very shallow angle maximizes smooth flow but results in a long, heavy nozzle. Typical small nozzles use an entrance cone *half-angle* of about 45 degrees; some commercial motors may use a somewhat steeper angle to make the nozzle as short as is practical.

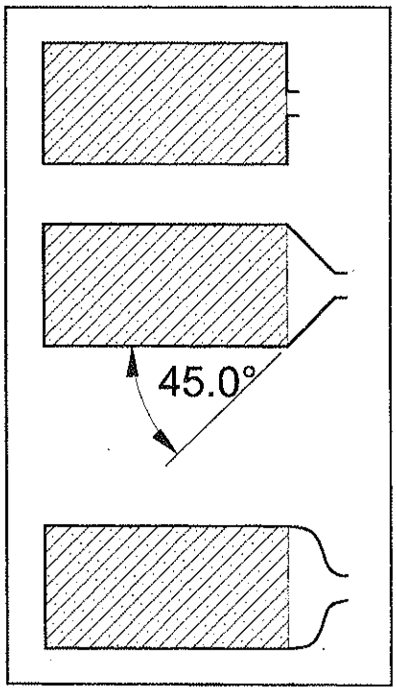

Figure 16: Top: flat entrance section used in some very small motors. Center: entrance cone with 45° half-angle. Bottom: entrance section with complex curve is somewhat more effective than a simple cone.

In a very large nozzle, a simple 45° entrance cone can make the entrance section rather long. Length means weight, and so in large nozzles the entrance cone may be a more complex curved shape, as shown in Figure 16, bottom. The curved shape is calculated to maximize efficiency and minimize turbulence in the gas flow.

THE EXPANSION SECTION

After the hot gases exit the chamber, they will expand until they are at the same pressure as the surrounding atmosphere. Also, they will cool during the expansion. Expanding gas can be made to do work, that is, to provide additional thrust. Note the *expansion cone* after the nozzle throat, shown in Figure 17. Aft of the nozzle throat, the hot gases expand against the walls of the expansion cone, and exert force against the walls as shown in the figure. This force is realized as additional thrust. Since the expansion cone produces additional thrust, it should be apparent that a properly designed expansion cone is more important than a properly designed entrance cone.

A perfect nozzle is designed so that the pressure (which is equal to chamber pressure at the nozzle throat) drops precisely to atmospheric pressure at the end of the expansion cone. Most experimental nozzles are less than perfect, but nonetheless provide a significant increase in thrust as compared to a simple hole.[8]

As with the entrance cone, the expansion cone's length, angle, and shape require compromise. A short cone does not allow enough time for the gases to expand properly. Thus, a longer expansion cone and shallow angle make the nozzle more efficient. On the other hand, a long expansion cone means a heavy nozzle, and past a certain point there is very little increase in efficiency with length. For most small rockets, a half-angle of about 15 degrees (shown in the figure) is about 98% as efficient as a "perfect" nozzle, and so this is commonly used.

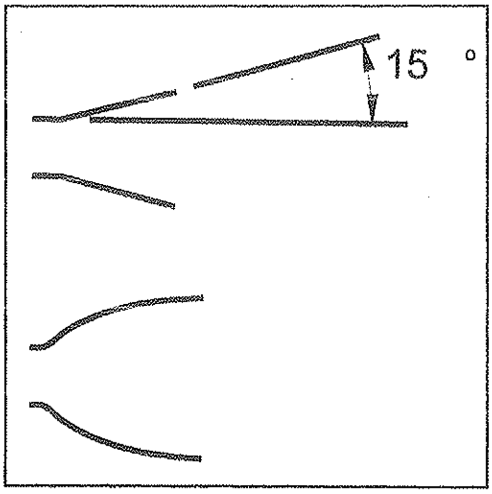

Figure 17: Top: simple expansion cone with 15° half angle. Bottom: optimized expansion section is slightly more efficient but complex to make, and is not often used.

In larger motors, an expansion section may have a profile similar to that shown at the bottom of Figure 17. The curves are carefully calculated to produce minimum turbulence and maximum expansion within the shortest practical length (longer nozzle = heavier nozzle). Many experimenters are not very concerned with obtaining absolute-maximum performance, and so the simple entrance cone/exit cone is most often used, even in modest-sized motors.

EXPANSION RATIO

As noted earlier, the perfect nozzle is designed so that the pressure drops, from chamber pressure at the throat to atmospheric pressure at the end of the exit cone. For the pressure to drop in this fashion, the area of the exit cone and the area of the nozzle throat must be in a particular ratio. This *expansion ratio* is:

$$E = \frac{\text{area of end of exit cone}}{\text{area of nozzle throat}}$$

Since area of a circle is equal to πr^2, we can write the expression as:

$$E = \pi r_{exit}^2 / \pi r_{throat}^2$$
$$E = r_{exit}^2 / r_{throat}^2$$

Example: consider a nozzle with a throat of 0.250" and an exit cone of 0.550". The radius of the throat is 0.250/2, and the radius of the exit cone is 0.550/2, so:

---

[8] Actually, since most large rockets operate at a variety of pressures (from atmospheric pressure on the surface, to almost zero at high altitudes), a "perfect" nozzle is perfect only at one particular altitude.

$$\mathbf{E = (0.550/2)^2 / (0.250/2)^2 = 4.84}$$

Is 4.84 an appropriate expansion ratio? That depends on several factors: chamber pressure; external (atmospheric) pressure; chamber temperature; exit gas temperature. Calculating the optimum expansion ratio is not simple. However, Propep[9] will do the hard work for you. Simply click on the box labeled "Boost Velocity and Nozzle Design" before you run Propep.

For example, assume that the simple propellant will be used in a motor with chamber pressure of 600 psi. The chamber pressure has been changed from 1000 to 600 psi, and the "Boost Velocity and Nozzle Design" box has been checked. The Propep results should look as follows:

```
  CODE                                         WEIGHT    D-H  DENS       COMPOSITION
   137 AMMONIUM PERCHLORATE (AP)               79.800   -602  0.07040     1CL  4H    1N    4O
   244 CARBON (AMORPHOUS)                       0.200    917  0.06370     1C
   779 POLYBUTADIENE/ACRYLONITRILE CO          16.400    314  0.03400   653C 854H  19O   72N
  1096 DER-331 EPOXY                            3.600   -661  0.04200    24H  16C    4O

THE PROPELLANT DENSITY IS 0.05866 LB/CU-IN OR  1.6237 GM/CC
THE TOTAL PROPELLANT WEIGHT IS  100.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   4.423072 H      1.291242 C      0.797051 N      2.799135 O
   0.679166 CL

****************************CHAMBER RESULTS FOLLOW    *****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV    GAS   RT/V
2662. 4332.   40.81   600.00   -45.09   249.87  1.2368  4.255   9.592

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=   10.376   10.378
NUMBER MOLS GAS AND CONDENSED=   4.2551   0.0000

  1.21526 H2O        1.00509 CO         0.66988 HCl        0.65182 H2
  0.39830 N2         0.28605 CO2        0.01283 H          0.00916 Cl
 6.02E-03 HO        3.68E-04 NO        7.48E-05 O         5.69E-05 O2
 3.26E-05 Cl2       2.94E-05 NH3       1.38E-05 CHO       1.37E-05 COCl
 8.58E-06 HOCl      4.51E-06 CNH       3.67E-06 CH2O      2.20E-06 OCl
 1.95E-06 NH2       1.25E-06 CNHO

THE MOLECULAR WEIGHT OF THE MIXTURE IS   23.501

****************************EXHAUST RESULTS FOLLOW    *****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV    GAS   RT/V
1310. 1899.    1.00    14.70  -105.22   249.87  1.2720  4.241   0.236

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    9.292    9.292
NUMBER MOLS GAS AND CONDENSED=   4.2408   0.0000

  1.00323 H2O        0.86869 H2         0.78651 CO         0.67912 HCl
  0.50466 CO2        0.39849 N2         0.00001 NH3        0.00000 H
 1.71E-06 CH4       1.64E-06 Cl

THE MOLECULAR WEIGHT OF THE MIXTURE IS   23.580

**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE**********

IMPULSE   IS EX     T*      P*      C*     ISP*  OPT-EX  D-ISP     A*M    EX-T
  226.8  1.2554   2361.   22.61  4811.1            5.54  368.3  0.24928  1252.
  228.8  1.2278   2393.   22.82  4868.2   188.5    5.66  371.5  0.25224  1310.
```

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[9] See the appendix for detailed information on use of Propep

```
BOOST VELOCITIES FOR PROPELLANT DENSITY OF  0.05866  (S.G. OF    1.624)

  5./22505.  10./17741.  15./15080.  25./11927.  30./10870.  55./ 7691.
 60./ 7282.  69./ 6653.  71./ 6529.  88./ 5641. 100./ 5152. 150./ 3800.
 175./3363.  200./3018.  300./2143. 1000./ 711. 3000./ 245. 5000./ 148.

 EXP.   EXIT   EXIT    EXIT OPTIMUM OPTIMUM VACUUM VACUUM SEA LV SEA LV
RATIO  PRESS  PRESS    TEMP IMPULSE IMPULSE IMPULS IMPULS IMPULS IMPULS
         ATM     SI       K     SEC      SI    SEC     SI    SEC     SI
   1. 22.819 2311.5  2393.   103.9   1019.  188.5  1849.  184.8  1831.
   2.  7.606  770.5  1954.   168.2   1650.  224.6  2203.  217.2  2152.
   3.  2.535  256.8  1574.   206.2   2022.  234.4  2298.  223.2  2211.
   4.  1.642  166.4  1445.   217.5   2133.  241.9  2372.  227.1  2249.
   5.  1.193  120.8  1356.   225.0   2206.  247.1  2423.  228.5  2264.
   6.  0.922   93.4  1289.   230.5   2260.  251.0  2461.  228.7  2266.
   7.  0.744   75.4  1236.   234.8   2302.  254.1  2491.  228.1  2260.
   8.  0.619   62.7  1192.   238.2   2336.  256.6  2516.  226.9  2248.
   9.  0.526   53.3  1154.   241.2   2365.  258.7  2537.  225.3  2232.
  10.  0.456   46.2  1122.   243.6   2389.  260.5  2555.  223.5  2214.
  11.  0.400   40.5  1094.   245.8   2410.  262.1  2570.  221.3  2193.
    [Remaining rows have been deleted as they are not needed]
```

The key columns here are the "Exp. Ratio", "Exit Press Atm" and "Sea LV Impuls Sec". Look at "Exp.Ratio" of 4. Moving across, you can see that gases exiting the end of the nozzle are at a pressure (Exit Press Atm) of 1.642 times atmospheric pressure. The specific impulse under these conditions is 227.1 seconds. At an expansion ratio of 5, exit pressure is 1.193 atmospheres and delivered specific impulse is 228.5 seconds. Both of these conditions correspond to an *underexpanded* nozzle, since the exit pressure is a bit higher than atmospheric pressure, and the gases will expand a bit more after the exit.

At an expansion ratio somewhere between 5 and 6 lies the exit pressure of 1 atmosphere and maximum specific impulse of 228.8 (the value from 'shifting' impulse, under the 'performance' line of Propep)[10]. At an expansion ratio of 6, the exit pressure is 0.922 atmospheres. This is an *overexpanded* nozzle. Delivered specific impulse for this ratio will be 228.7 seconds.

For the experimenter building simple motors, it should be apparent that there is a wide latitude in the expansion ratio *actually used*, in terms of specific impulse. For example, from the table above it can be seen that an expansion ratio of 3 will give sea level impulse of 223 seconds. This is only about 2% lower than would be produced by an optimum nozzle (228.7 seconds). An expansion ratio of either 4 or 6 results in a maximum loss of specific impulse of 1% for this propellant. To give a specific example, if the nozzle of a motor using with this propellant has a throat of 0.25", the exit cone could be anywhere between 0.5" diameter (E=4) and 0.61" diameter (E=6) with only a very small loss of impulse.

It is common practice for experimenters to make or purchase a large number of "stock"

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[10] A nozzle that is to operate at very high altitudes -- low exit pressure -- can provide a higher specific impulse than at sea level. The exiting gases expand more and can be made to do more work. Note that the *vacuum impulse*, or the specific impulse produced in a vacuum, is *higher* than the sea level impulse. This is one reason that the Space Shuttle's main engines have a very high expansion ratio, about 33. That high ratio maximizes the thrust obtained at high altitudes.

nozzles with a given exit diameter. The nozzle throat is drilled to an appropriate diameter for the desired K_n. The discussion of this section suggests that this practice does not reduce greatly the performance of the rocket motors so constructed.

THRUST COEFFICIENT C_F

It should be clear that an expansion cone of some sort can contribute a great deal to the delivered impulse. Without an expansion cone, the simple propellant would deliver only 184.8 seconds at 1000 psi. With an expansion section having an expansion ratio of 4, the impulse increases to 227.1 seconds -- an increase of almost 23 percent! The increase in impulse resulting from the expansion cone is often expressed as the *thrust coefficient*, C_f. The precise expression for thrust coefficient will not be described here (see Lanier or Sutton for an in-depth treatment). It will simply be noted that C_f is very roughly the ratio of *delivered* specific impulse to I_{sp}^*.

As chamber pressure increases, the expansion ratio needed for best performance also increases. The importance of C_f is: the greater that expansion ratio, the greater the value of C_f and the greater the delivered specific impulse. At 1000 psi, the simple propellant requires expansion of 8:1 to obtain maximum benefit from the nozzle. However, the increased pressure also increases the value of C_f. At 1200 psi, expansion of 9:1 is needed, but C_f would be even higher and the delivered specific impulse even higher, too. This is one reason that some experimenters design motors to operate at the highest practical chamber pressure.

NOZZLE DIMENSIONS

Calculation of rough nozzle dimensions can be quite simple -- and rough dimensions can be quite adequate for routine use. An expansion ratio of 4 is adequate for routine chamber pressures of about 300-600 psi. At E=4, with a 15° half-angle for the exit cone, and a 45° half-angle entrance cone:

-the exit cone diameter will be about twice the nozzle throat diameter,
-the exit cone length will be about equal to the diameter of the exit cone,
-the typical nozzle throat will be about half as long as its diameter,
-the entrance cone length will be found by subtracting the throat diameter from the propellant diameter, and dividing by two.

As an example, consider a motor that uses propellant of diameter 1.28", using a nozzle with 0.375" (⅜") throat. For such a nozzle:

Exit cone diameter = 2 × ⅜" = ¾"
Exit cone length = exit cone diameter = ¾"
Nozzle throat length = ⅜" × ½ = 3/16"
Entrance cone length = (1.28 - 0.375) / 2 = about 0.45"
Overall length = exit cone length + nozzle throat length + entrance cone length
= 0.45 + 0.1875 + 0.75, or 1.39"

EQUIPMENT AND SUPPLIES

For now we'll leave you to digest the theory that has been covered, and move to practical aspects. In propellant making and motor construction there are essential supplies and equipment, and there are some supplies and equipment that will be useful later on[11]. This book will concentrate on 29 mm motors for initial work.

Gotta have:
Notebook
Safety equipment
Safe place to work
Mixing bowl
Mixing stick
Balance or scale
Scrap can
Curing box
Propellant rack
Packing stick
Casting tubes
End plugs
Drill and drill bits
PBAN
Epoxy resin DER331 or similar
Ammonium perchlorate 200 micron
Lampblack
Single-use motor casing material
Nozzles
Epoxy glue (very slow)
O-rings
Cardboard or wooden disks (1" dowel)
Igniters
Launch system w/100 ft of cable
"Static test" stand
Video camcorder
Large land area for testing
Reloadable motor casing

Nice to get later:
Coring rods and mating plugs
Burn rate catalyst (CuO or Fe_2O_3)
Atomized aluminum -400 mesh
Finer (90 micron) and/or coarser (400 micron) ammonium perchlorate
Plasticizer (dibutyl phthalate or dioctyl adipate)
Kitchen-Aid mixer
Lecithin
Metal lathe
Thrust stand

For vacuum processing:
Vacuum pump
Vacuum plate
Safety valve and trap

Notebook: This should be a permanently bound notebook, not spiral-bound or looseleaf. Don't use scrap paper, don't use the back of your hand. Good record-keeping will make it less likely that you will repeat mistakes. Write as though someone else had to read it and understand it. That way you'll be able to understand it next year, when you pull that notebook off the shelf. Personally, I like a proper laboratory-type notebook with quad-ruled (graph paper) pages; they are very nice for data and for sketching.

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[11] As noted earlier, the procedures in this book are based on PBAN. If HTPB is selected as the binder, isocyanates will be needed as curatives instead of epoxy resin.

Any time a new batch of propellant is started, the following information should be entered in permanent ink, directly in the notebook:

Date started
Title of the experiment
Objective of the work (what specifically are you trying to accomplish)
Basic procedure to be followed (don't abbreviate)
Amounts of ingredients to be used
Amounts of ingredients ACTUALLY used
Calculations, if any
Results of the work
Conclusions

I know this sort of recordkeeping may sound overly scientific and "anally retentive". However, scientific procedure and a certain degree of anal-retentive behavior should be cultivated in experimental rocketry. It helps to keep the head attached to the shoulders.

A good rule of thumb: if it is to be written down somewhere, it is written *in the notebook*.

Safety equipment: must include the following at a minimum: water-type fire extinguisher; water bucket; cotton gloves; rubber gloves; cotton clothing; heavy canvas shoes; eye protection; appropriate respirator. The fire extinguisher won't put out burning propellant. It is used on other material ignited by the propellant. The water bucket is filled with water and kept by your side, into which you will dunk burning hands, if and when necessary. Cotton gloves covered with rubber gloves are considered by some to be a reasonable safety precaution. Rubber or plastic alone will melt into the skin if there's a fire. All clothing should be heavy cotton, or other fabric which does not melt (same idea). Eye protection should be chosen to protect against burns and impact. The respirator must protect against fine ammonium perchlorate and against aluminum dust. The filtering element must be disposable, because it is burned along with propellant scrap at the end of a session. Single-use paper masks are largely useless for capturing this sort of dust.

Safe place to work: Some people do this work in a garage (possibly even some manufacturers). I do not condone such activity. You should keep the following in mind all the time: "What is the worst that could happen if this stuff 'goes off'?" A workplace that is well-removed is a necessity, not a luxury. See the Safety Code.

Mixing bowl: A very heavy stainless-steel 5 quart mixing bowl. Mine came from Target, about $15. If you're not going to vacuum-degas the propellant, a thinner bowl will do, but don't get a smaller bowl. This size will do for batches from 200 g to 2 kg. Your bowl must be able to fit in your curing box.

Mixing stick: I use a ¾" Teflon rod about 18" long (stole it from my boss). Aluminum or hardwood will work (a hardwood dowel may be epoxy-coated for easier cleaning). NOT steel. A bicycle-type foam grip isn't a bad idea and may minimize blisters when hand-mixing.

Balance or scale: At a minimum, 600 gram capacity with 0.1 gram readability. Electronic scales run about $100-150. I use an old double-pan balance because it has a capacity of over 5 kg. DON'T skimp on your balance/scale. If you can't afford a scale you can't afford to make propellant and motors. One way to economize is to buy two scales, one 200 g ±0.1 g, and a second 2000 g ± 1 g. Two such scales together may cost less than a single 600 gram scale.

There are some kinds of mixtures that can be made properly by using *volume* measurements. Composite propellant is *not* such a mixture.

Scrap can: not really a can; a small cardboard box or large cup that will not leak. A big popcorn cup or oversize paper cup is great. All propellant leftovers, shavings, paper towels used for cleanup, wooden craft sticks, propellant drips, etc. are placed in the scrap can. At the end of the day (or more often if necessary) the can is removed to a safe location and an igniter is used to REMOTELY ignite the can contents. Of course, a new scrap can is needed for each session.

Curing box: build. See this topic in the appendix.

Propellant rack: A simple rack is shown at the right. It must fit easily in your curing box. The bottom should be fairly heavy, to eliminate tipping. Drill or holesaw the holes about 1 ¼" (to hold 29mm motors and grains), 1 ⅝" (for 38mm stuff), and 2 ¼" (for 54mm stuff).

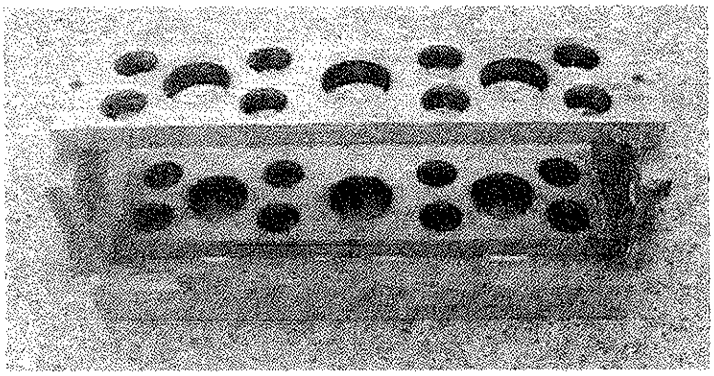

Figure 18: Wooden propellant rack will hold grains and motors in 29 and 38mm sizes.

Packing stick: a wooden dowel or aluminum stick, at least 4" longer than the casting tubes to be packed. I use a ⅝" aluminum rod, sawn and filed smooth on one end, for 29 and 38 mm casting tubes. If a wooden dowel is used, a coat of epoxy will make it easier to clean.

Casting tubes and liner tubes: casting tubes are used to cast the propellant. Liner tubes are used to insulate the casing from propellant flame[12]. Liner tubes need to fit snugly into the casing (most 29mm casings are 1.00" i.d). Casting tubes fit snugly in the liner tube. Some workers omit the liner and just use a casting tube that fits the casing. This may be ok for small aluminum motors and most phenolic-cased motors. However, larger motors usually need insulation, else the flame may burn/melt through the case.

---

[12] In the professional literature, the term "liner" generally means a material that is used to attach the propellant to the case or to the case insulation. However, the usage provided here -- "casting tubes" hold propellant, "liners" are insulation -- is in common use among experimenters, even though it is not technically correct.

Some workers use Estes BT-50 tubes as 29mm casting tubes. Another alternative is LOC body tubes for 24mm motors (they are 0.95" id.). RCS sells tubes of various sizes.

It is entirely possible to roll your own casting tubes. Galvanized thinwall metal conduit in ¾" size is 0.93" od, and can be used as a mandrel to make 29mm casting tubes. PVC pipe in 1" size is 1.31" od and can be used to roll 38mm casting tubes.

End plugs: need to fit tightly into the casting tube. A rubber stopper works, as does a Caplug® (plastic plug found in some gas and plumbing fittings). An alternative: squirt globs of pure-silicone caulking onto a square of foil, and stand casting tubes into these globs. Allow to stand at least several days to cure completely.

Machined casting tube plugs are discussed in the appendix, under "Coring rods"

Drill and drill bits: A good cordless drill or a drill press is needed to drill cores in the propellant. For 29mm grains, a ⅜" or 7/16" core is fairly standard. For 38mm grains, ½" core; for 54 mm grains, ¾" or ⅝" core. You'll also need a series of small drills for nozzle throats. A set of numbered drills (#1 through #60) is fairly inexpensive and very useful for 29 and some 38mm nozzles.

PBAN: Polybutadiene acrylic acid acrylonitrile prepolymer. About $12 a gallon. One gallon of PBAN can be used to make over 50 lb of propellant. A large plastic ketchup bottle or similar is convenient for dispensing PBAN. Label the bottle in large letters, permanent ink, on both sides, so no one can possibly mistake it for syrup (of course, once you smell the stuff you ought not to mistake it for anything edible).

It should go without saying that all propellant chemicals are kept locked away, out of the reach of children.

Epoxy resin: the generic technical name is "DGEBA epoxy resin" or "diglycidyl ether of Bisphenol A". Dow manufactures this stuff under the designation DER-331. Shell's brand is called EPON-828. Celanese, Ciba, Union Carbide, and other manufacturers will have similar material. Most workers think of epoxy as a "resin" that is cured; in this application, the PBAN may be considered the resin and the epoxy the curative.

One quart of DER-331 is about $10 and will cure a gallon of PBAN, with some epoxy left over. Again, a squeeze bottle is convenient for dispensing epoxy. An alternative to DGEBA epoxy is System Three epoxy resin; this is discussed in the section on propellant modifications and in the section on coring rods.

Ammonium perchlorate 200 micron atomized: Also known as AP, it is the preferred oxidizer for most experimental work. "Atomized" or "spherical" material is rounded and quite uniform, and makes the propellant easier to process than ground material. Available from pyrotechnics supply houses at about $6 a pound. Get at least five pounds to start.

Lampblack: almost-pure carbon, also known as "carbon black" or "Thermax", this is used as an opacifier. It's a fine black dust that stains anything it touches (in fact it is the pigment in many black inks). Can be very messy to work with. One pound costs about $5 and will last a lifetime unless you're building a space shuttle.

Single-use motor casings: Phenolic (1" id, 1/16" wall) is a hard, brittle plastic that will do for lower pressure (300-500 psi) motors; available from RCS and from McMaster-Carr. Aluminum will handle considerably higher pressure (about 1000 psi) in the same wall thickness, and can be obtained locally or from a number of aluminum suppliers. Important: do NOT use scrap aluminum. Fiberglass is expensive but as strong or stronger than aluminum, and is less dense. Both aluminum and fiberglass normally require some insulation between the propellant grains and the casing. There is a discussion of casing materials in the appendix.

Nozzles: single-use phenolic nozzles are available from RCS for about a dollar in 29mm sizes. Graphite is often the preferred material for nozzles as it can be removed and reused many times. But graphite is very messy to machine (see the appendix for machining instructions). Inexpensive graphite surplus stock for nozzles is available from Aerocon; custom-machined graphite nozzles are available from Dynamic Propulsion Systems and elsewhere.

Epoxy adhesive (slow): this is used to "pot" nozzles and make forward closures in single-use motors. You want the strongest epoxy that can be had. DER331 epoxy and Versamid curative are satisfactory. Both are about $10 a quart. Two parts of DER-331 with one part Versamid will cure in 2-4 hours at 140°F, with little or no exotherm and no significant distortion. Three parts DER-331 and two parts Versamid will cure at room temperature in 24 hours. Both are thick but the product is extremely strong.

Hobby epoxy can be picked up at the local hobby shop, but is rather more expensive than the bulk material. System 3 and West Systems epoxy can be obtained via a number of distributors. Both have gotten good reviews from hobbyists in the model rocket community. The slowest possible curative should be used, for maximum strength and working time.

O-rings: 1" o.d. x 3/32" thick (about 0.81" i.d.). Some workers omit them in single-use motors but the author's experience has been that they minimize blow-by.

Cardboard or wooden disks: used as insulating disks for single-use motors. Can be punched or cut out of thick cardboard, or wooden disks can be sawn from the appropriate size dowel rod. They must fit *tightly* in the casing. This is discussed in the section on making single-use motors.

Igniters: discussed in the appendix.

Launch system w/ at least 100 ft of cable: you do NOT repeat NOT want to be near an experimental motor when it is being ignited. Don't even think about using your Estes system to ignite an experimental G-motor or even an E-motor. If you can't figure out (or look up) how to build a simple launch system using a 100' extension cord and a 12 v car battery, you should not be making motors. A relay system is a good idea; the Summer 1996 issue of Sport Rocketry gives a design for a relay launch system. For motors larger than 640 N-s (J and higher) more than 100' of cable is necessary.

For a launch system using ordinary extension cord, the necessary electrical fittings are available in any electrical supply or hardware store. Just make sure you keep the launch system and control box out of the hands of little children who might think that these things can be plugged into an outlet...

"Static test" stand: for small motors (29 and 38mm) this may be a piece of ½" concrete reinforcing bar hammered into the earth. The test motor is strapped to it with hose clamps, nozzle-up. The "stand" is surrounded by sandbags, earthen berms, timbers, or other material to direct an explosion upward. You WILL have explosions...

For larger motors a permanent test place will be needed. Keep in mind the adage "What is the worst that could happen IF...?"

Large land area for testing: unless your backyard borders on a genuine wilderness, it is not suited to testing motors. Do not (repeat, DO NOT) test your motors inside the Podunk city limits. The cops will find you or angry neighbors will turn you in. At the least, your motor-making days will be over. And it is entirely possible that you will end up in jail, with a criminal record.

It goes without saying that you need the written permission of the landowner. NAR and TRA list launch field sizes for various sizes of motors. You must have *at least* that size of field for experimental motor testing, even though the motors won't be going into the air. Intentionally. At first.

Reloadable motor casings: not absolutely necessary but they make it less expensive to fly the motors. Discussed in the appendix.

Video camcorder: this is used to videotape your test results. It gives a fairly accurate measure of burn time, which can then be used to calculate chamber pressure and other quantities.

Coring rods and casting tube plugs: not necessary but more convenient than drilling cores. These are covered in the appendix.

Burn rate catalyst (CuO or Fe_2O_3): used to increase the burn rate of a formulation. According to the literature Fe_2O_3 is a better catalyst; CuO is a little harder to use but gives a prettier flame (blue-purple). One pound is about $4-6 and is sufficient for about 100 lb of propellant.

Atomized aluminum -400 mesh: used to increase specific impulse in larger motors, aluminum is not as effective in smaller motors. But it does increase I_{sp} somewhat, and it also minimizes combustion instability to some extent, promoting smoother burning of the propellant. If it is used, it makes up about 1-15% of the propellant formulation.

Some aluminum comes "lumpy" from absorbing moisture and must be screened first. Coarse screens such as window screen or similar will allow fairly large lumps to fall through. Skylighter and Firefox sell screens of various mesh size. Be VERY careful about "dusting" (see below).

Caution: once a screen has been used for aluminum, NEVER use it for anything else. Period. It is IMPOSSIBLE to get it completely clean, and residue of aluminum can react with something else. In other words, have separate screens for aluminum, AP, etc.

Fine metal powder is one of the most hazardous materials used in rocket propellant. The dust "hangs" in the air and can be ignited by a static spark.[13] So one must be very careful indeed to avoid producing such dust. When dispensing aluminum or other fine powder, motion must be slow and deliberate. The powder is not to be dropped from any significant height; instead, the spoon or spatula is brought close to the surface of the liquid ingredients and turned slowly, so the powder falls from the smallest practical distance.

Finer (90 micron) or coarser (400 micron) ammonium perchlorate: for increasing or decreasing burn rate, and for increasing solids loading of propellant. Amount needed depends on the type of propellant to be produced. For increasing solids loading, about one pound of each for every 4-5 pounds of 200 micron AP.

Fine AP also may "lump" badly, and should be sieved. Stainless steel screen is suited to this purpose. WARNING: once a screen has been used for AP, NEVER use it for anything other than AP (read the warning above regarding screens and aluminum). Also, do not use *brass* screen with AP, as the copper from the brass can cause problems.

Plasticizer (dibutyl phthalate or dioctyl adipate): this reduces the viscosity of the mix but may decrease strength as well. Dioctyl adipate or DOA is mentioned very frequently in the literature and is fairly low in viscosity. Dibutyl phthalate has been reported as being rather compatible with mixes containing epoxy resin. The proportion in propellant does not usually exceed 2-3% (in PBAN propellant), so one quart is sufficient for about 50 lb of propellant.

Kitchen-Aid mixer: for machine-mixing larger batches. See the appendix on "machine mixing". Warning: do not use the home mixer for this. It will be contaminated as a result, and can never again be used for mixing food. If you are even thinking of using the wife's mixer, either buy her a new one, or don't make propellant ("I'll buy a new bowl and blade, honey" is not acceptable...)

Lecithin: a *surfactant* that reduces the viscosity of propellant. Only of limited usefulness for hand-mixed propellant; more useful if the propellant is to be machine-mixed. Used at about 0.1-0.2% in a formulation, so one pound is a lifetime supply.

Metalworking lathe: useful for making nozzles, forward closures, other neat fixtures. A small hobby lathe such as the Taig or Sherline can be had for as little as $250, and will

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[13] Ellern reports that aluminum of the size commonly used for propellant making will "fall" at only ½" per minute! In other words, dust tends to "hang" in the air for a long time, creating a long-lasting hazard.

make such parts for motors up to 54mm. Motor casing construction requires a bigger lathe, most of which start around $2000.

Electronic thrust stand: for measuring thrust from a motor. Costs about $250 to make a small one, suitable for 29 and some 38 mm motors. Described in the appendix.

For vacuum processing: vacuum pump, vacuum plate, safety valve and trap: a vacuum system for degassing propellant can be cribbed up for about $100, and will give much more uniform propellant. It's highly recommended. Details are in the appendix.

THE SIMPLE STARTER PROPELLANT

Contrary to what some authors might have you believe, it isn't necessarily difficult to formulate a working AP propellant. If you're looking simply for a formulation that will push a rocket fairly well, there's lots of room to work. A good "starter" mixture might be:

- -about 15-25% binder-fuel
- -about 75-85% solids, of which
  - -0-20% aluminum (optional, not required)
  - -a little burn rate catalyst or other solid additives
  - -the rest is AP

A mixture that fits this description and has good physical properties (strong, reasonably flexible) is very likely to make a working propellant. It may not be the best propellant in the world but it will outperform blackpowder by over two to one, and will rival or surpass performance of some commercial "consumer" composite propellants.

For the starter propellant, for which vacuum processing is not required, there are just four ingredients:

Ingredient	**Mass**	**Percent**
Ammonium perchlorate (AP), 200 micron atomized	187.04 g	79.8%
Lampblack (carbon black)	0.47 g	0.2%
PBAN	38.46 g	16.4%
Epoxy DER331	8.41 g	3.6%

Table III: The simple starter propellant

These amounts will make about 16" of propellant grain for 29mm motors, enough for about four test motors. The propellant will burn with a bright yellow flame and with just a touch of black smoke. It will produce I_{sp} of about 200 seconds in small motors, which can be increased with proper motor design.

In this mixture, the ammonium perchlorate is the oxidizer and the PBAN cured with epoxy resin is the fuel. The lampblack is used as an *opacifier*. It makes the propellant opaque. A translucent propellant may absorb ultraviolet light from the flame zone. This can cause combustion to start deeper within the propellant grain (rather than at the surface), causing a CATO.[14]

The propellant is referred to as 80% solids because (of course!) 80% of the mixture is solid AP and lampblack, 20% is liquids. Notice for this simple propellant that a number of ingredients that professionals and advanced experimenters use, have been left out.

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[14] The opacifier may not be absolutely necessary for this propellant, since the cured propellant is medium brown in color without the lampblack. My personal preference is to be safe rather than sorry...

Those ingredients are discussed later, but for now things are being kept simple.

One difficulty in any propellant is obtaining an appropriate *cure ratio*, the relative amounts of PBAN and epoxy. The proportions given for the starter propellant should be appropriate for this initial experiment; those proportions can be "tweaked" later if desired.

> [Should you elect to use HTPB and one of its curatives in place of PBAN and epoxy, consult the section on this subject in the appendix. You will need to use a different proportion of HTPB to curative than is given for the simple propellant. Information on calculating proportions is given in the section on mixing HTPB propellant]

PROCEDURE

1. Read the "Safety" section at the beginning of this book. Do it now. Know what you're getting into.

2. The mixing bowl is placed on the balance. The bowl is tared; that is, the balance is "zeroed" with the bowl in place. If a mechanical balance (rather than an electronic one) is being used, the bowl is weighed and the weight recorded in the notebook.

3. PBAN is added to the bowl until 38.46 g has been added (Figure 19). Of course, if the balance is good to 0.1 g then 38.5 g of PBAN is weighed. This means "between 38.4 g and 38.6 g." It does not mean "somewhere in the neighborhood of 40 grams." The exact amount is needed so the work can be reproduced.

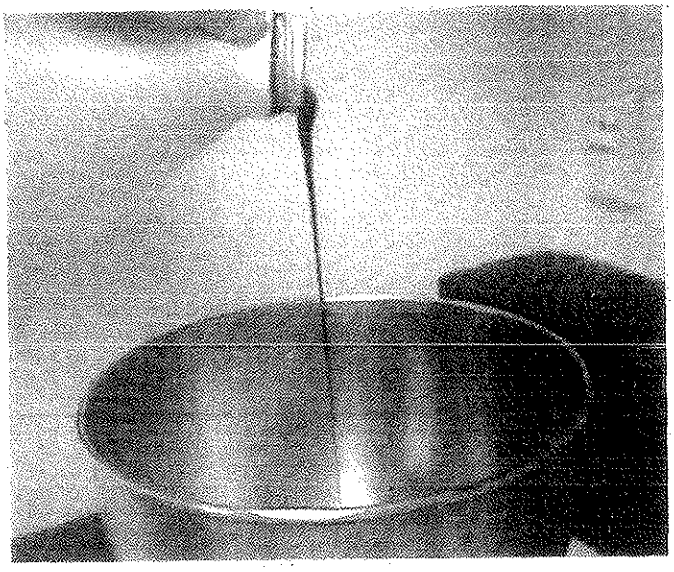

Figure 19: Adding PBAN to the mixing bowl.

   If you're not used to weighing, and you're using a mechanical balance, you'll need to "sneak up" on the weight. Here's how it's done: weigh the empty bowl. Let's say it weighs 301.2 g. You want to add 38.5 g of PBAN. Of course the final weight should be 301.2 + 38.5 = 339.7 g.

   So: the balance is set to about 330 or 335 grams. The PBAN is added slowly til the balance tips, indicating "gone over". Now the balance is set to 339.7 g, and PBAN is added even more slowly til the balance just barely "balances".

PBAN is very thick, about like cold molasses. It's kind of hard to stop the flow, or to add just one drop. It may take a little practice. If too much PBAN is added, it's possible to dip out some of the excess with a wooden stick. Do NOT return this excess to the container; throw it away. (Rule #1 in chemical work: never return a chemical to its container once it's been removed)

4. The mixing bowl and its contents are tared again (that is, the balance is re-zeroed).

5. Lampblack is added to the bowl a little at a time, until 0.47 gram has been added (0.5 gram of lampblack is ok if the balance is good to 0.1 gram), as shown in Figure 20. Don't cheat, get it right. A separate clean spoon is used for each solid chemical. Keep the spoons separate; never get them mixed up (mixups can be avoided if only one chemical is open on the workbench at any given time). The weight of lampblack actually used is recorded.

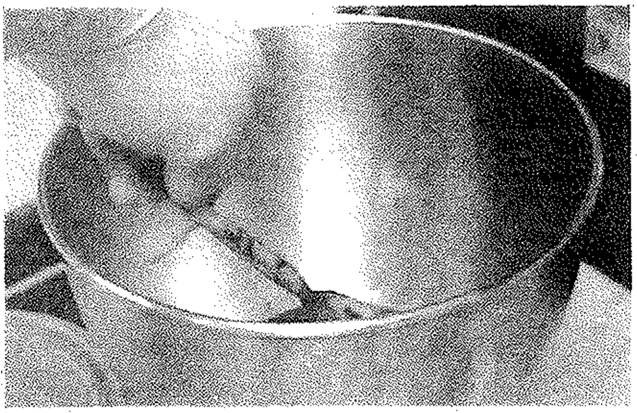

Figure 20: Adding lampblack to the mixing bowl. The spoon is kept close to the surface of the PBAN to avoid dusting.

It's good practice to add the lampblack close to the surface of the PBAN. That is, don't drop the fine powder from a great distance. That causes "dusting" and can be dangerous. Dust from lampblack and dust from fine AP together are more sensitive to friction than the same mixture in liquid PBAN.

6. The mixture is slowly stirred until the lampblack is completely wetted by the PBAN. Then the lampblack is mixed into the PBAN until the mixture appears to be uniform. The time required to do this is recorded. Now the mixture is mixed again for that same length of time. That is, if it took seven minutes of mixing for the mixture to appear uniform, another seven minutes of mixing is indicated. It's easy to under-mix, virtually impossible to over-mix. The approximate mixing time is recorded.

When mixing a powder into a liquid, it's normally good practice to stir the mixture very slowly til the powder is completely wetted. The finer the powder, the more slowly the mixture should be stirred.

Don't mix fast, do mix thoroughly. Fast is not good here. It's unlikely that the mixture will be heated dangerously by friction when hand-mixing. However, fast mixing will whip bubbles into the mixture, which is bad. Use a smooth, fairly slow rotary action. About one stroke per second or a little slower is a typical mixing speed.

If some of the lampblack has landed on the walls of the container, scrape it down into the rest of the mix with the end of the mixing stick or a scrap of cardboard. Or wipe clean the upper inside part of the bowl with a dry paper towel.

7. Did you take off your eye protection at any time during these operations? If so, put everything away. Propellant making requires maturity that you do not have, apparently. Resume work only when you are prepared to use good judgement. Removing eye protection is bad judgement.

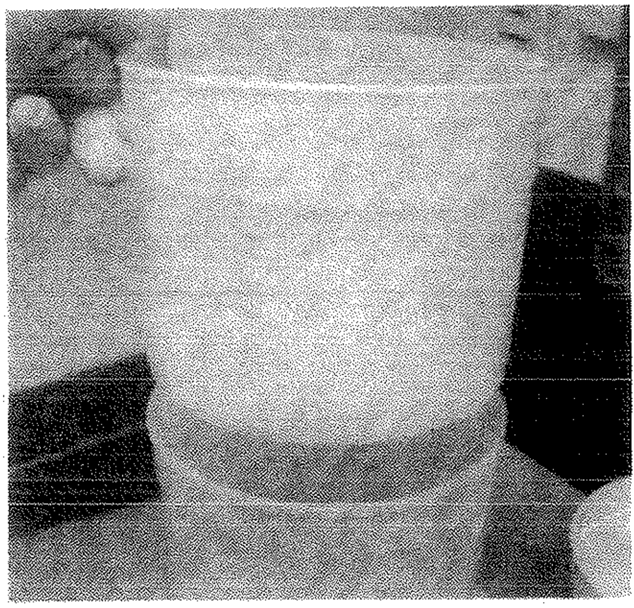

Figure 21: Sieving the AP. This sieve was made by heat-sealing a stainless-steel 40 mesh screen into a plastic container. The AP is being sieved into a separate container and will be added after sieving.

8. If you've had your eye protection and other safety equipment in place all this time, tare the bowl and its contents again. From here on, when weighing or taring the bowl, leave the mixing stick in the bowl.

9. About a third of the AP is added. If the AP is lumpy it should be sieved first (Figure 21). Some workers use a tea strainer with very fine mesh, and break up lumps gently with a short length of stout wooden dowel, or with a ceramic pestle from a mortar and pestle. The mixture is slowly stirred until the AP is fully wetted by the mixture. Then it is mixed until the mixture appears uniform, and the time recorded. Then it is mixed again for that same length of time.

   Consistency of the mixture should be about that of a thick milkshake now. The mixing bowl (with mixing stick in there) is placed in the curing box at about 140°-150°F to thin it a little (reduce the viscosity). Also, the bottle of epoxy curative is placed in the curing box to warm. The epoxy doesn't have to be warmed but it will make mixing just a touch easier, later on.

10. When the bowl is warm, it is tared again. Record the length of time the bowl was warmed. You'll want to know this later.

11. Another third of the AP is added. The mixture is again stirred and mixed as in Step 9. The bowl and contents are warmed again as needed.

    The mixture never becomes "easy" to work with. It will be thick no matter what. But warming it makes it less difficult to mix.

12. The last portion of AP is added and again mixed as in Step 9. Of course, it's not necessary to add precisely one-third, of the AP in each step. But when all the AP has been added, there must be a total of 187.04 grams of AP. Some workers prefer to weigh carefully the entire amount of AP into a paper cup and add it from there, rather than weighing the mixing bowl.

    The mixture will be pasty, sticky, and stiff. Imagine a mixture that is half sugar and half cold peanut butter, but a little more sticky. Or imagine barely-melted tar plus sand. That's what you'll have. It's going to take some elbow grease to mix. Warm it up again as needed.

    A rotary motion is likely to cause the stuff to clump to the walls of the bowl. You may want to use a combination of a rotary and a "mashing" motion, as though you were mashing very hard potatoes. Slow and easy does it. Rest every now and then.

13. When all the AP has been added, the bowl is warmed again.

14. While the mixture warms up, two 18" casting tubes are prepared by capping one end of each tube, so that it is liquid-tight (see "End plugs" under "Equipment and Supplies"). Leaks will cause problems. A wrap or two of masking tape around the joint will help it to seal. When the tubes are ready, they are placed in the rack so they don't have to be held upright to fill.

15. The mixing bowl and its contents are tared again. The (warm) epoxy is added to the mixture until 8.41 grams has been added. The propellant is mixed for at least 20 minutes, scraping down the walls of the container at least three times.

    PBAN mixtures have such a long potlife that it's permissible to add the epoxy before adding the last portion of AP. That makes the propellant easier to mix. PBAN often takes 6-12 hours to thicken noticeably after adding curative, though your experience may differ.

    [If vacuum processing is to be performed, this is the time to do it]

16. The mix may be allowed to cool somewhat so it isn't quite so sticky. It's easiest to work with when it's about the consistency of soft clay or very stiff bread dough.

17. The end of the mixing stick is used to pack the mixture solidly into the bottom and slightly up the sides of the bowl, about ⅜-½" thick. This will work out some of the bubbles.

18. A pair of rubber/plastic gloves is used over the cotton gloves. A small amount of the mixture, about the size of a large marble, is scooped up. It is rolled solidly into a ball (to remove as many voids and bubbles as possible) then rolled into a sausage-shape and dropped into the tube. The packing stick is used to pack it down. You are not trying to tenderize a steak with a mallet here. Instead, the propellant is tamped firmly (but gently) a dozen times, twisting the stick with a rotary motion

at the end of each stroke, so the mixture doesn't cling as badly to the end of the stick (Figure 22).

The objective is to get the propellant into the tube with as few bubbles or voids as is possible. If the propellant tends to stick badly to the gloves, allow it to cool even more so that it is stiffer. Or use a tongue depressor stick to scrape the mixture off the gloves.

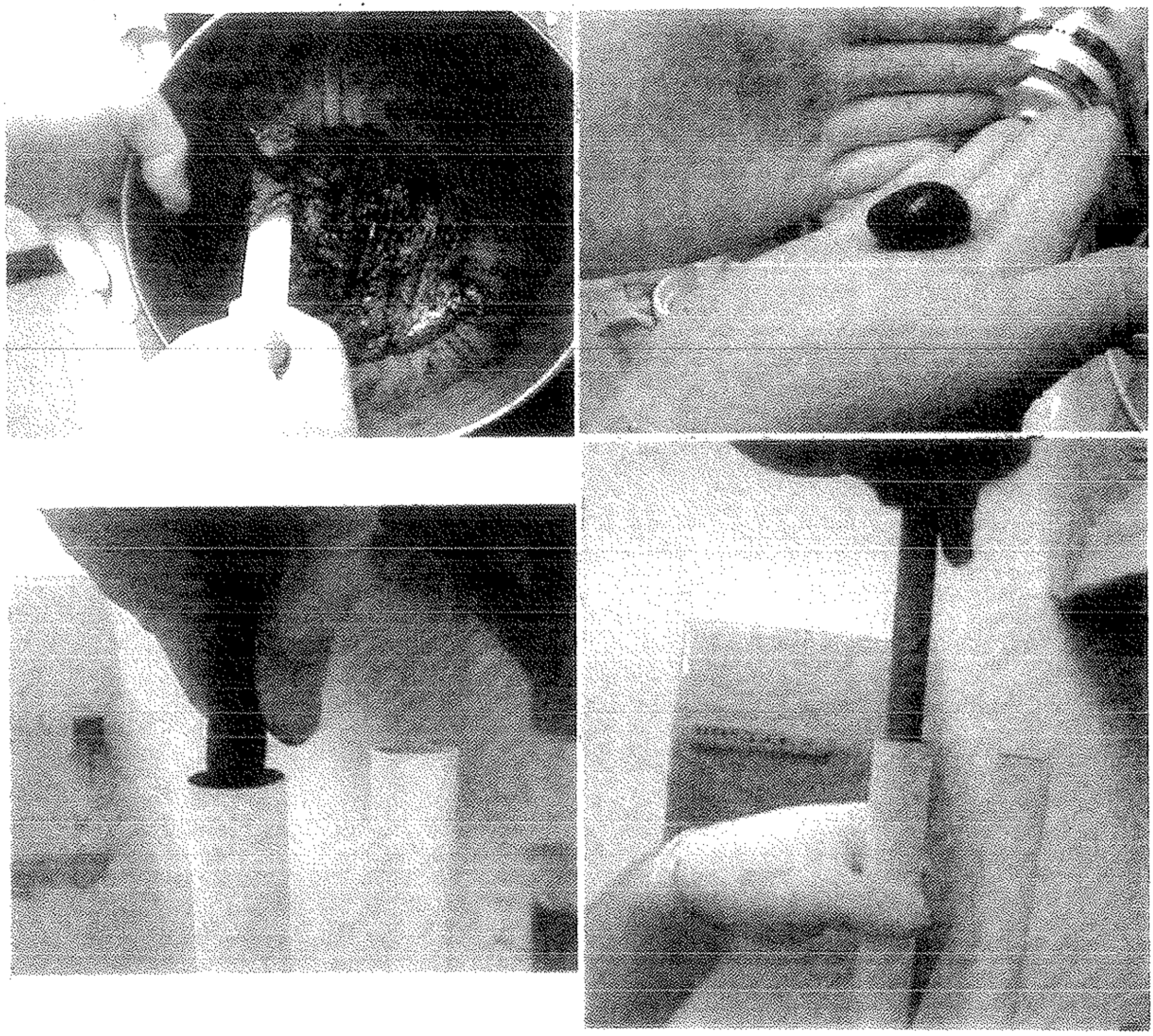

Figure 22: Scoop up a wad of mixture... ...roll it into a ball... ...roll it into an oblong and drop it into the casting tube... ...and pack firmly with up-and-down and twisting motions.

Things are going to get pretty messy. Try to do the "rolling" with the palms of the gloves and "tamp" holding the stick with the fingertips. A short piece of liner tube or a sheet of paper wrapped around the upper end of the casting tube may be used to minimize stickiness on the outside of the casting tube.

Don't try to pack too much propellant at once. For a 1" diameter tube, a marble-sized lump each time is plenty. Yes, this is time-consuming (it takes about 45 minutes to pack two 18" tubes of propellant)[15].

19. Repeat the rolling and packing until the mixture has been used up. Ideally there should be a little less than one 18" tube full. If there's more than a tiny bit left over, the propellant may have bubbles and may produce problems. Next time, try packing in smaller lumps and tamping more carefully.

20. The tube of propellant is placed upright in its rack in the curing box at about 140°F. Some workers stand the propellant tube in a large paper cup, just in case (a leaking propellant tube makes a mess). The propellant is cured for at least two days. Check it at the end of this time; the propellant should be fairly solid and slightly rubbery, though it may still be a little tacky. If it's still soft and squashy, it is returned to the box for another few days. Keep checking until the propellant is cured. It may take up to a week, possibly even longer, depending on additives and the amount of curative.

21. Be sure to clean up thoroughly afterward. Keep the gloves on, and wipe/scrape out as much of the propellant from the bowl as is possible, using paper towels, a popsicle stick, and/or a stiff card. A "citrus" (orange) type hand cleaner with pumice works very nicely to remove the remaining residue. Propellant-contaminated paper towels and other un-cleanable stuff go in the scrap can, to be disposed of properly.

22. When the propellant has cured completely, it is removed from the curing box and allowed to cool completely.

23. A sharp razor knife is used to trim off one end of the propellant stick square and clean. The propellant is marked every 2" with the point of the knife. A strip of paper or a square-cut motor casing may be used as a guide to cut on the marks. It may be easiest to cut the whole way around the paper tube first, then cut through

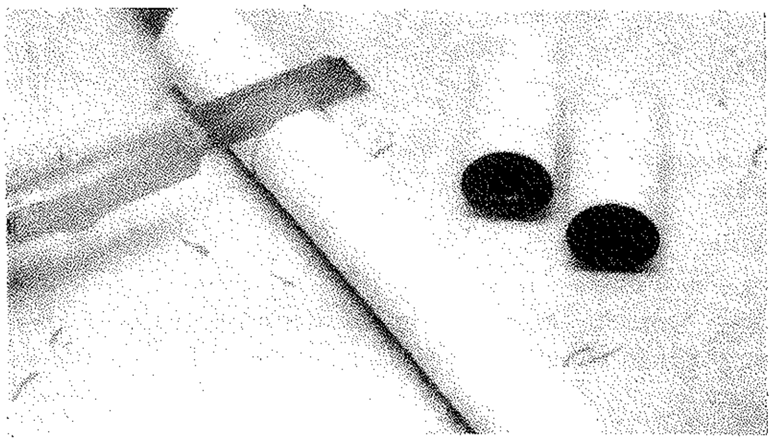

Figure 23: Cutting a stick of propellant into individual BATES grains.

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[15] Most beginners seem to want to work with small motors, which is why these instructions specify 29mm as a "starter" size. But if your budget allows, 38mm is rather easier to work with. A larger ball of propellant (size of a small walnut) can be packed each time, and it's generally easier to see what you're doing. Also, 38mm motors burn longer and so the burn time and ballistic properties can be determined more accurately.

by pressing the blade into the groove while rolling the tube (Figure 23). You do have your goggles and cotton gloves on, right? And the bucket of water is nearby, right?

24. Each grain is weighed. For good technique, with 0.95" id tubing (BT-50), the weight of each grain should be at least 18 grams per inch of length. That is, a 2" long (undrilled) grain should weigh at least 36 grams. If one grain weighs much less (more than a gram or so lower) than the others, you may have imbedded a nice (NOT!) air bubble in there. That one is set aside for discard or other use. If *all* your grains weigh significantly less, you may have some "gassy" propellant; be prepared for possible failure.[16]

25. A sharp ⅜" drill bit is used to make a core lengthwise through each grain of propellant (Figure 24). A cordless drill at low speed is used. The hole is drilled as concentric as possible; drilling part way from one end, then drilling from the other end to meet the first hole often works well. This work is done over several sheets of newspaper to collect the dust and shavings. DO NOT let that dust and shavings accumulate; clean them up after drilling each grain, discard them in the scrap can, and burn (from a distance) the scrap can every day or more often.

    Some workers recommend drilling a smaller hole (¼" or 3/16") as a "starter" hole, then enlarging this to the proper size later. A smaller hole is easier to keep concentric. However, very small drills should be avoided as there can be a considerable amount of friction when drilling such holes.

    A brad-point (woodworking) drill bit tends to give a cleaner hole in propellant. However, the ordinary type of "jobber" drill is better for enlarging a small hole, as it tends to "wander" less.

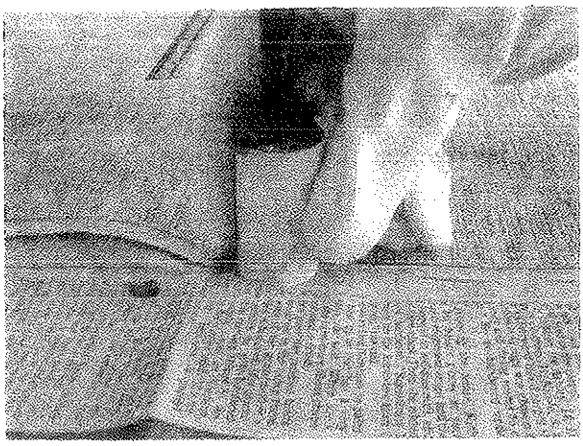
Figure 24: Drilling the core in a BATES grain. Extreme caution must be observed here. If the propellant "gums up" the drill bit, it may be too tacky to drill.

The finished grains may be stored in a heavy plastic bag, labeled with permanent marker as to the type of propellant, the date, and other important details. Some workers photocopy the data sheet for that propellant, and store the photocopy in the bag. Others

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[16] *One author suggests making trial batches of "propellant" using fine table salt such as "popcorn" salt or similar stuff instead of AP. It's a good suggestion that allows you to perfect* your technique inexpensively. If Tepanol or other bonding agent is being used, a good alternative to table salt is ammonium chloride or ammonium sulfate (both available as fertilizer), ball-milled or ground to an appropriate size. The Tepanol will bond to these substances in the same fashion as it does to ammonium perchlorate.

stamp or write the date on each grain.

When finished there should be seven or eight propellant grains, ready to be used for test motors. Well, *almost* ready...

TROUBLESHOOTING THE STARTER PROPELLANT; PHYSICAL PROPERTIES

One nice thing about a simple propellant is that there aren't many ways to screw up. But we need to take a look at it anyway. I'm going to make you very unhappy now, because we're going to ruin some of your nice new propellant. Pick two of the propellant grains at random, and slice them longways into pieces (over a sheet of newspaper; goggles; gloves; water bucket). Look for bubbles. Examine for uniformity. Bend, twist, and squeeze the propellant. Good propellant will bend a fair bit before it cracks or breaks, it will spring back (though not necessarily very fast) when it's squeezed, and it will not have too many bubbles. Try to peel off the paper casting tube. Also look at the other grains. Examine the cut ends. Sight down the core against a bright sky, and look for pockets or large bubbles. Here are some potential problems:

Propellant cracks readily when squeezed or bent

PBAN propellant may be less flexible than HTPB propellant, but in small motors that may not be extremely critical (strength may be more important than flexibility). If it is squeezed hard, it may crack even when it's quite useable as propellant. But it is also possible that (a) it wasn't mixed thoroughly enough, or (b) too much curative was used.

The solution to (a) is obvious. On the other hand, if you think there may have been too much curative, a *cure schedule* determination is in order. That is, you must determine the amount of cure agent needed for good propellant. There are two ways to determine a cure schedule. One is by calculation and is discussed later under "Cure Calculations". The other is the empirical method which will be described here.

1. Another batch of propellant is made just as before, but this time the epoxy is not added (stop after Step 12). This is sometimes called a *prebatch*. The total weight of this prebatch should be 225.97 grams.

2. 48.2 grams (not 48.3, not 48.1) of prebatch is weighed into each of four small plastic cups. Four short (4") lengths of casting tube are plugged.

3. To each cup, a different amount of epoxy is added. This will take some careful weighing and a little figuring. The original batch was 3.6% epoxy, or 3.6 grams epoxy per 96.4 grams other stuff. 48.2 grams is exactly half of 96.4. So each part of the prebatch would take 1.8 grams of epoxy (half of 3.6) if the original formulation was used.

   However, the original cure was too hard, so the amount of epoxy should be *decreased* slightly. Some reasonable amounts of epoxy to try for each might be 1.6, 1.4, 1.2, and 1.0 grams for each (if you put different amounts of prebatch into the cups, you'll have some more difficult calculations to do, and you're on your own...).

4. Each cup is mixed thoroughly with a (separate) wooden craft stick. Each test

portion is rolled and packed into a separate casting tube. Each tube is carefully labeled and they are placed in the curing box at 140-150°F for about a week.

5. The tubes are removed and allowed to cool. A 2" grain is cut from each, and a core drilled in each. Any grains that are too soft to drill properly are discarded (do I need to say that these go into the scrap can?). The remaining grains are checked for flexibility, strength, and lack of separation (see below). Good propellant should not separate from the casting tube. It will deform when pressed but will return to its shape, and it will also bend a good bit before breaking.

   As noted in the section on "Coring Rods", a softer (reduced amount of curative) propellant may be useful if coring rods are to be used.

6. The amounts of prebatch and epoxy needed are recorded for the propellant with the best properties. The amount of each ingredient in that portion is calculated; it will be exactly half of the percentage for AP, lampblack, and PBAN, and of course you know how much epoxy was weighed into that prebatch. Those amounts can be entered directly into the "Batch" section of ProPel (directions for ProPel are found in the appendix).

Propellant was prebatched as described above, but none of the samples had desirable properties

It is possible that all the sample of propellant as made above might be "leathery" rather than rubbery. The propellant may work anyway. However a small amount of plasticizer can change the product from leathery to rubbery. A good proportion of plasticizer to begin with is about 1.5-2%. Plasticizer must be mixed *thoroughly* with the propellant, along with the PBAN. If mixing is insufficient the finished propellant may be weak, and it may not adhere well to the casting tube.

Propellant was soft and gummy

It's most likely that there wasn't enough epoxy. So do the same cure schedule determination as above, but this time *increase* the epoxy by small steps. Incidentally, if the propellant is too soft to drill, it may still be useable for D-slot grains. And almost any propellant, whether too soft, too hard, or too "bubbly" can be used as "booster" propellant for igniters.

It is also possible that the propellant was not allowed to cure long enough. A good start here would be to double the cure time; if that does not make a significant change, the cure time was probably not the problem.

Another possibility is too much plasticizer, if plasticizer was in fact used. Reduce the proportion of plasticizer.

Finally, the cure temperature may have been too low or too high. A too-low temperature can make the product rather soft. And a too-high temperature can make it "rise" like bread dough, also giving a soft, gummy texture. This is more common with HTPB propellant than with PBAN propellant.

Too many bubbles (density too low)

Without vacuum degassing, there will be bubbles in the propellant. In fact it's very likely that there will be a few bubbles even *with* vacuum. The question is, just how many bubbles ARE "too many"? To answer that question, start by weighing the propellant grains (before drilling) and calculating the density of each. The ProPel "Density" spreadsheet will make this easy.

The *theoretical* density of this propellant (density if there were absolutely no bubbles) should be 0.0587 lb per cubic inch (lb/in^3). With good, careful work, it's possible to get a density that averages 90% or better of this value; that is, 0.053 lb/in^3 or higher. Density that is much lower than 90% of theoretical density may cause the propellant to be unuseable. Under pressure, the bubbles are compressed to a fraction of their size, causing tears and fractures that cause rapid burning and CATOs.

If density is very low, try more careful packing and smaller lumps of propellant (roll *solidly*; don't try to pack loose propellant into the tube). If density is *still* low, an alternative fix is to increase the solids content to about 82% or even higher, by adding more AP. Higher solids content increases the density for two reasons: more (dense) AP will increase the theoretical density. And, most workers find that it's actually easier to get rid of bubbles from a higher-solids propellant, as long as there's enough binder to maintain decent strength. If additional AP is added, the *amount* added must be recorded carefully, so that the propellant can be reproduced later.

To reproduce the modified propellant, simply enter the total amount of each ingredient *actually used* in the "Original Batch" column of the spreadsheet. For example, if you make the batch described in Table IV, then have to add 20.5 grams of AP to this batch in order to get the right consistency, the total amounts that have been used are: 207.54 g AP, 0.47 g lampblack, 38.46 g PBAN, and 8.41 g epoxy[17]. Enter these into the "Original Batch" column and you should find that the new solids content is 81.61%

However, high-solids propellant may exhibit another problem, namely...

Propellant separates from casting tube easily

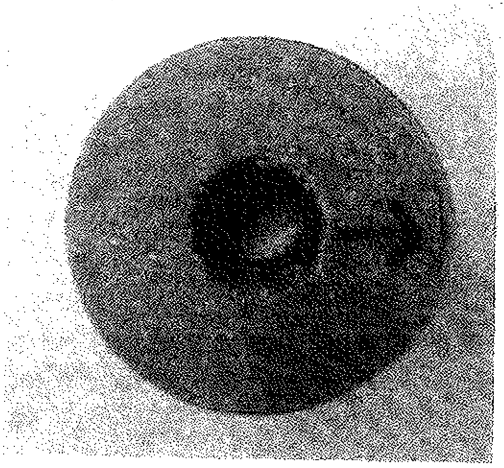

Figure 25: Separation of propellant from casting tube.

Sometimes when looking at the cut end of a grain, you may see that the propellant has

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[17] This new propellant composition will have a slightly higher theoretical density, which may be calculated using Propep. The experimenter should shoot for 90% of the theoretical density, whatever it may be.

separated a bit from the paper tube, as can be seen in Figure 25. Or you may find that the casting tube peels off of the propellant very easily. This is a potential problem with very high-solids propellant, in that there's not enough binder to soak the tube and bond to it properly. So one approach is to reduce somewhat the solids content of the propellant.

An alternative is to coat the inside of the tube with PBAN-epoxy mixture (16.4 to 3.6 parts, same as used for the binder) or with your favorite epoxy adhesive, and allow it to cure (or better yet, just allow it to set) before packing the propellant. There should be just enough mixture to wet thoroughly the entire inside surface of the tube. An applicator can be made from a disk of foam rubber the same diameter as the tube. This disk is screwed to a dowel and soaked in the coating mixture, then run into the tube. It's a messy job.

Separation can occur when the cure temperature is too high, or if the propellant is cooled too quickly. Check that temperature every once in a while. To avoid possible separation and distortion, the cured propellant may be allowed to cool, then should be cut into grains almost immediately, and cores drilled or coring rod removed.

If separation does occur, it's not necessarily a disaster. That part of the propellant surface can be *inhibited* by filling the crack with a little epoxy.

Propellant mixture cracked and fell apart as it was being rolled into balls

Try molding the propellant into a ball with the fingertips, and rolling again. If the propellant continues to crack, there are several possible reasons. The propellant may not have been mixed thoroughly enough (mix it more thoroughly). The mixture may be too cold (warm it). Or the solids content may be too high (reduce it).

Propellant "rises" out of the end of the casting tube

This may happen if the cure temperature is too high. The curing box should be set to the curing temperature well before the propellant is placed in the box. Once the propellant is in the box, the temperature should not be adjusted unless absolutely necessary.

Propellant that rises too much will be "foamy" and low in density. This may happen more frequently with propellant that uses low-viscosity epoxy. The reactive diluents are a bit more volatile than epoxy resin itself. The propellant may also appear to be softer than usual, due to its open structure. This problem can also appear with HTPB propellant, especially when faster curatives are used at too-high curing temperature, or when too much cure catalyst is used (these terms are discussed later).

Propellant becomes hard and brittle as it ages

This too is more common with HTPB formulations and likely won't be noticed immediately. The propellant appears to be properly cured after a day or a few days. But over several weeks or longer, the propellant hardens until it is brittle. It may also shrink away from the casting tube.

Ordinarily this means that way too much curative (possibly a slow-acting curative) was used. A solution is to do a cure schedule, starting with about half of the amount of curative that was originally used. Another cause is the use of a volatile solvent to make mixing easier, or the use of a volatile plasticizer. In both cases, the solution to the problem is – don't use that solvent/plasticizer!

CONSTRUCTING STATIC-TEST MOTORS

I know you're anxious to fly a finished motor, but you've got to do some static testing first. You don't want your nicely constructed model to turn into confetti, do you?

For static tests, single-use motors are indicated. A few initial efforts will probably CATO, and each time a motor catoes, a new casing is needed. Of course, if you are rich you may choose to use commercial casings for all your work, that's up to you...

NOZZLES

Phenolic nozzles (Figure 26, left) are available from RCS for about a dollar each. Nozzles with about 0.1" throat are suitable for static tests and can be drilled to the size desired.

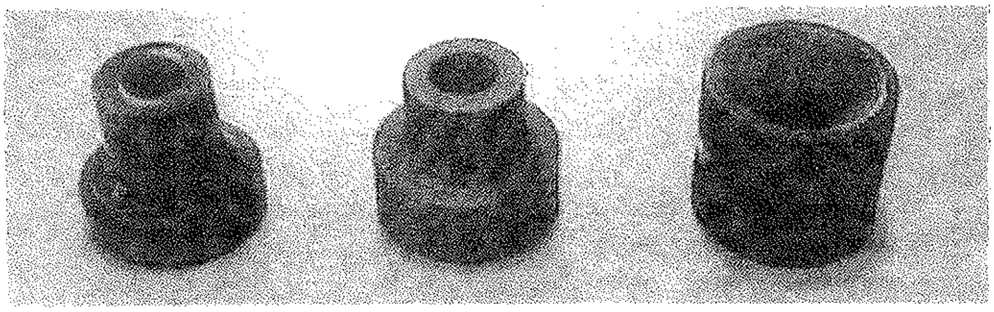

Figure 26: Left: glass-reinforced phenolic nozzle. Center: graphite nozzle for single-use motor. Right: graphite nozzle from commercial reloadable motor is less satisfactory for single-use motors (see text).

Custom-machined graphite nozzles (center) of the proper shape are excellent; they can be removed from the casing and re-used many times. Details on machining graphite nozzles are provided in the appendix.

Graphite nozzles from commercial reloadable motors (right) may not be as satisfactory for single-use motors. A "shoulder" or recess is desireable to hold the potting epoxy.

CASINGS

Grade XX paper phenolic tubing 1" id, 1⅛" od, is generally suitable for casings and is available from McMaster-Carr under the trade name "Garolite". This tubing will stand pressures around 400 psi. Cost is about $7 for a three-foot length. McMaster-Carr also sells stronger CE and LE grade phenolic, as well as superstrong G-10 fiberglass. Fiberglass casing requires an insulating liner between the casing and the propellant grains. The liner isn't a bad idea for phenolic casings either. RCS also sells phenolic and fiberglass casings.

Contrary to intuition, aluminum casings are surprisingly cost-effective for single-use motors. Aluminum alloy 6061-T6 tubing, seamless drawn, 1⅛" od, 1.009" id is less than $3 per foot (April 2000 price) when bought in 100 foot quantities. Considering that aluminum tubing of this size will handle up to 1000 psi or even more, that isn't bad (about $1.50 for a G-motor casing). The aluminum-cased motor CATOs that I have seen have resulted in the casing bulging, "ripping" or in loss of a closure; I have not see an aluminum case fragment, though certainly it could happen.

Important: the aluminum tubing commonly sold in hardware stores, etc. is often (always?) inferior to proper 6061-T6 alloy. Obtain the proper material, please. A discussion of casing materials is found in the appendix.

The procedure below assumes that phenolic casings and single-use phenolic nozzles will be used. If instead aluminum casings are planned for all flight motors, it would be well to use aluminum casings for the test motors as well. The pressure limits will be similar. Details on aluminum casings follow the procedure below.

SINGLE-USE TEST MOTOR CONSTRUCTION

1. The casing is cut to length with a fine hacksaw. Two- or three-grain motors should be suitable for initial static tests. Two 2" grains, plus 1" for the nozzle, plus ½" for the forward epoxy, gives 5 ½" for casing length.[18] Don't clamp the casing too tightly in the vise when sawing or it may crack. Sand the ends of the casing smooth when finished.

2. Very coarse sandpaper (36-60 grit) is used to rough up the inside of each end of the casing for about 1" in length. The casing is rotated so that the sanding grooves are round and round, not up-and-down (Figure 27, left). An additional measure that will retain epoxy better is a Dremel tool or sanding burr that will cut deep grooves in the casing (center). Alternatively, four or six holes may be drilled crossways through the casing (right). If this is done, masking tape must

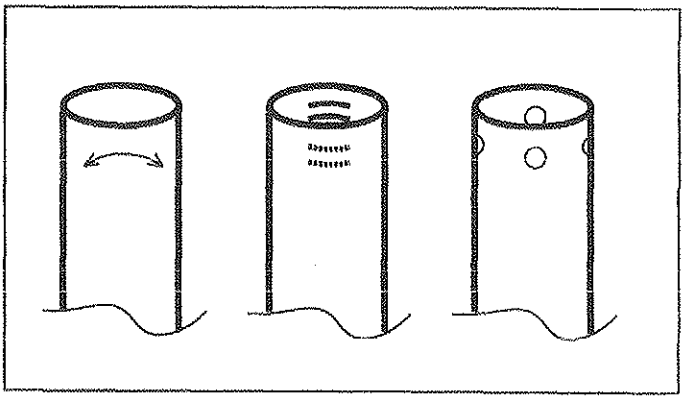

Figure 27: Left: sand the inside of the phenolic casing from side to side. Center: three or four sets of grooves cut with a Dremel tool or similar are better for anchoring the epoxy. The grooves should be about as wide as the spaces between them. Right: four or six 1/4" holes drilled crossways can be used instead. Wrap a strip of tape around the motor after drilling to retain the epoxy.

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[18] It would seem that we're already deviating from procedure; BATES grains are supposed to be about 1.5 times as long as their diameter, not two times. But phenolic nozzles *erode* somewhat during the burn; the nozzle throat diameter increases slightly. This is enough to decrease K_n during the burn and make an otherwise-neutral motor somewhat regressive. So to combat that tendency, motors using phenolic nozzles may be constructed with grains that are about twice as long as their diameter. If graphite nozzles are being used instead, three-grain test motors with 1.5" long grains would be more appropriate.

be wrapped around the casing on each end before pouring epoxy to seal the nozzle and forward closure.
Important: epoxy does not adhere to some types of phenolic very well. If you don't do a good job of sanding or cutting grooves, the nozzle or the forward epoxy may pop out. Be forewarned.

3. The nozzle is pushed into one end of the casing. If it is a loose fit, the shoulder is wrapped with masking tape until it fits snugly but not tightly. The nozzle is removed and a little strong (30 minute or 2 hour) epoxy is rubbed around the shoulder of the nozzle and around the inside end of the casing. The nozzle is now pushed into that end of the casing until about ⅛" or less protrudes. Let the epoxy stand long enough to "set".

4. Now the casing is stood on end, nozzle-up, and additional epoxy is poured into the recess between nozzle and casing (Figure 28). Don't overfill. Allow the epoxy to set. I usually mix a little graphite or lampblack into the epoxy. Making the epoxy opaque is thought to minimize the depth of epoxy destruction during the burn, since destructive UV doesn't penetrate the lampblack. And, of course, it looks good.

   Pour very slowly in the same spot, and let the epoxy run into place around the nozzle. Don't pour "around" the nozzle, as that will often leave a large bubble which can cause a burn-through.

   If thick, slow-curing epoxy is being used, heating both the casing and the mixed epoxy in the curing box will make the job easier. Bubbles will work their way out more easily. Likewise, if a vacuum setup is available, a short vacuum treatment of the assembly before the epoxy sets will remove bubbles very quickly. Be careful not to let the epoxy bubble over the edge!

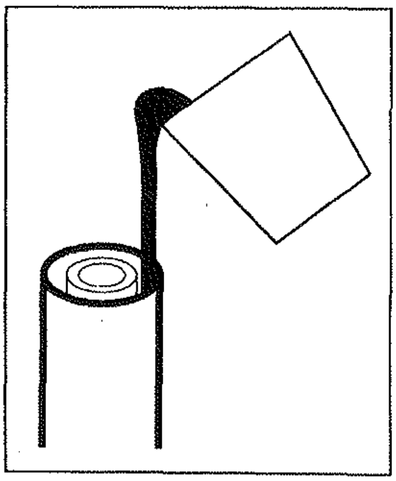

Figure 28: Potting the nozzle with epoxy. Pour in one place, not "round the nozzle" to avoid bubbles.

5. The nozzle throat is drilled to an appropriate diameter. Deciding on an appropriate nozzle throat is something of a matter of guesswork for a new propellant. But as a rule of thumb, a reasonable trial for a propellant using 200 micron AP oxidizer and no burn rate catalyst might be $K_n = 200$ or a little less. At $K_n = 200$, a 2 grain motor, 2" long grains, 0.93" propellant diameter, ⅜" core, has a nozzle throat of about 0.211". A #4 drill is 0.209"; a #3 is 0.213". On initial tests, "too large" is often better than "too small", so the #3 drill bit is used.

6. The casing is turned upside down and the grains slid in place (but see Step 7). They should fit snugly but not tightly. If they're loose, masking tape may be used around each grain as needed. If there's enough room, the grains can be masking-taped together; the tape at each joint acts as a little additional insulation. Be sure the grains have been pushed against the nozzle.

7. If a liner tube is to be used, the liner should be cut to about ¼" longer than the propellant grains. The grains are slid into the liner tube with about ⅛" of tubing projecting from each end. One end of the tube is "crimped" by rolling the assembly against the workbench, as shown in Figure 29. That end is inserted into the casing and the assembly is slid into place, seating it firmly against the nozzle.

   Note: if the liner fit is loose, masking tape or paper tape is wrapped around the liner until it is a snug fit.

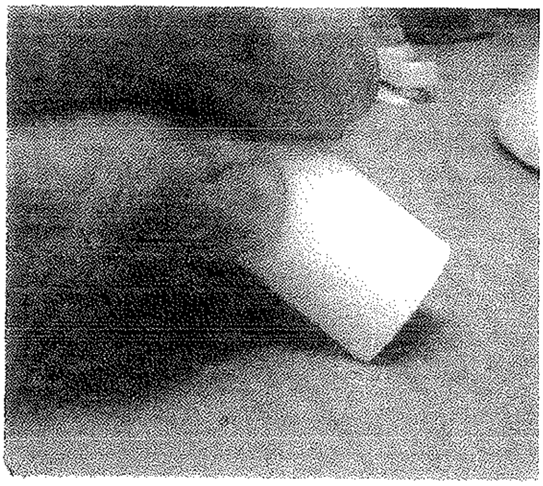

Figure 29: Crimp the end of the liner that will go into the casing against the nozzle.

8. A thick cardboard or thin wood insulating disk is slid into the casing. It should be a *tight* fit. A 1" dowel may be used to press it against the propellant grains. A little epoxy may be used to seal the edge of this cardboard insulating disk to the casing.

9. Before the epoxy sets completely, a 1" od o-ring is slid into the casing and pressed tightly against the insulating disk with a 1" dowel rod. The epoxy is allowed to set. Some workers omit the o-ring but without it the motor may burn through the forward epoxy.

   One way to make a bunch of plywood disks is to cut (holesaw) rough disks of ⅛" plywood, center drill them, and mount on a ¼" bolt. The bolt can be chucked into a drill press and a coarse rasp and sandpaper applied to bring the disks to the desired size. A scrap of plywood or cardboard can be glued to seal the hole. Alternatively, discs may be cut ¼" thick or thicker from dowel rod of the appropriate size.

10. When the o-ring epoxy has set, the forward end of the motor is filled with more epoxy. Again, it is very important here that bubbles be eliminated. A bubble at the edge, near the propellant, can cause a blow-by. Allow the motor to stand until the epoxy has fully cured.

The finished motor (Figure 30) is ready to be static-tested.

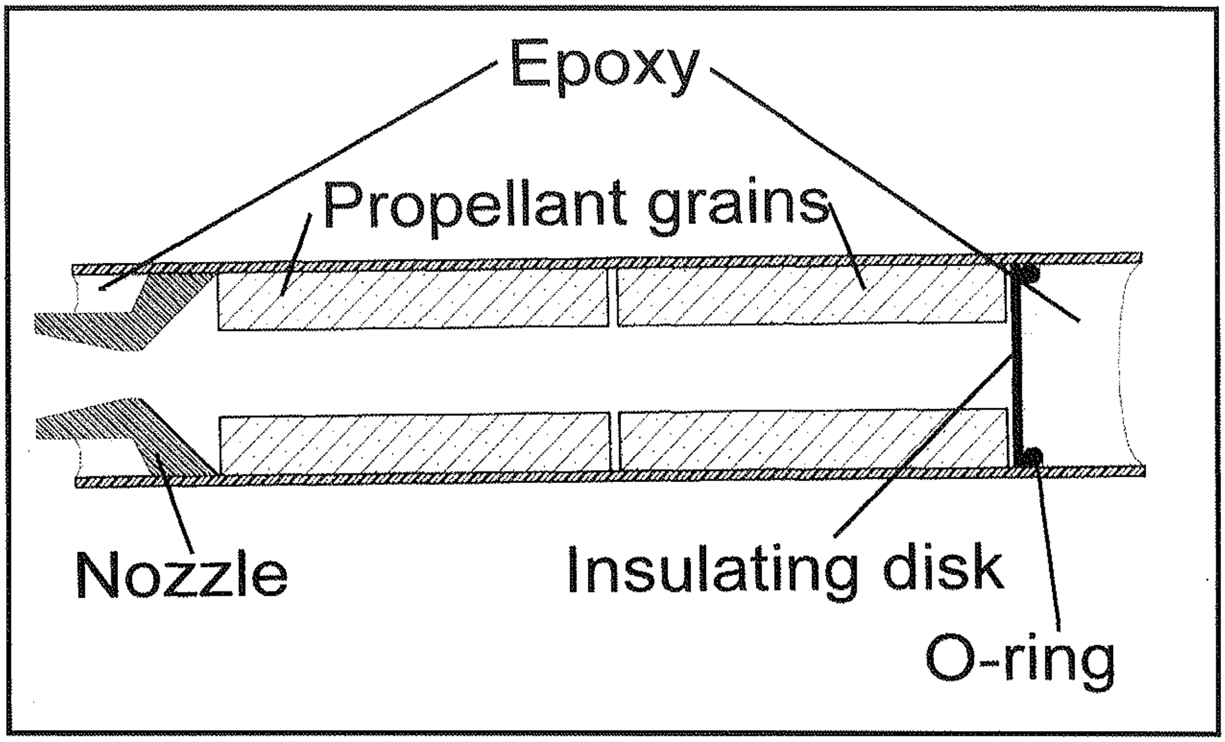

Figure 30: Cross section of the static-test motor

OTHER MATERIALS AND CONSIDERATIONS

If aluminum casings are used, a lathe is used to cut deep grooves into the inside of each end. Sanding may not work. Aluminum is ductile, and it will "give" somewhat under pressure. So unless the grooves are much deeper than grooves from sanding, the epoxy may debond from the case. This will cause the nozzle or the forward closure to blow out. Two or three grooves about 1/16" wide each are cut near each end of the case, about half the depth of the tubing wall. That is, if the tubing has 0.058" wall, the grooves are cut about 0.029" deep. A cutting bit is shown in the section of the appendix on "Reloadable Motors".

If using graphite nozzles, they should be machined as directed in the section on "Making Nozzles". If a liner tube is to be used, the nozzle should have a recess about ⅛" deep, such that the liner tube will slide over the shoulder for that length. That will better protect the casing from the hot gases. Of course, the liner is cut long enough to fit this recess.

For a burn time of more than a few seconds, graphite nozzles may require insulation, to keep from burning/melting through the casing. Again, see the section on "Making Nozzles" for details.

Some workers use silicone caulking instead of an O-ring to seal the forward end. When the silicone has cured, it is topped with epoxy in the usual fashion. The author has not attempted this, as the method described above has been found to be adequate. However, this would give an alternative if your motors suffer "blow-by".

Do not make too many motors for your initial tests; two or three at most. If your motor-construction skills aren't up to snuff, motors may cato because of the improper construction. If ten successive motors have been made this way...you've wasted materials for ten motors. So make just a few motors, test them, then make more.

Explosion of test motors may be minimized by using a burst diaphragm in the forward closure of the motor. This is a device with a thin disc of metal designed to burst at a given pressure. The author has not experimented with burst diaphragms but they would appear to be highly useful for the experimenter (especially in reloadable motors), and are worth investigating.

STATIC TESTS

Start by gathering your motors, igniters, a proper launch system, and a helper to your test location. These motors will be *LOUD*, so be certain that the location is well-removed from civilization. The helper should understand what you are doing; his/her primary purpose is to go and/or call for help if it becomes necessary. A cell phone is a very good idea (remember, this is dangerous work; don't be complacent).

Pound the "test stand" into the ground. For initial work this may be a 3' long piece of concrete re-bar ½" dia. Leave a foot standing above the ground. Clear the area immediately around the test stand of grass, etc. It's a good precaution to soak the area around the stand with water.

The motor is attached, nozzle-up, to the re-bar with two hose clamps. The hose clamps must not be tightened so much that they stress the case (especially phenolic). The motor will probably generate about 20-30 lb of thrust, so keep that in mind as you tighten the clamps.

Sandbags or heavy timbers are piled around the motor to AT LEAST a foot high. Alternatively, a foot-deep hole may be dug, the re-bar pounded in the bottom of the hole, and the motor fastened in place so that it's well below ground level. You do not want to be able to see the motor (other than the end of the nozzle) when it ignites.

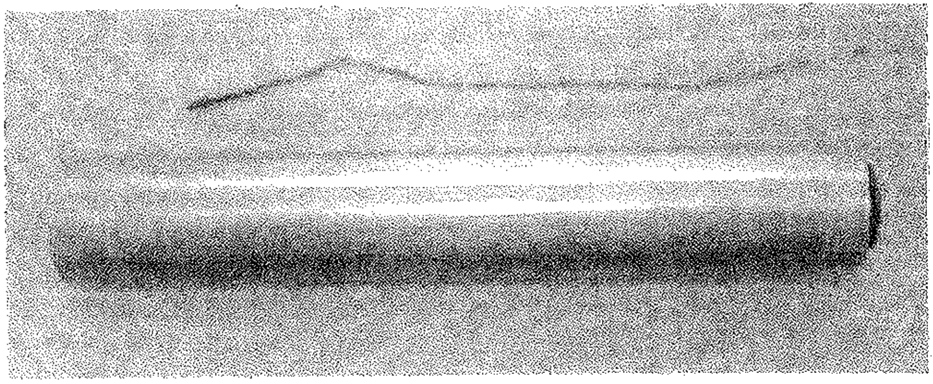

Figure 31: The igniter will be inserted completely into the motor, with the head of the igniter near the front (forward closure). The igniter is bent so that the head will press against the propellant core.

An igniter is connected to the launch clips (ever since a minor but scary accident involving a shorted relay, I always connect the igniter first, then insert it). The igniter is bent about 2" from the head, just enough to put a kink in it so that the head will press against the propellant core. The igniter is inserted into the nozzle and up the core as far as it will go[19]. Place a wrap of masking tape around the nozzle end of the case, taping the wire of the igniter to the aft end of the case. That will keep it in place better, and reduce "spit igniter" syndrome.

Back off. Count down and press the button. Yes, it's ok to hold your breath.

One of seven things will probably happen.

(A) After a moment the motor starts with a satisfying ROAR and continues for a second or so. You done good.

(B) A tiny puff of smoke exits the nozzle, no sound. Possibly the igniter burned without igniting the propellant. Try a new igniter. Make sure it's against the propellant this time. If the propellant is really hard to ignite, a strip of booster propellant taped to the igniter head will usually do the trick.. The author has not found the starter propellant to be at all difficult to ignite.

Note: if this happens several times with the same motor, epoxy may have "leaked" down from forward or nozzle closure during cure, coating the surface of the propellant. That surface is now inhibited and the motor does not have enough surface area to ignite properly. Been there, done that. If this is suspected, the motor is unuseable and should be disposed of properly. For future work be more careful in the "sealing" steps 3 and 9.

(C) A puff of smoke and a momentary loud PFFT!, then nothing. The motor chuffed; chamber pressure was too low, possibly because the nozzle throat was too large. On the next trial reduce the nozzle throat diameter; try a nozzle throat that will make K_n about 20% larger. Or possibly the igniter was not inserted fully to the forward end.

(D) A puff of smoke, a PFFFFT!, then silence, then another PFFFFT!, then the motor comes fully to life and burns properly. That's also a chuff; chamber pressure is just a little bit low. For the next motor reduce the nozzle throat a little less than in (C); use K_n about 10% larger.

(E) Motor starts with a PFFFFT! then suddenly goes WHAPPP! and comes apart, throwing propellant grains and other parts into the air. You've had a CATO; chamber pressure was too high. If the propellant was burning let it burn itself out, extinguish any surrounding fire with water. Decrease K_n by 20% or so for the next try.

Note: if the motor spits out the nozzle or the forward epoxy without shattering the case, the casing may not have been sanded or grooved sufficiently to hold the

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[19] The igniter head must be all the way up the core, touching the propellant. In this way, combustion starts at the forward end of the motor and naturally progresses down the core, igniting the entire propellant surface quickly and bringing the motor up to pressure quickly. If the igniter is inserted halfway, the forward part of the exposed propellant may not ignite quickly, and this can cause a "chuff".

epoxy. Take more care in this operation next time.

(F) Motor immediately goes WHAPPP! and into pieces. Chamber pressure much too high. K_n should be decreased by 30% or more.

(G) Motor ignites, then flame comes out somewhere it isn't supposed to. You've had a *blow-by*. These can be caused by a poor fit between insulating disk and the case, or by a large bubble in the sealing epoxy. If you didn't use an o-ring, use one for the next motor. If you did use an o-ring, K_n may be too high; decrease K_n about 20%.

MORE TESTS

You'll need to know what range of K_n to use. One way to do this is obvious. Example: your first motor at K_n=200 chuffed. You tried a second motor with K_n=250 and it worked. Try K_n = 300. If that works, go to 350. If the motor at 200 works, and the one at 250 blows, try 150. It's kind of hard on the nerves to destruction-test, but it's certainly simple and direct.

As noted before, aluminum casings are stronger than phenolic casings. So a propellant might be used over a wider range of K_n with aluminum casings than the same propellant in phenolic casings. For example, I found that the simple propellant worked well from K_n = 160 to 205 in phenolic casings; the range was extended to K_n = 310 in aluminum casings. If mostly reloadable motors are to be flown, the test motors may also use aluminum casings, so that performance can be better gauged and made more consistent.

Actually, it *is* possible to use reloadable motors for static testing. A two-grain 38mm motor is a good size for such tests. In this size, the nozzle throat generally is large enough to avoid clogging problems, and the burn time is a fair bit longer than a 29mm motor, which gives a more accurate measure of burn time.

If this approach is to be taken, one might begin with a nozzle throat that would give a very low K_n, perhaps 120 or thereabouts. A chuff ordinarily won't hurt the motor casing; a cato will destroy it. If the motor chuffs at K_n=120, move to K_n=150, then 180, and so on. Keep in mind that a cato will destroy the casing, probably the nozzle, possibly the forward closure. Be cautious.

BALLISTIC PARAMETERS FROM STATIC TESTS

It is entirely practical to design small working motors simply by using a working range of K_n. But for a better handle on propellant performance and motor design, the *ballistic parameters* should be determined for your propellant. The main parameters needed for motor design are the burn rate coefficient *a* and the burn rate exponent *n*. Once these are known, working motors may be designed *and* performance (thrust, burn time, etc.) predicted.

It would be nice if the ballistic parameters could be calculated using solids loading, AP particle size, amount of burn rate catalyst, etc. Unfortunately, they CANNOT. In fact, scientists have been working on just that sort of problem for some time now, and still have not come up with a reliable, accurate way to predict ballistic parameters from propellant composition. For now, ballistic parameters can ONLY be found by actually burning some propellant.[20]

For proper determination of *a* and *n*, test motors with perfectly neutral burns (endburners) are needed, and the chamber pressure is measured during the burn. Lanier gives details on this subject in his book and on his web site; the work is not at all beyond the capabilities of a good experimenter.

But for rough-and-ready determination of ballistic parameters, several test burns of Bates grain motors can be videotaped and the burn time measured. For a given propellant, burn time is related to chamber pressure. Burn time can be measured reasonably accurately with a camcorder, and a rough value of chamber pressure can then be calculated. Using two or more successful burns, *a* and *n* can be calculated and used to design motors. The "Ballistic" spreadsheet in ProPel gives a simple way to do this.

Keep in mind that ProPel will give *rough* values of *a* and *n* from burn times. For more accurate values, chamber pressure must be accurately measured and motors that are truly neutral must be used, as per Lanier's book.

When videotaping a motor, keep the camcorder a good ways back and use the zoom (how far back? Well, it's your camcorder...). Before starting the countdown, give the date, motor type, and a quick verbal description so that all the information is on tape. Run the camcorder at SP or the fastest speed.

Most camcorders run at 30 frames per second. To be certain, videotape a stopwatch for exactly ten seconds. Play back that tape frame by frame and count the frames. Divide the number of frames by 10; that's the number of frames per second.

After videotaping the motors, go back and count the frames from full motor-on to burnout. "Motor on" is when the motor comes to full thrust, not when ignition begins.

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[20] Although values of *a* and *n* are given for several propellants in Table V, these values should be considered to be approximate. The burn characteristics of a propellant depends on the composition, but may also depend on the nature and source of the ingredients, the worker's technique, etc.

There should be a good tail of flame out of the motor when you begin counting frames. When the tail has died to about half its full-on length, stop counting frames.

Divide the number of frames for each motor by the number of frames per second for that camcorder, and you have a rough measure of the burn time. At least two motors of significantly different K_n values will be needed.

For those in doing the calculations manually (for whatever strange reason...), the relationships needed are:

Burn rate = web thickness (inches) / burn time (seconds)
Chamber pressure = Isp*(sec) × density (lb/in^3) × burn rate (in/sec) × K_n
and Burn rate = $a \times P^n$

Hypothetical example: two motors were constructed, each with two grains, 0.93" od, 0.375" core, 1.5" long. Motor #1 had a nozzle throat of 0.21" and burned for 2.33 seconds. Motor #2 had a nozzle throat of 0.19" and burned for 1.77 seconds. Propellant Isp* is 188.6 seconds, density is 0.054 lb/in^3.

For both motors, the web, or distance the propellant burns from core to wall, is (0.93-0.375)/2, or 0.2775".

Motor #1 burn rate is 0.2775/2.33 = 0.119 in/sec
Motor #1 K_n is 167.7 (using ProPel)
Motor #1 chamber pressure is 188.6 × 0.054 × 0.119 × 167.7 = 203.5 lb/sq.in

Motor #2 burn rate is 0.2775/1.77 = 0.157 in/sec
Motor #2 K_n is 288.9
Motor #2 chamber pressure is 188.6 × 0.054 × 0.157 × 288.9 = 461.4 lb/sq.in

Now Vielle's law is applied, and things get a little hairy.

Motor #1: $\text{burn rate\#1} = a \times P_1^{\,n}$
$0.119 = a \times 203.5^n$

Motor #2: $\text{burn rate\#2} = a \times P_2^{\,n}$
$0.157 = a \times 461.4^n$

Two equations, two unknowns (remember when your algebra teacher told you that you'd need that algebra? She was right!). Divide the first equation by 203.5^n, and divide the second by 461.4^n:

$a = 0.119 / 203.5^n$
and: $a = 0.157 / 461.4^n$

Since both of these equations are equal to *a*, we can set them equal to each other:

$0.119 / 203.5^n = 0.157 / 461.4^n$
rearranging: $0.157 / 0.119 = 461.4^n / 203.5^n$
divide and rearrange: $1.319 = (461.4 / 203.5)^n = 2.267^n$

Now take the logarithm of both sides (you don't remember logarithms either?? Tsk.)

$$\log 1.319 = n \times (\log 2.267)$$

and $$n = 0.3357$$

Now that we have *n*, plug it into either expression of Vielle's law:

$$a = 0.119 / 203.5^{n} = 0.119 / 203.5^{0.3357}$$
$$a = 0.0200$$

There now, wasn't that easy??

If you found this to be a bit difficult, the ProPel spreadsheet may be easier..

FLIGHT MOTOR DESIGN

Blackpowder and "skyrocket" type rocket motors often are made by the *empirical* method. A motor is constructed and tested. If it CATOs, the formulation is changed to slow the burn rate. If it doesn't perform well, the formulation is "hotted up" to burn faster. This continues until the formulation works well with the motor design. To make a larger or longer motor, the entire process is repeated.

Motors can be made the same way with composite propellant, if desired. However, all the static testing and calculation described earlier was performed to *characterize* the *propellant*. Once a propellant has been properly characterized, a different motor can be *designed* for that propellant, with reasonable assurance that the motor will work. So the results from a G-motor static tests can be used to design motors from E to I size, perhaps even larger. In short, the *formulation* is kept the same; it is the *motor design* that is changed. The method of preparing propellant grains and using components to construct a motor makes it relatively easy to change a motor design, with reasonable success each time.

As noted earlier, it's not absolutely necessary to know the burn rate coefficient and exponent in order to design flight motors. But at a minimum, the range of K_n over which the propellant is successful must be known.

DESIGN CONSIDERATIONS: EROSIVE BURNING AND NOZZLE/CORE SIZE

A "first and foremost" requirement for composite motor design is: ***the nozzle throat area must be smaller than the core cross-sectional area.*** For a Bates motor this simply means that the nozzle throat diameter must be smaller than the core diameter. If the nozzle throat is the same size, or larger than, the core, a dangerous condition occurs in the core -- flow of gases at sonic speed. As you might imagine, when hot gases flow at the speed of sound over the propellant, they tend to be rather...disruptive...to the propellant. A motor in which this occurs is very likely to CATO dangerously.

It should be noted that the author has heard accounts of composite motors which had a core smaller in diameter than the nozzle throat. Some have even worked. But for composite propellant motors that is the exception, not the rule.

Some workers then think "I'll make the nozzle just a little smaller than the core, so that I can get as much propellant in the motor as possible". This too is a recipe for unpredictability, even disaster. For when the core and the nozzle throat are close to the same size, *erosive burning* takes place. This phenomenon itself is not easily explained but its effects are well known. It is almost as though the rapidly-flowing hot gases in the core cause the propellant to "wear away" more quickly than usual.

One effect of erosive burning is an initial increase in burn rate. This continues until the core size has increased sufficiently to limit erosion. This faster burn is accompanied by an increase in pressure. And both are accompanied by reduced specific impulse for that portion of the burn. This last may occur because gases and even burning propellant or oxidizer particles are ejected before they have time to react completely.

This begs the question: how *much* smaller than the core should be the nozzle throat?. The answer varies with the reference. The literature suggests that the nozzle throat area should be one-fourth or even one-sixth the area of the core. Experimenters are often more liberal. One rule of thumb used by some experimenters is that the nozzle throat should be the diameter of the core, or smaller.

That's not always easy to achieve in practice. But *a nozzle throat that is three-fourths the diameter of the core, or smaller*, often shows only minor effects from erosive burning. Keep in mind that in most motors, the core diameter increases during the burn. If the nozzle throat remains the same size, this means that the degree of erosion decreases as the burn progresses.

Care must be taken to avoid erosive burning in a higher-pressure motor. Since erosive burning increases the chamber pressure during the erosive phase, a motor that is "on the edge" in terms of pressure, may CATO if it is made erosive. So a motor that is designed to be erosive should be designed also to operate at a *lower* pressure than a similar, but non-erosive motor.

Erosive burning is not necessarily a bad thing. An initial "spike" of thrust is desirable for some motors, to get the rocket quickly off the pad. This can be achieved by designing a slightly erosive motor with a fairly small core. The initial erosion produces the desired thrust spike. As the core grows in diameter, the erosive burning subsides and the motor burns with a constant thrust.

The literature notes that erosive burning is more severe with slower-burning propellant than with faster-burning propellant.

Finally, some extreme designs may be subject to erosive burning to a greater degree than simpler designs. Very long, thin motors often require a tapered or stepped core, smaller at the top and larger at the bottom, to minimize the effects of erosive burning.

OTHER DESIGN CONSIDERATIONS

Some parameters that should be considered in constructing a flight motor include:

- Total impulse desired
- Propellant type to be used
- Physical size requirements
- K_n and nozzle throat desired
- Burn time desired
- Core size and type
- Delay (if used)

Selection of one parameter may "fix" another, as will be seen. Commonly, total impulse of the motor is the starting point. The following procedure may be employed to design a motor and provide a fair estimate of motor performance parameters.

SIMPLE DESIGN PROCEDURE

1. Determine the total impulse of the motor to be constructed. A rough rule of thumb

is 1 gram composite propellant = about 2 N-s total impulse (if your propellant is well characterized you may have a different value for this relationship)[21]. For this example, a motor of 200 N-s (H-motor) will be designed. So about 100 grams of propellant will be needed in the motor.

2. For the purpose of this exercise, the propellant will be assigned the following characteristics: gives good performance from K_n = 160 to 375; burns at 0.12" per second at K_n=160; burns at 0.18" per second at K_n=375. Your propellant may of course differ widely from these characteristics. Use the values of *a* and *n* for your propellant to determine the burn rates at the different values of K_n.[22] If values of *a* and *n* are not available, the motor may still be designed, but its performance (thrust, etc.) can only be estimated at best.

3. Select a motor diameter. A standard 29mm motor will take grains that are slightly under an inch in diameter. If a BATES motor is to be made, the grains might be 2" long, 0.93" diameter BATES grains with ⅜" core. Such a grain weighs about 28 grams, so the motor would take four grains. It is practical -- though rarely necessary -- to cut one grain slightly shorter than the others to achieve a specific length or total impulse. This will make the motor slightly more regressive. For this exercise, assume that the four grains will be used, giving 112 grams of propellant and about 224 N-s total impulse, slightly more than originally planned.

4. Calculate the "web" or propellant thickness from core to wall. For a coreburning or BATES grain this is:

   web = (propellant o.d. - core dia.)/2
   = (0.93 - 0.375)/2 = 0.2775 inches.

5. Find the nozzle throat required at the high and low values of K_n. The ProPel spreadsheet is an easy way to do this. At K_n=375, the nozzle throat required would be 0.218". At K_n=160 the throat would be 0.333". Of course, any value of K_n between 160 and 375 could be used.

6. Determine burn time and average thrust at both ends of this range of K_n:

   Burn time = web (inches) / burn rate (in/sec)
   Average thrust = total impulse (N-s) / burn time (sec)

At K_n=160: **Burn time = 0.2775 in / 0.12 (in/sec) = 2.3 seconds**
Average thrust = 224 N-s / 2.3 sec = 97 N

This might be a questionable design, since the nozzle throat is large enough to produce significant erosive burning. It's quite possible that it would work anyway,

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[21] One gram of propellant, divided by 453.6 g/lb, multiplied by Isp in lb-s/lb, multiplied by 4.45 N/lb. In other words, multiply your specific impulse by 4.45 and divide by 453.6 to get the total impulse from one gram of propellant.

[22] The "Ballistic" spreadsheet in Propel provides the average burn rate at the two values of K_n selected.

since the chamber pressure at K_n=160 is significantly lower than it would be at a higher K_n.

At K_n=375: Burn time = 0.2775 in / 0.18 (in/sec) = 1.54 seconds
Average thrust = 224 N-s / 1.54 sec = 145 N

Note that in each case the burn time is fixed by the web and the value of K_n to be used. Likewise, the average thrust is fixed by the total impulse and burn time.

In summary:

29mm motor, about 224 N-s, using four BATES grains 2" long, 0.93" dia., ⅜" core.
Nozzle throat 0.218" gives an H-145
Nozzle throat 0.333" gives an H-97

ALTERING THE DESIGN

Suppose that a higher thrust and shorter burn time is desired for this motor. One way to achieve this would be to increase K_n. Unfortunately, that approach has its limits; remember that chamber pressure is related to K_n.

Another alternative is to use a larger core; this gives a smaller web and shorter burn time. The downside here is that more grains will be needed and the motor must be longer.

Example: a burn time of 1 second is desired for this 29mm motor (H-224).

For a one-second burn time the propellant web must be 0.12" (at K_n=160) or 0.18" (at K_n=375), since those are the burn rates in inches per second. A web of 0.18" will put more propellant into each grain. With a web of 0.18", the core must be 0.57" diameter. Using 2" long grains of this core size, each grain will weigh just over 20 grams[23], so five grains will be needed. A five grain motor at K_n=375 will require a nozzle throat of 0.274"

Of course the core size is rather odd in this motor. In practice it may be easier to compromise and use a ½" core, for which a coring rod is available. For a ½" core at K_n=375, a five-grain motor would require a nozzle throat of 0.264". Each grain will weigh about 23 grams, so the five-grain motor will provide about 230 N-s of impulse. This compromise would give a web of 0.215", a burn time of 1.19 seconds and average thrust of 193 N. If this is not satisfactory, the original design could be used and the larger core drilled.

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[23] The ProPel notebook can be used to find the weight of a grain. Use the "Batch" spreadsheet and enter the propellant density and grain dimensions, using any propellant formulation you like, with a waste amount of zero percent. Look at the total propellant weight; that will be the weight of the grain.

EXAMPLE #2: I-MOTOR, 450 N-S, 29MM

If 450 N-s of impulse is desired, the motor must contain about 225 grams of propellant. In 29mm format, that corresponds to eight 2" propellant grains as described above. At K_n=375, the nozzle throat would be 0.333" -- quite large compared to the core. Since the pressure at K_n=375 will be high, the erosive burning seen with such a large nozzle may push the motor "over the limit"; it may cato.

At K_n=160 the nozzle throat would be 0.472 -- which won't work.

What to do? As before, we can use a larger core, say 0.5", then redesign. With a 0.5" core the 2" long grain weighs about 23 grams. Ten grains will be needed to construct the motor. With 10 such grains, and at K_n=375, the nozzle throat will actually be larger at 0.373". But now it's sufficiently smaller than the core, so that the erosion should not be horribly severe (If K_n=160 is selected instead, the nozzle throat would be 0.572" -- which won't work).

It's worth noting that this I-motor with 0.5" core now has a web of 0.215". The burn time will be 0.215/0.18 = 1.19 seconds. With a total impulse of 450 N-s this motor will have an average thrust of about 380 N.

Summary: 29mm motor, 450 N-s, I-380, ten grains 2" x 0.93 x 0.5" core, nozzle throat 0.373.

REDESIGN: I-MOTOR, 450 N-S, 38MM

Let's see what happens to this motor in 38mm size. A typical grain size for 38mm is 1.28" od propellant, core diameter 0.5", grain length 2.25" Each grain weighs about 60 g, so four grains would weigh 240 g, and give 480 N-s. At K_n=160 the nozzle throat would be 0.426". It would make for an erosive burn but would likely work, since the motor would be operating at a relatively low pressure at this low K_n. At K_n=375 the nozzle throat would be 0.279; very little erosion if any.

The web is 0.39", so the motor at K_n=160 would have a burn time of about 0.39/0.12 or about 3.2 seconds, an I-150. At K_n=375 the burn time would be about 0.39/0.18 or just over 2 seconds, an I-220.

Note that the 38mm motor design would be about 10" long; the 29mm would be about 22" long. Not only would the smaller diameter motor be unwieldy but it is rather extreme and might require a "stepped" core (larger diameter cores at the bottom, smaller at the top) or other special work to minimize erosive burning.

OTHER GRAIN CONFIGURATIONS

A Bates grain is simple to work with but isn't best for everything. Let's look again at a 29mm, 450 N-s motor with this propellant. Suppose that we want to make the motor burn for about 2.5 seconds. In a Bates grain, that's not possible; the propellant burns too fast at any workable K_n. One alternative would be to change the propellant and make it slower burning. Another, possibly simpler, would be to change the grain configuration.

For example, a C-slot 3/16" wide, going to the center of the core, would give a web of about 0.46" (distance from the end of the slot to the propellant wall). At a burn rate of 0.18"/sec, the burn time would be just over 2.5 seconds. Problem here is that any motor is a compromise. With a C-slot, a longer burn is accompanied by a greater need for insulation along the side of the slot.

A D-slot generally is easier for the experimenter to make than a C-slot. To make a D-slot grain, two lines are scored (with a razor knife) down the side of the casting tube, to mark the width of the slot. A piece of angle iron may be used as a guide to insure that the lines are straight (similar to marking a body tube for fins). A razor knife may then be used (Figure 32) to gently slice off the D-shaped piece of propellant. Deep scores when marking the tube will help to guide the razor knife straight. It may be easiest to "rock" the knife up and down, rather than using a sawing motion. Alternatively, some workers use a hacksaw blade and a wooden guide to cut D-slots.

Note that a D-slot will burn somewhat longer than a C-slot. The "web" is from the surface of the cut to the opposite side of the grain.

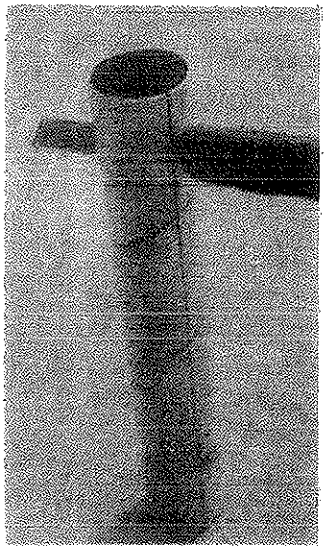

Figure 32: Cutting a D-slot grain

D-SLOT ESTIMATION; 450 N-S, 29MM

A very rough idea of the performance of a D-slot can be had by making a couple of assumptions. First, assume the D-slot is neutral and has a constant burn rate and pressure. Second, assume that the maximum burn area will be a rectangle as wide as the grain diameter and as long as the grain length (for finding the nozzle throat from K_n). Neither assumption is perfect but both will do for a first approximation.

As an example, let's use a 16" length of propellant grain, 0.93" diameter, with a D section sliced off that is 0.25" thick. The grain weighs 225 grams, so that gives 450 N-s total impulse. The web is

Web = 0.93 - 0.25 = 0.68 inches

The maximum area of burning propellant is a rectangle 16" long and 0.93" wide.

Burn area = 0.93 × 16 = 14.9 square inches

We can assume that we want K_n to be 375 at that point, since a D-slot is progressive then regressive, and we should not exceed the maximum K_n.

$$\begin{aligned} & K_n && = \text{burn area / nozzle area} \\ \text{so:}\quad & \text{nozzle area} && = \text{burn area} / K_n \\ & && = 14.9 / 375 \end{aligned}$$

= 0.0397 square inches nozzle throat area

That throat can be shown to be 0.225" in diameter. The burn time will be equal to 0.68"/0.18 (in/sec) or 3.78 seconds; the average thrust will be 450 N-s / 3.78 sec or 119 newtons -- an I-119

The author does not have the skills to write a spreadsheet that will model accurately C-slot and other core geometries. However, such a spreadsheet in Excel is currently available at modest cost from Troy Prideaux (e-mail GEORDI@c031.aone.net.au) With it, one can input the dimensions of a variety of grains, including C-slots, and obtain estimated thrust, chamber pressure, etc. The spreadsheet is extremely well-constructed and is highly recommended.

For those wishing to design grain shapes, http://home.iae.nl/users/aed/gdp/gdp.htm is a source for the Grain Design Program, which will model the ballistic behavior (burn rate, etc.) for many types of grains.

SINGLE-USE FLIGHT MOTOR CONSTRUCTION

The techniques that follow have been successful for 24, 29 and 38mm single-use motors. The author has not attempted larger diameter motors with this technique, and it is not known whether the technique given will work for them. Keep in mind that larger diameter = more force on the nozzle and on the forward closure. A 29mm motor at 800 psi chamber pressure exerts about 600 lb of force on the forward closure. A 54mm motor at that pressure would exert about 2500 lb of force; a 98mm motor will produce almost 8000 lb of force on the closure!

Flight motors are constructed in virtually the same manner as are static-test motors. The only real difference is inclusion (if desired) of a delay grain (see the "Sermonettes" for information on delay grains). For this exercise it will be assumed that the four-grain H-145 motor described in the previous section will be constructed, and a delay grain will be included. Use of a phenolic casing and phenolic nozzle will again be assumed, though aluminum or fiberglass casings are highly recommended for their greater strength.

1. The casing is cut to length with a fine hacksaw. Length should be the total grain length, plus 1" for the nozzle, plus 1¼" for the forward closure. So for a motor with four 2" grains, the casing should be 10¼" long. The ends are smoothed as before.

2. The inside of each end of the casing is roughed or grooved as described in "Construction of Static-Test Motors", Step 2.

3. The nozzle is inserted and potted with epoxy as described in Steps 3 and 4 on static test motors.

4. The nozzle throat is drilled to the calculated diameter. For this motor operating at $K_n = 375$, the nozzle throat was calculated to be 0.218". If a drill bit of that exact size is not available, one may be used that is slightly larger, or the nozzle may be reamed to size with a tapered reamer (available at most hardware stores, for reaming sheet metal).

5. The grains are slid in place as described in Steps 6 and 7 on static test motors. If a side-burning grain (C-slot, D-slot, moonburner) is used, a liner ordinarily is required, and the procedure for using a liner should be followed.

6. A ¼" hole is punched or drilled in the center of the cardboard or wooden insulating disk, if there is not already a hole there. For cardboard, an ordinary center punch works well.

7. The delay grain is cut to length, or it may be drilled carefully to the appropriate depth. To drill the grain, a ⅛" drill bit may be held in the fingers (a power drill may drill too deep). The author recommends the use of commercial delay grains. For most commercial delays, drilling the delay 1/16" deep will shorten it by 2 seconds.

A small bead of epoxy is applied to the edge of one end of the delay grain. If the delay has been drilled, the edge of that end is glued. DO NOT cover the entire end of the delay grain with epoxy or it won't ignite. DO be sure that the entire edge is sealed, else epoxy may leak through when the delay is potted. The delay is centered on the disk of cardboard and the epoxy allowed to set. The assembly should look like Figure 33.

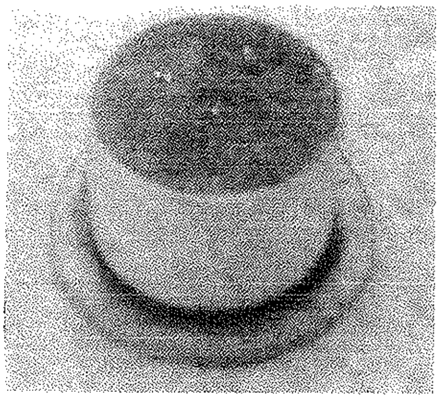

Figure 33: Delay grain and insulating disk, ready for insertion.

This disk (delay grain UP) is pushed into the casing on top of the propellant grains. A casting or liner tube makes a nice tool for this. A little epoxy is used to seal the edge of this cardboard insulating disk to the casing[24]. An o-ring is inserted as described in the section on static test motors, and the epoxy is allowed to set.

10. A ruler is inserted into the forward end until it touches the delay grain. Note this distance. The outside of the motor is marked this same distance from the forward end, so that you know exactly how far it is from the forward end of the motor to the end of the delay grain (Figure 34).

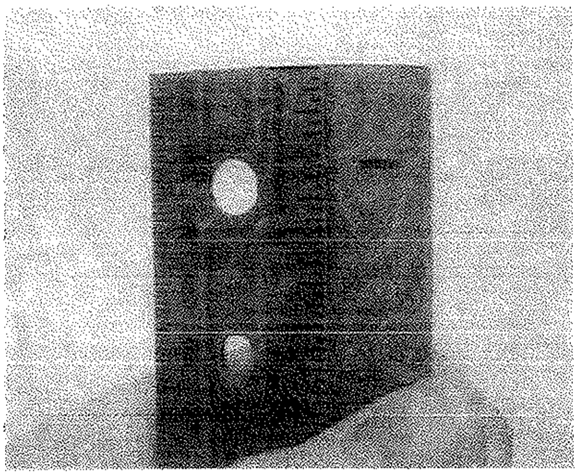

Figure 34: Marking the casing to determine the depth to drill.

11. The forward end of the motor is now filled with epoxy, *past* the mark that was made, but *not* to the top. About ⅛" or so of empty casing must be left for the ejection charge (if electronic ejection is to be used, this does not apply). And there should be at least 3/16" of epoxy on top of the delay. The assembly is allowed to cure completely.

12. If the delay is to be used solely for tracking smoke, the motor is finished. If motor

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[24] The author has heard of using silicone caulking for this purpose, since pure silicone is quite heat-resistant and flexible. If silicone is used to seal at this point, it is likely that the o-ring may be omitted, but the caulking must be allowed to cure completely before potting the forward closure with epoxy. That may take 24-48 hours or more. There should be no vinegar-like smell remaining.

It might be advisable to use GE Silicone II for this purpose, rather than "any old" silicone. GE Silicone II produces ammonia as it cures, rather than acetic acid. The latter has the potential to be a problem in contact with composite propellant.

ejection is to be used, the motor is stood on end. A ⅛" bit is used to drill slowly into the forward epoxy. You must stop when you reach the delay propellant. The mark made in Step 10 will show about how deep to drill. If you do not reach the delay there will be no ejection; if you drill too deep the delay will be too short. A drill press is much better for "feeling" your way in than is a hand drill.

Ordinarily you can tell when you hit the delay; the drill will feed much more easily. A small drill bit pushed into the hole against the delay grain will feel the rubbery texture of that propellant. Don't push too hard or you may punch a deeper hole in the delay.

The turnings from this operation are disposed of with other propellant in the scrap can. Don't just throw them in the trash, as they WILL contain a little delay propellant.

13. Enough FFFFg black powder is added to fill the hole just drilled. Then enough additional BP for the ejection charge (which will depend on the size of rocket to be launched) is added. The end is capped with a disk of masking tape (seal those edges!), or with a thin disc of cardboard over the ejection charge, using a dab or two of CA adhesive at the edges of the disc. The motor details (total impulse, class, average thrust, delay time, propellant type, etc.) are recorded on the casing.

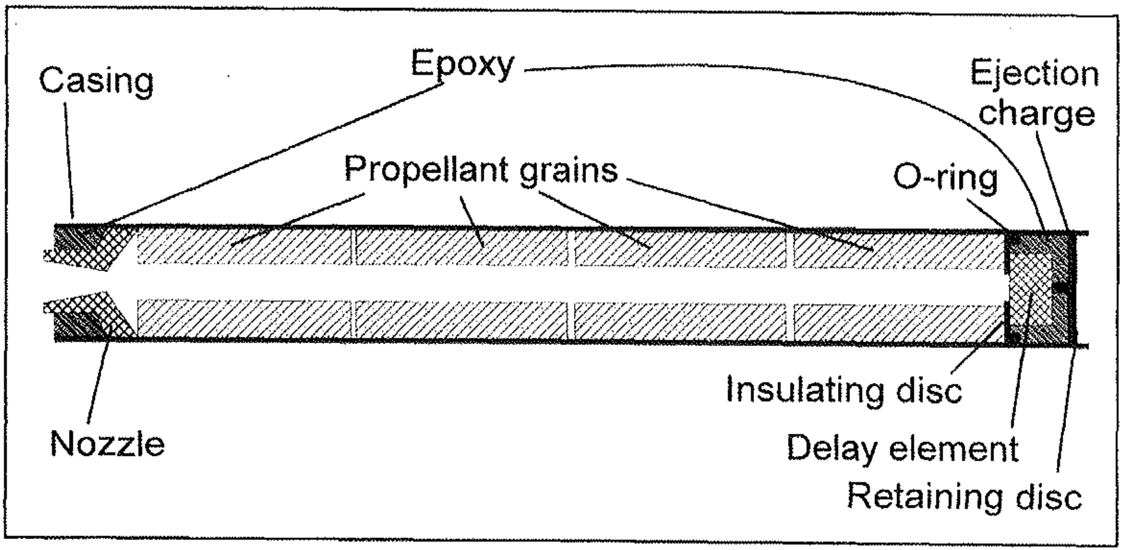

Figure 35: Diagram of finished flight motor with delay grain and ejection charge

MODIFYING THE STARTER PROPELLANT

A rocket motor represents a compromise in terms of cost and performance. This is also true of a given propellant. The starter propellant was designed for simplicity, low cost, and reasonable impulse. But it has a rather modest burn rate, and gives a yellow flame with almost no smoke. Some workers may prefer propellant that burns faster or slower, or with higher specific impulse, or one that produces black smoke or white smoke, or one with a colored flame. In this section, the nature of some modifications to the propellant will be examined.

Several tested propellants that were modified from the starter propellant are represented in Table V. The reader must understand that the number of *possible* modifications is almost limitless. Hence, modifications will be discussed in rather general terms. It is not possible to be quantitative unless a literature reference is available -- and sometimes not even then.

Although general effects of certain modifications (increase in burn rate with reduced oxidizer particle size) are well known in many cases, specific effects (how much does the burn rate increase?) vary with the reference. This is expected. Composite propellant is a *heterogeneous mixture*, not a homogeneous solution or pure compound.

The behavior of a homogeneous solution or pure compound may be predictable because the atoms are completely, intimately mixed and are everywhere the same. Mixtures, on the other hand, may and often do have widely different properties (even when the sources of ingredients are the same) due to variations in surface nature, shape of particles, source of materials, impurities, different processing techniques, etc., etc.

OXIDIZER PARTICLE SIZE

The burn rate of AP propellant generally depends on the particle size of the oxidizer. Rumbel reports that the burn rate is a function of the average particle size of the AP. However, it is not a *linear* function, as can be seen from the data in Table IV.

A decrease in particle size of a factor of about 10, from 200 to 18 μm, increased the burn rate only by a factor of approximately two. Summerfield and Kuo's book reports burn rates at about 750 psi of roughly 0.85" per second for 55 micron AP, 0.75" per second with 98 micron, and 0.65" per second for 265 micron.

As can be seen in Table IV, the burn rate exponent n does appear to change slightly as particle size decreases. However, *correlation* of this exponent and particle size is not apparent; there does not seem to be a way to predict exponent from particle size, and in fact the variation in exponent may be random.

In practice, it may be difficult for the experimenter to reduce particle size to a very great extent. Fine AP may make the propellant mixture much thicker, especially when hand-mixing. Machine mixing may alleviate this problem to some extent.

Mean particle size, micrometers	*a*	*n*	Burn rate @ 1000 psi
200	0.021	0.40	0.34 in/s
134	0.023	0.40	0.37
118	0.023	0.40	0.37
81	0.023	0.42	0.41
62	0.023	0.43	0.44
59	0.028	0.40	0.45
18	0.029	0.44	0.60

Table IV: PVC plastisol propellant, 75% AP oxidizer; adapted from "Propellants Manufacture, Hazards, and Testing", pp 64-65[25]

In contrast, some commercial propellants do use extremely fine AP, as can be inferred from Table IV. This sort of propellant is workable because (a) the propellant is machine-mixed; (b) a surfactant ordinarily is used; and (c)the correct *proportions* of particle sizes of oxidizer are used (see the appendix on pourable propellant).

Of course, burn rate can be *decreased* by increasing the AP particle size. This usually has the additional effect of making the propellant easier to mix. However, some workers have reported problems with larger particle sizes. The author has noted that 400 micron AP is more likely (than finer material) to "pop out" of the propellant surface as the propellant is cut. That in turn implies that these coarse particles of AP may pop out during combustion and reduce the delivered specific impulse or cause erratic burning.

One final point relates to extremely small particle sizes of AP. Summerfield reports that when AP is finer than a few microns in size, the burn rate actually *increases* with decreasing particle size. This is of interest only to the professional, since such fine particle sizes are extremely difficult to produce and would be highly dangerous in any event. Such ultrafine AP can combust spontaneously, and for professional work it often is shipped already dispersed in liquid binder.

METALS IN PROPELLANT: SPECIFIC IMPULSE

Since about 1950, it has been known that fine aluminum, magnesium, silicon, or other reactive metal (*thermic agent*) will increase delivered specific impulse in AP and other propellants. The reactions of aluminum and magnesium with oxidizers are extremely *exothermic* (give off heat) and increase the chamber temperature. This means that the exhaust gases will exhaust faster, creating more momentum thrust. Aluminum and silicon can be used with PBAN because the protective oxide coat on each particle adheres very well to the metal[26], and keeps the metal from reacting with PBAN. Magnesium does form a coating of MgO, but it is not as adherent. So magnesium will

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[25] Values of *a* were calculated from the burn rates and values of *n* presented in the reference. Trends are difficult to establish as the different propellants presented here may have different particle size *distributions* (example: all-200 micron vs half 100 micron and half 300 micron; same average particle size but different burn characteristics).

[26] Technically speaking, silicon is not a metal but a metalloid. However, in this context it behaves and reacts much like a metal.

require a more adherent coating before using it with PBAN. Uncoated magnesium in PBAN will cause bubbles and will make the PBAN harden within a matter of minutes.[27]

A point of debate has to do with the *amount* of metal added to the propellant. By experimenting a bit with Propep, it can be determined that about 15-20% aluminum in a typical AP propellant will give maximum (theoretical) I_{sp}. The limit is reached when the higher temperature is offset by the increased amount of solid or liquid material (metal oxide) in the chamber and exhaust. However, such large amounts of aluminum may not be effective in *small* motors (a formulation containing 10% aluminum is provided in Table V; note the value for delivered specific impulse vs. that of the simple propellant).

Much of the important reaction of aluminum appears to occur in the *gas* phase. The solid particle of aluminum is thought to detach from the propellant surface, and begins to vaporize. It is this vapor that reacts with the products of decomposition of AP and/or binder. Clearly this process takes time, and in small motors there may not be enough time for the particle to be consumed before it exits the nozzle. The finer the aluminum and the better dispersed it is, the more efficiently it should burn.

A used nozzle from a reloadable motor (using aluminum-containing propellant) provides evidence for the lack of effectiveness of large amounts of aluminum in small motors. The entrance cone, and possibly the exit cone and throat of the nozzle will be seen to be covered with slag. The higher the percentage of aluminum, the more slag is seen. Presumably the slag is largely aluminum oxide; however, sometimes the material under the slag is shiny, suggesting unburned aluminum metal. More important, this slag is part of the propellant that has *not* been ejected from the motor and has therefore not contributed to thrust.

One author reports that a small portion of extremely fine metal may aid in combustion of coarser metal. That is, a propellant that has 10% 20 micron and 2% 5 micron aluminum may burn the aluminum almost as efficiently as if the metal were all 5 micron. The author of this book has not investigated this idea, and so its validity in small motors would be a matter of speculation (or future experiment...).

In larger motors, it is apparent that aluminum does contribute significantly to impulse; presumably larger motors are more efficient than smaller ones.

METALS IN PROPELLANT: OTHER EFFECTS

In addition to an increase in I_{sp}, addition of thermic agent to propellant may increase burn rate to some degree (consistent with the data in Table V)[28]. There are two effects relative

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[27] PBAN is a weak acid. It is not sufficiently acidic for it to react with aluminum, because of the adherent layer of aluminum oxide on the metal; magnesium and zinc are another story.

[28] Metal and burn rate is widely reported in the literature. Based on those reports, it would appear that burn rate *may* increase when metal is added. Or it may not change. Or it may decrease. Apparently there is dependence on metal particle size, oxidizer particle size, oxidizer particle size *range*, and the type and proportion of metal. In short, this means that the results an experimenter obtains are for his/her work, and may not necessarily be "general".

to this in composite propellant. The metal produces an increase in combustion temperature, which ordinarily should result in feedback of heat to the propellant surface, increasing its burn rate. But there is also a heat sink effect; the metal must be brought to its melting point (or boiling point) and to its combustion temperature; these processes absorb heat. The net effect is that burn rate is affected rather mildly. In some instances, burn rate may actually be decreased by a thermic agent, depending on the specific composition of the propellant.

Rumbel notes that burning rate increases (from about 0.45 in/s to 0.55 in/s at 1000 psi for the propellant under study) by addition of about 10% of either aluminum or magnesium to PVC plastisol propellant. He also notes that the pressure exponent tends to decrease slightly with addition of these metals; this means that the burn rate coefficient must increase somewhat. Finally, he notes that magnesium appears to be more effective than aluminum in increasing the burn rate, even in large particle sizes up to 250 micron. This may be due to the fact that magnesium has a lower boiling point than aluminum and/or because magnesium will readily undergo reaction in the solid phase.

Magnesium is reported to improve the low-pressure burning of composite propellant. Some magnesium-containing propellants burn at pressures under 100 psi, whereas about 200 psi is required to sustain combustion of many ordinary composite propellants.

A thermic agent in composite propellant can greatly reduce *combustion instability*. When all products of combustion are gases (as with the simple propellant and similar) the chamber may have a tendency to "resonate" at a particular frequency. If this happens, burning may speed up in "pulses", at this frequency. This sort of combustion causes severe pressure spikes that can tear a rocket motor apart within a tiny fraction of a second. Small amounts of solids or liquids in the exhaust and chamber gases serve to dampen the resonance (dampening of sound in a snowstorm is a similar phenomenon). The thermic agents all produce oxides that are solid or liquid at chamber temperatures[29].

When aluminum or silicon is used to replace oxidizer in a propellant, they increase propellant density and generally improve flowability, since they are more dense than the solids they replace. Magnesium is less dense than ammonium perchlorate and will reduce propellant density slightly. In the author's experience, metals added to PBAN propellant tend to improve tensile strength and stiffness of the cured propellant, and also make it somewhat easier to process (a bit less sticky).

A final property of thermic agents is that they produce a bright white flame and white "smoke" in the exhaust. That bright flame is a combination of the high chamber/exhaust temperature and the solids in the exhaust. The smoke is merely the oxide of the thermic agent. The amount of smoke depends on the proportion of thermic agent. At less than

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[29] The simple starter propellant does not contain metal, but the author has not encountered any combustion instability problems in approximately fifty (29mm/38mm) test firings of the propellant. Of course, that does not mean that such problems will not be encountered by others. A modification of the simple propellant for larger motors might include a small proportion of aluminum to avoid this potentially disastrous problem.

about 3-5% thermic agent, very little smoke is seen.[30]

When making an aluminized propellant, the aluminum is simply added to the PBAN in place of the lampblack. It is very important that every effort be employed to avoid hazardous "dusting". The mixture is stirred very slowly and carefully until the aluminum is fully wetted. It is then mixed *thoroughly* before adding oxidizer, to avoid solid-to-solid contact of oxidizer and metal (fine metal is considered far more hazardous than lampblack).

BURN RATE MODIFIERS: CATALYSTS

As the name implies, a burn rate modifier changes the burn rate of a propellant. For increase, a *burn rate catalyst* is used. To slow the burn rate a *burn rate suppressant* is employed.

Most burn rate catalysts for ammonium perchlorate propellants are *transition metal oxides* (TMO's). These include copper(II) oxide (CuO, "black copper oxide"), iron(III) oxide (Fe_2O_3, "red iron oxide"), manganese dioxide (MnO_2), some chromium compounds and other iron compounds, and a few other metal oxides.

The precise manner in which a TMO increases the burn rate is still not clear. What *is* clear is that there are several mechanisms, which may apply to different degrees in different propellants and at different pressures. A TMO may do any/all of the following:

-increase heat absorbed by the binder at the surface, and aid in binder regression.
-catalyze binder decomposition near the surface (by several mechanisms)
-supply more reactive fuel species to the flame
-speed up AP decomposition into NH_3 and $HClO_4$
-speed up decomposition of reactive $HClO_4$ formed by AP decomposition
-alter the decomposition products of AP and binder
-form thermally unstable metal perchlorates

Most burn rate catalysts are used in relatively small amounts; 0.05-1%. For most catalysts, more than about 2% does not appear to increase the burn rate in relation to its amount (adding 4% catalyst doesn't double the burn rate vs. 2% catalyst). Too much burn rate catalyst does decrease the specific impulse of the propellant, due to reduced oxidizer content.

Most TMOs are solid or liquid at combustion chamber conditions, and tend to minimize combustion instability in the same fashion as do thermic agents. However, TMO's are used at relatively low concentrations. Thus an additional agent (i.e., a few percent aluminum) to minimize combustion instability might be employed.

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[30] Atmospheric conditions will dictate the amount of smoke seen. You have undoubtedly noticed that AP composite propellant produces a great deal of smoke on humid days. This is caused by the gaseous exhaust product hydrogen chloride. HCl has a great affinity for water. The gas will cause water to condense out of the air and will dissolve in that water as tiny droplets of hydrochloric acid. Breathing exhaust fumes from AP composite propellant is not a recommended activity...

For commercial motors, red iron oxide appears to be the most commonly used catalyst. It is reported to aid in decomposition both of binder and of AP. It appears to increase the burn rate by increasing the burn rate coefficient rather than the exponent. And it is a good catalyst at the modest pressures commonly employed in experimental motors. A faster-burning formulation using iron oxide is provided in Table V. Note that 1% iron oxide is substituted for 0.2% lampblack in this formulation. Thus, the proportion of AP is slightly reduced, and the theoretical specific impulse is very slightly reduced as well. In practice, it can be seen that there is no significant change in specific impulse delivered.

As with aluminum, the burn rate catalyst is simply stirred into the mixture in place of lampblack. Although burn rate catalysts themselves are often nonhazardous, anti-dusting precautions should still be taken, since some catalysts (in the dry state) may sensitize ammonium perchlorate to an undesired degree.[31]

Some experimental workers making smaller motors prefer black copper oxide to Fe_2O_3. The flame from a propellant made with copper(II) oxide has a lovely violet or blue-tipped tail, often with shades of magenta. Copper oxide also increases the ignitability of most mixtures. However, it also appears to increase the burn rate exponent, sometimes unworkably. One worker has reported a burn rate exponent of about 0.45 for a mixture containing 1% CuO. The beginner would be well-advised to use CuO only after some experience with iron oxide.

Empirical evidence suggests that the *source* of the burn rate catalyst may have a significant effect on the propellant burn rate. It is suggested that the experimenter obtain a consistent supply of burn rate catalyst if it is to be used. The purchase of several pounds to insure consistency would be a wise precaution.

A common misconception of the beginner is that a burn rate catalyst increases the specific impulse. As can be seen from Table V, the test motors that use the iron oxide propellant and the simple propellant produced virtually the same I_{sp}. The iron oxide propellant burns faster, which means that it produces more thrust (G177 vs. G102) — but for a shorter period of time.

One other burn rate catalyst worth mentioning is *copper chromite*, $Cu_2Cr_2O_5$ or $2CuO{\cdot}Cr_2O_3$. Copper chromite has two very interesting properties in AP propellant. First, the burn rate of composite propellant may be increased about 25% by addition of only 0.2% copper chromite, according to Rumbel. Second, copper chromite tends to increase the burn rate *coefficient*, and in fact has a tendency to decrease the burn rate exponent. However, copper chromite is rather difficult for the experimenter to obtain, it is expensive (typically $20-50/lb), and "modern" copper chromite is reported to be much less effective than the material produced twenty years ago.

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[31] Some workers suggest that the burn rate catalyst be dry-mixed thoroughly with the AP before adding that mixture to the binder mixture. It is this author's opinion that such is unwarranted and unadvisable. In any event, if the propellant mixture is truly mixed thoroughly, the burn rate catalyst will be dispersed through the binder anyway. There is little reason to perform the potentially hazardous operation of pre-mixing dry burn rate catalyst and oxidizer in *most* cases, though such mixing may be helpful in specific instances.

A burn rate catalyst for AP will not necessarily be an effective burn rate catalyst for other oxidizers, and vice versa. Red iron oxide works with AP and potassium perchlorate propellants, but is of rather little effect in ammonium nitrate (AN). To increase the burn rate of AN propellant, ammonium dichromate [$(NH_4)_2Cr_2O_7$] or potassium dichromate [$K_2Cr_2O_7$] are commonly employed; about 1-4% is required. Another AN catalyst is *Prussian Blue*, an extremely fine blue pigment compound with the chemical name of iron(III) ferrocyanide, $Fe_4[Fe(CN)_6]_3$. Reports of its use suggest that the AN must be milled very fine, along with the Prussian Blue, for this mixture to be effective (see the footnote on the previous page). Prussian blue also is reported to be effective in AP propellant. At least one literature source reports carbon black as a burn rate catalyst for AN propellant[32].

One problem that should be anticipated with burn rate catalysts is *sensitivity* to friction and impact. Often, addition of a burn rate catalyst not only makes a propellant burn faster but also makes it easier to ignite. Consequently, it may be more likely to ignite from friction or from impact. This means that appropriate care and precautions should be taken with compositions that contain a large proportion of burn rate catalyst (or thermic agent). Drilling such compositions, or pulling coring rods from them, should be approached with caution.

BURN RATE SUPPRESSANTS

For reducing the burn rate of AP propellant, the suppressant most commonly used (by experimenters) is *oxamide*. A formulation using 3% oxamide is provided in Table V. Note that lampblack is still used in this propellant. Oxamide is colorless, thus an opacifier is still required. Note that the burn rate of this propellant is about 60% that of the simple propellant. Some workers use a small amount of oxamide to compensate somewhat for the faster burn characteristics of a propellant that is not vacuum-processed.

Oxamide has the desirable property of acting as a fuel; in fact, according to Sarner it is a monopropellant in its own right. Thus, performance does not decrease as much as with other burn rate suppressants. Generally speaking, other suppressants must be used in rather larger proportions than oxamide and thus performance can be affected greatly. However, the reduced specific impulse seen in the test motor of Table V (as compared to the other propellants) may be partly the result of low chamber pressure for that particular motor.

Most burn rate suppressants make the propellant more difficult to ignite. There was no difficulty igniting the oxamide-containing propellant with the igniter described in the appendix; however, for higher levels of oxamide, a "boosted" igniter may be helpful.

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[32] Magnesium increases the burn rate of AN propellant. However, the magnesium is not a *catalyst* here; instead, it participates directly in the combustion reaction. The author's attempts to increase further the burn rate of Mg-AN propellant by adding catalyst (such as ammonium dichromate) have been unsuccessful. A catalyst works by increasing the rate of one particular micro-"step" of the reaction. It would appear that whatever process is speeded by catalyst is still slower than the Mg-AN reaction itself. To increase the burn rate of AN-Mg propellant, finer Mg is sometimes used.

Other substances that have been reported to lower propellant burn rates include calcium carbonate, calcium phosphate, ammonium chloride, ammonium sulfate, diammonium hydrogen phosphate, and lithium fluoride[33]. The latter is reported (Summerfield) to be the most effective suppressant for AP composite propellant, but fluorides are quite toxic and a bit difficult to find. The author has not personally tried any of these, and cannot report on their utility. Calcium carbonate and calcium phosphate lower specific impulse more than does ammonium chloride (which is a rather weak oxidizing agent). For the experimenter who cannot obtain oxamide, these may be reasonable substitutes. However, it should be noted that calcium carbonate and calcium phosphate both are basic and may react with PBAN.

SOLIDS LOADING

The solids loading of a propellant can be decreased or increased -- within limits. Decreasing the proportion of solids will produce a propellant that:

-is more easily mixed, even "pourable".
-has lower specific impulse unless thermic agents are added to compensate.
-tends to "settle" as it cures. This is not an insurmountable problem; the mixture in the casting tube will have a rubberlike layer at the top. That layer may simply be sliced off. Settling is less of a problem with PBAN than with HTPB, because of the increased viscosity of PBAN.
-produces black smoke. At lowered oxidizer levels, there is a considerable excess of fuel. Some of the fuel combustion products exit the nozzle as carbon particles -- black smoke.
-is less corrosive to nozzles. A high oxidizer content tends to create an "oxidizing" exhaust that will erode nozzles (even graphite nozzles) more readily. Lowered oxidizer content is less "harsh".
-has a slightly higher burn rate exponent, according to Rumbel. However, it is interesting to note that Rumbel also reports a PVC propellant that is 60% AP; the propellant tends to have a constant burn rate (about 0.1 inch per second) at pressures between 200 and 1000 psi.

Increasing the solids content generally increases specific impulse, may reduce the burn rate exponent slightly, minimizes settling, makes for a "clean" flame, is more corrosive to nozzles, and often eliminates pourability.

The practical limits for solids loading for experimental propellants using AP and PBAN binder are around 70%-84%[34], though this depends on the actual composition and ingredients used. Solids loading below 70% may make the propellant more difficult to ignite, specific impulse may be rather low, chuffing can occur even at normal chamber

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[33] Inconsistency abounds in reports of burn rate catalysts and suppressants. Data in Shorr and Zaehringer's book indicates that ammonium chloride has virtually no effect on burn rate of AP propellant. Summerfield and Kuo's book notes that ammonium chloride is a burn rate suppressant.

[34] It can be shown mathematically that the maximum solids loading theoretically possible in an AP-PBAN propellant is 85.3% when a single spherical particle size of AP is used. Higher solids content is possible by using a variety of particle sizes.

pressures, and settling may be severe. Above 80-82%, machine-mixing is generally required to distribute binder evenly. Above about 84% several problems appear from low binder content. The binder may not wet the casting tube sufficiently for a good bond. The propellant may be structurally weak. And there may be too many voids in the propellant, causing a high and/or unpredictable burn rate.

For propellant bound with HTPB, which is both stronger and less viscous than PBAN, the solids limit can be increased to 88% or even slightly higher. However, for the casual experimenter this is of limited interest. Ultra-high solids propellants do not provide significant increase in specific impulse. The simple propellant has I_{sp}= 238 at 80% solids loading. Increasing this to 84% solids (AP) increases specific impulse to about 248 seconds, while at 88% solids I_{sp} is about 253 seconds (and the propellant is much more difficult to process). In practice, a motor that produces 620 N-s total impulse with the simple propellant would produce about 690 N-s with the solids increased to 88% (assuming no change in general composition). Significant, but not extreme.

For maximum solids loading, at least two and preferably three or more sizes of AP are needed. Propellant with a single size of AP tends to be *dilatant* and difficult to mix (see the appendix on pourable propellant). To obtain maximum solids loading with minimum viscosity, the approximate ratio for 400:200:90 micron AP can be shown to be about 5:15:3.

TYPE OF OXIDIZER: AMMONIUM PERCHLORATE

AP is the most commonly used oxidizer for composite propellant, both by the amateur and in military/NASA propellants. Rocketry enthusiasts often refer to the propellant itself as "AP", but that's actually just a part of the propellant, though a rather large part.

AP has several advantages over other oxidizers. First, it provides higher specific impulse than any other common oxidizer. AP propellants without metal deliver I_{sp} around 200 seconds, even in small motors. In larger motors, with high solids loading and with thermic agent added, specific impulse can go as high as 265 seconds.

Also, AP produces only gases (nitrogen, hydrogen, water vapor, chlorine, hydrogen chloride) as its combustion products. That is one reason for the high impulse of AP propellant. The more gas produced and the less solid, the higher the impulse in general. A side effect of this property is that there may be very little smoke in the exhaust. That's more important for military propellant than for amateurs. However, if a "clean" exhaust is desired, AP (or AN, as will be seen later) must be used as the oxidizer.

AP is available *spherical* (spheroidal, atomized) or *ground*. Propellant made with spherical AP is easier to process, because the round particles slide over one another easily during mixing. The standard spherical sizes commonly available to the experimenter are 90 μm (micron), 200 μm, and 400 μm[35]. Finer material is occasionally

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[35] Some of the AP available to the experimenter from pyrotechnic sales companies is reported to be government/military surplus that is considered "out of date" after a certain length of storage. However, AP does not "go bad" as long as it remains uncontaminated.

available. For comparison, 400 µm is about the size of sand or ordinary table sugar. Ground or milled AP has been powdered in a ball mill or hammermill, and the particles may have sharp edges rather than rounded ones. However, ground AP can be as suitable for propellant as spherical AP, since it has a wide distribution of particle sizes. For more information on this topic, see the references.

AP propellant burns at a moderate rate, from 0.1 to 1 inch per second, depending on additives, particle size, and pressure. This burn rate is nearly ideal for BATES grains and other common, easily-made grains. Also AP propellants tend to have a fairly low burn rate exponent (0.2-0.5); this gives the experimenter a much better chance of success.

AP is not prohibitively expensive, about $5/lb at the time of this writing from pyrotechnics supply houses, less in large quantities. That translates into about $1 worth of propellant in a typical H-motor. Still, it's the most expensive oxidizer in common use by experimenters.

POTASSIUM PERCHLORATE, $KClO_4$ (KP OR KPERC)

KP is normally available as "powder" of no specific particle size. Propellant with KP has a somewhat lower specific impulse (typically 190-210 seconds) than the same propellant with AP. However, KP is denser than AP, so that the KP propellant can have a higher *density impulse* than the AP propellant. That is, a motor of a given length and diameter can hold more KP propellant (by weight) and have slightly more total impulse than the AP motor.

KP propellant can be made to burn faster than AP propellant, well over 1" per second at high pressure. This makes it useful for some endburning motors.

One product of KP combustion is solid K_2O (which is one reason that Isp is lower for KP propellant than for AP propellant). The exhaust thus includes a dense white "smoke". The flame itself is often slightly purple, from the potassium in the flame.

Generally speaking, KP is more difficult for the beginner to use in composite propellant. KP propellant has a very high burn rate exponent, around 0.7-0.8. Motors are more sensitive to minor variations in nozzle diameter and are more likely to CATO. Perversely, the propellant can be rather difficult to ignite reliably.

Some workers have suggested using both AP and KP in propellant, taking advantage of KP's lower price, higher burn rate, and higher density. However, Rumbel reports that such mixtures have almost the same high burn rate exponent as KP alone, even when the proportion of KP is only about 20%. The advantage of adding KP to an AP mixture would appear to be limited.

AMMONIUM NITRATE, NH_4NO_3 (AN)

AN has been used for some time as a propellant oxidizer in military ordinance. It is extremely cheap and readily available. There are no solids in the decomposition products and there is no HCl or Cl_2 in the exhaust. These gases have been suggested to be an environmental problem in major space launches, though for the experimenter this should not be a major issue.

AN propellant has about the same specific impulse as the corresponding KP propellant. The lower density of AN means that its propellants will also be lower in density than either AP or KP mixtures. In practice, this means that a 29mm motor 9" long that contains AP propellant might be a mid-H motor, delivering about 240 N-s of impulse. The same physical size motor using AN as the oxidizer may deliver only 160 N-s -- a high-G or low-H motor.

A real problem encountered by the experimenter is that AN is very hygroscopic, meaning that it will absorb water from the air. In fact, it can absorb enough water to dissolve itself. So AN propellant must be protected from moisture during processing and in fact until just before launch. AN propellant is often difficult to ignite, sometimes more so than KP propellant.

To be useful, AN propellants must be very high in oxidizer (at least 80% by weight) or they must include a thermic additive. Magnesium is often used for this (10-25% by weight), though some workers have reported success with small proportions of silicon[36]. AN propellant without magnesium normally burns extremely slowly, around 0.05-0.1 inch per second. Even with magnesium added the burn rate is only slightly higher. For the worker who is interested in long burn times at low thrust, AN may be worth investigating.

One final problem with AN has to do with *phase changes*. AN undergoes a change from one crystal structure to another at about 90°F. If AN propellant grains are allowed to warm above this temperature, the AN crystals expand slightly. When the propellant is cooled again, the AN contracts. This causes the crystals to tear away from the binder and may cause erratic burning.

Phase-stabilized AN is available from CP Technologies. This material has a small amount of a nickel salt that eliminates this phase transition. It is possible for the experimenter to produce phase-stabilized AN but the effort is hardly worthwhile unless very large quantities of AN (several hundred pounds) are required.

It should be noted that the phase-change problem is not necessarily a major drawback if the propellant is used soon after it is prepared.

OTHER OXIDIZERS

Potassium nitrate is a time-honored oxidizer used in blackpowder rocket motors. It burns at a much lower temperature than the other oxidizers mentioned, and produces a great deal of solids in the exhaust. As a result, it gives much lower specific impulse (maximum about 150 seconds) than other oxidizers. Although the author has not tried

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[36] Fine aluminum or magnesium can undergo a violent reaction with AN in the presence of moisture. Since AN is so very hygroscopic, great care should be taken when preparing such propellants.

it in composite propellant, others who have done so have reported that it makes for a difficult-to-ignite propellant. Its major advantage is cost; it is available in bulk from fertilizer supply houses for about $40/100 lb.

It should be noted that potassium nitrate propellants using various sugars as fuel have been investigated *very* thoroughly by Richard Nakka. His web page covers this topic in outstanding detail, and is highly recommended for both general and specific information even if one is not making this type of propellant.

Strontium nitrate is actually poorer than potassium nitrate in terms of specific impulse. However, it has a rather high density, which compensates somewhat for the lower I_{sp}. Strontium nitrate enjoys some use as an added oxidizer in AP composite propellant because it produces a beautiful red flame. The author has not experimented extensively with strontium nitrate in PBAN propellant, but some initial work suggests that it does not react with PBAN.

Mixing any nitrate with ammonium perchlorate can cause problems. An *exchange reaction* can occur, forming hygroscopic ammonium nitrate; propellant that absorbs moisture is undesirable.

Barium nitrate is even worse in performance and properties than is strontium nitrate. It adds a green tint to the flame, but few have been able to make a brilliant "green" flame composite motor using barium nitrate. Barium compounds are rather toxic and should be handled with care. Likewise, the exhaust is toxic; the experimenter should consider the effect of his/her experiments on the surrounding land used for the launch.

Colored flames often require somewhat higher temperatures than are produced by a non-metal-containing propellant. Thus, a metal (magnesium or aluminum) is usually added to propellant that is designed for colored flame. However, too much metal tends to "wash out" the colored flame, since a high metal content produces a brilliant white flame. Some experimentation is required to obtain a proper tint. An appropriate "starting point" might be about 5% metal.

Generally speaking, the experimenter may want to obtain significant experience with ammonium perchlorate propellant before attempting to use other oxidizers.

BINDERS

There is little reason for the experimenter to choose from binders other than HTPB and PBAN. However, the others do warrant some discussion.

CTPB or carboxyl-terminated polybutadiene is similar in nature to PBAN, but does not have the "acrylonitrile" portion of the molecule, so it provides a slightly lower specific impulse than PBAN. CTPB is reported to be cured with epoxy. The literature reports that this cure reaction is slow and incomplete, and that special curing agents are needed for complete cure.

In *PVC plastisol* propellant, the binder is very finely powdered polyvinyl chloride with (roughly) an equal weight of plasticizer. At room temperature the PVC is virtually insoluble in the plasticizer. When the temperature is raised to about 275-350°F for 5-30 minutes, the PVC dissolves in the plasticizer and forms a rubbery mixture, similar in consistency to flexible vinyl tubing. To make propellant, the oxidizer, plus a hydrogen scavenger and other minor ingredients are added to the mixture before it is heated.

PVC plastisol propellant has virtually an indefinite potlife, since the PVC does not dissolve significantly in the plasticizer until it is heated. However, for the experimental worker, the heating process is likely to be a problem. The dissolving temperature is not very far below the decomposition temperature of AP. For very sensitive propellants, this is an area of potential danger.

Silicone polymer has been used as a binder for certain types of pyrotechnic rockets. See the Journal of Pyrotechnics #8, 1998, p. 31 for an extensive article on the subject.

Stellite-C is the trade name for a rigid low-melting (140°F) binder marketed by Prodyne. To make a Stellite-C motor, the binder is grated to a fine powder, then mixed with the other ingredients. The mixture is poured into the casting tubes and heated slowly in an appropriate oven. Prodyne gives complete directions for this material.

The author has found that melted Stellite-C is rather viscous and does not mix well. The resulting propellant has a fair number of tiny voids (Prodyne recommends that K_n of about 100 be used as a start). It does not bond well to paper tubing unless a fairly large proportion of binder (20% at least) is used. The finished propellant is brittle and not particularly strong unless it is *thoroughly* mixed. And if motors made with Stellite-C are stored in a hot car, the propellant can sag and ruin the motor.

SPECIAL EFFECTS: SMOKE

"Smoke" consists of microscopic particles of a substance. As noted earlier, a modest amount of black smoke (soot) may be produced by using a very fuel-rich mixture. Reducing the oxidizer loading to 75% is generally sufficient for black smoke.

The rich cloud of black smoke produced by commercial "smoky" propellant is often the result of zinc dust (20-40%) added to the propellant. Zinc has a fairly low melting point and is a vapor at chamber temperatures. In the exhaust the vapor condenses to form tiny particles of pure zinc, which (because they are so very small) appear black. Unfortunately, untreated zinc cannot be easily used in PBAN; like magnesium, it will react with the carboxyl group. Untreated zinc can be used in HTPB propellant.

Zinc also decreases the specific impulse. However, it is so dense that this is offset to some extent. If one compares two same-sized motors, one using a propellant containing a large proportion of zinc, while the other uses a standard AP propellant, the two may produce about the same total impulse. The motor using zinc will weigh a good deal more than the one without, though.

Aluminum is quite suitable for *white* smoke. Up to 20% aluminum may be added to the propellant to produce a large cloud of white smoke (aluminum oxide). Aluminum increases chamber temperatures, though, and propellant that contains aluminum tends to erode nozzles more than does propellant without metal.

Other colors of smoke are difficult if not impossible to obtain with AP formulations. Most colored smoke (i.e., smoke bomb) is actually a dye that is dispersed -- but not decomposed -- by a low-temperature flame. In a rocket motor, the chamber temperature is so high that any such dye would break down and decompose.

SPARKS

One of the most popular motors for high powered rocketry is/was the "Silver Streak"; a modified blackpowder motor that gave off a large shower of sparks on ascent. The spark effect is relatively easy to obtain in composite propellant, but it comes at a cost. Since the motor dumps *burning* solid particles out the nozzle, it is in effect dumping incompletely burned propellant. This means that the specific impulse will be lowered greatly. A typical "sparker" might produce I_{sp} of only about 120 s. Also, the bits of burning solid play havoc with the nozzle, since they strike the entrance cone at somewhere around sonic speed. A graphite nozzle that would give 20 uses with an ordinary propellant might give only 4-10 uses with sparker propellant.

Fairly coarse metals (20-60 mesh) usually are used to create the sparks[37]. For white sparks, titanium appears to be the metal of choice. About 10-20% titanium has been suggested as a reasonable proportion to use, depending on the amount of spark desired.

When using titanium in propellant it is EXTREMELY important that the cores be molded (with a mandrel) rather than drilled. Titanium is very hard, and when drilled it tends to throw sparks. This could prove disastrous in propellant work.

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[37] In blackpowder motors used for fireworks, coarse charcoal is often added to reduce the burn rate and provide a nice "tail". Such charcoal might be worth trying in a composite motor, though it's possible that the charcoal would burn almost completely before it exited the nozzle.

Simple	**Fast**	**Aluminum**	**Slow**	**Ingredient**
17.3	17.3	17.3	17.3	PBAN
2.7	2.7	2.7	2.7	DGEBA epoxy
79.8	79	70	76.8	200 micron AP
0.2			0.2	Lampblack
	1			Red iron oxide
		10		-400 mesh aluminum
			3	Oxamide
0.0587	0.0590	0.0612	0.0582	Theoretical density, lb/in^3
0.053	0.053	0.056	0.053	Density obtained, lb/in^3
238	237	260	232	Theoretical I_{sp} at 1000 psi
0.033	0.079	0.038	0.018	Burn rate coefficient (a)
0.33	0.26	0.31	0.37	Burn rate exponent (n)
Test Motor Results				
G102	G177	G117	G65	Motor, two (0.93×2×0.375") grains
56.5	56.2	57.5	56.0	Propellant wt., grams
0.204	0.228	0.204	0.190	Nozzle throat, inches
214	171	214	246	Initial K_n
112	112	115	102	Total impulse, N-s
202 s	203 s	204 s	186 s	Delivered specific impulse
1.10 s	0.62 s	1.07 s	1.56 s	Burn time

TABLE V: Comparison of Selected Experimental Propellant Composition and Properties

COMMENTARY ON TABLE V

All four propellants were 80% solids, hand-mixed, hand-packed, without vacuum processing. Coring rods were used to form the cores, hence the proportion of PBAN to epoxy used was 32:5. Values for burn rate coefficient, burn rate exponent, and other experimental quantities should be viewed as suggestive rather than representative. That is, though other workers may obtain different results than shown here, the addition of 1% iron oxide to a given propellant mixture should increase the burn rate at modest chamber pressure by roughly 50% over the same propellant without iron oxide. The source of ingredients, mixing and packing technique, etc. are variables that may affect the final results.

The test motors were designed simply to illustrate a typical motor for that propellant; they were not optimized. In particular, the values for specific impulse may vary considerably from user to user. The motor containing slow propellant has significantly lower specific impulse than the others, but that may be the result of lower chamber pressure. Likewise, the motor containing aluminized propellant does not exhibit particularly high specific impulse, but that may be the result of several factors.[38]

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[38] Aluminum-containing propellant that uses a single size of AP tends to show *agglomeration* of the aluminum. The aluminum "clumps" into larger pieces during combustion and is not as efficient as it would be otherwise. Agglomeration is reported to be caused in part from the relatively large pockets of binder that are seen in monomodal-AP formulations. It may be reduced by using several particle sizes of AP.

SCALING DOWN AND SCALING UP

The techniques described here have been used primarily in 29 and 38mm BATES-grain motors. Of course, many workers may be interested in smaller or larger motors.

SCALING DOWN

Very small motors tend to be less efficient than larger ones. The burn characteristics of a given propellant in a 38mm motor may not translate well into an 18mm motor.

One problem in small motors arises with the tiny nozzle throats that often are required. A small throat tends to clog more readily than does a larger throat, especially with metals-containing propellant. Tiny throats also contribute to "igniter spikes". In a motor with a large throat (over 0.25"), the area taken up by the igniter wires running through the throat is insignificant compared to the throat itself. For very small throats, however, the wire causes a very significant decrease in throat area, just after ignition but before the motor can eject the wires or burn them. A smaller throat, of course, means a higher K_n. The result is an initial pressure spike[39]. The smaller the throat, the greater this effect and the greater the (momentary) increase in K_n. Very large igniter leads in a very small nozzle throat can lead to a CATO.

Some workers have reported combustion instability (chuffing) in motors smaller than 29mm, even with propellant that works well in larger motors. Propellant for such motors would be well-advised to contain metal, to minimize such instability.

Thus, the experimenter must be careful when working with small motors; they may cato or otherwise misbehave more frequently than larger ones. The author has found this to be especially true with motors using throats smaller than about 0.15". The problem can be minimized by maximizing the nozzle throat. This means using a propellant that burns at a very low K_n (high burn rate), or by employing motors that are rather long (higher propellant area).

The upshot is: the individual who wants to make "Estes-size" motors (18×70mm) in composite propellant may well find himself out of luck. Do not be surprised if a lot of the tests CATO. Most workers constructing 18×70mm motors do so using blackpowder-type propellant.

For 24mm motors, phenolic tubing ¾" id, 15/16" od, 3/32" wall is a stock item from McMaster-Carr and US Plastic Corp. Having both thicker wall and smaller i.d., this tubing appears to handle substantially higher pressure than the 1" id, 1⅛" od phenolic. Estes BT-20 body tubes make convenient casting tubing in this size. This tubing is more

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[39] Although there are many complaints about Aerotech's Copperhead igniters among rocketeers, that igniter was well-engineered with respect to this problem. The uninsulated copper foil takes up much less throat area than does a pair of 24 gauge insulated wires, and the igniter spike is less prominent, if it appears at all.

difficult to "pack" than larger diameter tubing. Rather small portions (size of a very large pea) must be rolled and packed.

Aluminum tubing is not readily available in 15/16" (virtually 24mm) od. One alternative, of course, is to use a commercial 24mm casing. Another is to obtain the more-readily-available ⅞" od aluminum tubing (¾" id) and use an adapter for 24mm motor mounts. It is practical to make G, even H-motors using this size of tubing.

SCALING UP

The largest motor constructed by the author to date is a K-motor. The author does not have the experience needed to instruct others in scaling-up motors. However...

...there is a great deal more to scaling up a motor than simply increasing all dimensions by the scale factor. For example, a 75mm M-motor has about 100 times as much propellant and total impulse as a typical 29mm G-motor. About 100 times as much heat is generated by the M-motor, much of which is dissipated by the casing and other parts. However, the surface area of the casing increases by a factor of only 10 or so over that of the G-motor. Simply put, that means that: casing strength may need to be increased disproportionately; insulation requirements often are greater than expected; nozzle strength may become a problem. All of these are non-trivial considerations. Thus, scaling up to very large motor sizes will involve considerable design work, which should not be approached by trial-and-error but by scientific forethought.

The author is not an engineer and will not attempt to cover the considerations required in scaling up. Instead, the reader may obtain the necessary information on strength of materials, heat flow, etc. from appropriate engineering texts. See the appendix for the URL of a very useful motor-design publication from DARK.

Large motors should be *designed*, *engineered*, rather than just scaled-up.

APPENDICES

WHAT IS PROPEP?

PropEP is a freeware *Prop*ellant *E*valuation *P*rogram, written about fifteen years ago by several scientists at Martin-Marietta. It will calculate certain useful propellant parameters.

What parameters does PropEP provide?

Among other things it calculates: propellant density, chamber temperature, exhaust temperature, composition of the chamber/exhaust gases, specific heat ratio, specific impulse (frozen and shifting), characteristic impulse, and density impulse. There is an option to calculate optimal nozzle expansion.

PropEP results should be viewed with caution. The equilibria used to perform its calculations are somewhat arbitrary and may be outdated (I don't know what the equilibria are and cannot speak with certainty here). And some entries in the propellant component database are erroneous. Nonetheless, I've found it to be very useful.

What is GUIPEP?

GUIPEP is a wonderful graphic interface for PropEP, written by the Landshark, Art Lekstutis. Both PropEP and GUIPEP are available at

http://www.lekstutis.com/Artie/PEP/Index.html

Thank Art profusely, as his interface has made PropEP (literally) a hundred times easier to use. Buy him a beer or ten when you see him.

How do I use GUIPEP?

Instructions for installing GUIPEP are on the web page noted above. It requires Windows 3.1 or higher and a math coprocessor. PropEP alone (w/o GUIPEP) can be run on any IBM with a coprocessor, but take my word for it, you don't want to.

The program creates an icon (shows a beaker, graduated cylinder, etc) under Windows. To use the program after installing, just double-click on that icon. After a few moments a window will appear, with ten blocks for entry of a propellant combination. A click on the arrow to the right of a block will bring down the complete list of substances available.

A default formulation loads when you run the program. For practice, run that formulation. Simply click on "Run" then "Single Run". A DOS window will appear, with some program information, and you will be prompted to "Carriage return to continue". Press "Return". Some moments later, the DOS window will disappear and the Notepad window will appear, with the results. The output should be similar to the one shown below:

```
 AP-R45            Run using June 1988 Version of PEP,
 Case  1 of  1       6 Jan 2000 at 11:29:29.11 am
 CODE                                 WEIGHT    D-H  DENS       COMPOSITION
 137 AMMONIUM PERCHLORATE (AP)          74.000    -602  0.07040    1CL  4H   1N   4O
 305 CUPRIC OXIDE                        1.000    -439  0.22780    1CU  1O
 846 R45M                               13.300     -30  0.04330  667C 999H   5O
 368 DIOCTYL ADIPATE                     7.500    -733  0.03320   42H  22C   4O
 266 CASTOR OIL                          1.600    -626  0.03460   62C 111H   9O
 742 PAPI                                2.500    -202  0.04480  224C 155H  27O  27N

THE PROPELLANT DENSITY IS 0.05909 LB/CU-IN OR  1.6356 GM/CC
THE TOTAL PROPELLANT WEIGHT IS   99.9000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   5.113044 H     1.672553 C     0.648261 N     2.652899 O
   0.629803 CL    0.012572 CU

****************************CHAMBER RESULTS FOLLOW****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY   CP/CV     GAS   RT/V
1883. 2930.   68.02  1000.00   -52.39   249.99  1.2746  4.871   13.964

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    9.222    9.223
NUMBER MOLS GAS AND CONDENSED=   4.8712   0.0000

  1.47902 CO          1.45972 H2          0.78721 H2O         0.61725 HCl
  0.32391 N2          0.19328 CO2         0.00854 CuCl        0.00130 Cu3Cl3
 3.54E-04 NH3        2.26E-04 H          1.19E-04 CH4        9.73E-05 Cu
 7.20E-05 Cl         4.55E-05 CNH        2.67E-05 Cu*        2.06E-05 CH2O
 9.87E-06 HO         2.81E-06 CNHO       2.11E-06 CHO

THE MOLECULAR WEIGHT OF THE MIXTURE IS   20.508

****************************EXHAUST RESULTS FOLLOW****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY   CP/CV     GAS   RT/V
 920. 1196.    1.00    14.70  -104.22   249.99  1.2980  4.612    0.217

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    8.621    8.605
NUMBER MOLS GAS AND CONDENSED=   4.6125   0.0263

  1.50761 H2          0.91546 CO          0.62936 HCl         0.62233 CO2
  0.49270 H2O         0.32399 N2          0.12057 CH4         0.01412 C&
 1.22E-02 Cu&        2.37E-04 NH3        1.31E-04 Cu3Cl3

THE MOLECULAR WEIGHT OF THE MIXTURE IS   21.536

**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE**********

IMPULSE   IS EX      T*       P*       C*     ISP*  OPT-EX  D-ISP      A*M    EX-T
  207.6  1.3088   1631.    37.01   4253.8             7.27  339.5  0.13224    696.
  212.5  1.2675   1662.    37.53   4339.1    168.5    8.72  347.5  0.13489    920.
```

What does all that mean?

The output looks formidable but much of the information isn't really critical to the beginning solid-propellant experimenter.

The first section lists each ingredient used, its density, its heat of formation, and its molecular formula. These come straight from the data tables of the program. It also gives the weight of each ingredient that was input for the formulation.

Next is the (theoretical, calculated) propellant density, both in lb/cubic inch and in grams/cubic centimeter. Also given is the total weight of the batch based on the amounts of materials entered.

The NUMBER OF GRAM ATOMS section gives the number of "gram atoms" (moles, for the chemistry geeks) of each element in the mixture.

The next part provides the chamber results. The chamber temperature (in Kelvin and in Fahrenheit) are given, as well as the chamber pressure (atmospheres and psi) and several other parameters. Later on you may find the specific heat ratio (CP/CV) to be a very useful quantity for various calculations. In fact, some of the CP Technologies software uses this value.

At the bottom of this section, the NUMBER OF MOLS GAS AND CONDENSED is given. This isn't particularly important in terms of motor design, but does give a rough idea of the efficiency of the propellant. The more efficient propellants will have a minimum of "condensed" (solid or liquid) material in the chamber. This particular propellant should be quite efficient since the number of moles of condensed matter in the chamber is zero. Propellants that contain thermic agents will be less efficient, as evidenced by solids and liquids present.[40]

Following this is a table listing a bunch of formulas and numbers. These are the (calculated) number of moles of each species that is in the chamber. For this formulation, when 99.9 grams of the mixture is burned, the chamber will contain 1.47902 moles of carbon monoxide, 1.45972 moles of H_2, 0.78721 moles of H_2O, etc. Most of this information is incidental; however, a "*" or "&" after an ingredient indicates a liquid or solid, respectively.

At the end of this section, the average molecular weight of the chamber species is given. This too is useful if you use the CP Technologies software.

The next section gives the same sort of information, but for the *exhaust* rather than the chamber.

Finally, the PERFORMANCE section gives specific impulse. The top number in the first column (207.6) is *frozen* specific impulse, the bottom value (212.5) is *shifting* specific impulse in seconds.[41] The "shifting" value is the one most often quoted for a propellant. To the right is the characteristic exhaust velocity C*, the characteristic specific impulse I_{sp}*, and several other parameters. C* is another way to express specific impulse; in fact,

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[40] "Less efficient" doesn't necessarily mean "lower impulse". For example, a small amount of aluminum reduces efficiency but the increased chamber temperature may more than make up for the loss of efficiency. Or not; it depends on aluminum content and on other factors as well.

[41] "Frozen" means that all chemical reactions are assumed to occur in the chamber, and no further reaction occurs until the products are past the nozzle. This is an imperfect assumption. "Shifting" means that the chemical reactions occur *instantaneously* and equilibrium is attained instantly. This too is an imperfect assumption... Note that the values generally do not differ by much.

many workers prefer to quote C* values. The characteristic specific impulse is used in the ProPel notebook to calculate motor performance.

How do I change the ingredients or enter my own formulation?

Just click on the ingredient and scroll down the list until you find the one you want. To delete an ingredient, just click on the "weight" of that ingredient, and delete the weight.

The chamber pressure and exhaust pressure entries may also be changed as desired.

How do I enter other substances in GUIPEP that aren't on the list?

1. Copy the PEPCODED.DAF file to another directory. That's just in case you mess up the way I have, and ruin the file.

2. Load the PEPCODED.DAF file into your word processor. The WP will convert the file from ASCII to its own type of file.

3. Change to a monospaced font, with small font size so that the columns line up properly. Courier New font (8 point) works well on WordPerfect.

4. Go to the bottom of the file. The last entry in my file is:

```
1097 HEXAMETHYLENE TETRAMINE 12H 6C 4N 0 0 0 236 .0481]
```

   A hexamethylene tetraamine molecule has 12 hydrogen atoms, six carbon atoms, and four nitrogen atoms. Its heat of formation is 236 calories per gram (values for heat of formation can be found in the CRC Handbook of Chemistry and Physics, among other references). Its density is 0.0481 lb/in^3. Those are the quantities needed for a new substance. The zeroes between "N" and "236" are placeholders for additional elements.

5. The next entry should be 1098, of course, so move to the next line and type "1098". Be sure to space properly to get the columns lined up. Then enter the name of your compound and the other information specified in step 4.

6. When you've entered the new substance, save the file (as an ASCII or TEXT file, not a Word Perfect or Word file!). Be sure to close that file in your word processor before running GUIPEP or you'll get an error.

If you try a PropEP run with the new file and the results are garbled, you probably messed up the file. Load the emergency copy of the PEPCODED.DAF file you saved, and try again. Been there, done that.

What does the "multiple calculation" do?

It's useful for examining effect of oxidizer-fuel ratios and such. To see how it works:

1. Run GUIPEP

2. Change the "Ammonium Perchlorate" weight to "69.1"

3. Click on the empty box below the PAPI entry. Scroll down and click on "Aluminum (Pure Crystalline)".

4. Click on the "Weight" column and enter "5". Now you have a formulation that is 5% aluminum.

5. Click on "Run" then "Multiple Run". A new window (Variable Selections) will appear.

6. Click on the "Ammonium Perchlorate" entry under "X-dimension". A list of ingredients will appear; click on "Aluminum"

7. Click on the "Maximum %" box and enter "30".

8. Click on the "Number of" box and enter "6".

9. Click on the "Calculate" button. GUIPEP will go through its routine. You will see it calculate run 1 of 6, etc., then the Windows Notepad will appear.

10. Scroll down through the notepad. You will find the results of six successive runs. The first will have 5% Al, the last will have 30%. The remaining ingredients will have been scaled back so that the total each time is 100%.

Look at the specific impulse for each of the six runs. You will find that this particular mixture produces maximum I_{sp} at about 15% aluminum (about 248 seconds). Past this percentage, the increased temperature provided by the aluminum apparently is offset by the increased amount of solid and liquid aluminum oxide (and other species) in the exhaust.[42]

I got a density of zero (or other low number) for my propellant. What happened?

Probably have at least one ingredient has an entered value of zero for density. Go to the PEPCODED.DAF file and change that density to its correct value. Densities of many substances can be found in the CRC Handbook of Chemistry and Physics, the Merck Index, and other chemical references.

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[42] It's worth noting that the best impulse isn't necessarily the best practical performance, especially in model and hobby motors. Standard black powder (75/15/10 potassium nitrate, charcoal, sulfur) is much lower in impulse than, say, an 85-15 mixture of KN and charcoal. But standard black powder performs better in endburning motors, because it burns faster than the 85:15 mixture of KN and charcoal.

I see only one entry for ammonium perchlorate. Doesn't the particle size matter?

The particle size certainly affects the burn *rate*. But PropEP and GUIPEP have nothing to do with burn rate (nor burn rate coefficient, nor burn rate exponent), so the particle size makes no difference in PropEP.

There are several entries for R45 (and for PBAN, Al, Mg). Which one do I use?

For R45 the entry labeled "R45 HTPB (UTC)" has density closest to that of HTPB that is commercially available, and its heat of formation is comparable to that published elsewhere. For PBAN the first "POLYBUTADIENE/ACRYLONITRILE CO" entry is used for the same reason (the density I have measured for PBAN is 0.0340 lb/in^3). For aluminum and magnesium use the "Pure Crystalline" entries. The "non-reactive" entries will give the correct density but incorrect impulse and other parameters, because they assume that the metal does not react.

There's no entry for Tepanol, DER331 epoxy, PSAN, 2-ethylhexyl acrylate, etc. What do I do?

Generally, the lower the amount of a component, the less important its effect will be. Most substances present in less than 1% can generally be omitted from GUIPEP runs. So it's probably safe to omit Tepanol, PDMS, lecithin, etc. entirely, or just substitute that amount of extra HTPB or PBAN in the calculation.

For DER331 epoxy the "EPOXY 201" entry may be used. CP Technologies' phase-stabilized ammonium nitrate (PSAN) is about 3% nickel complex, so for a formulation that is, say 60% PSAN, two entries could be used, "AMMONIUM NITRATE" and "NICKEL OXIDE". Make the nickel oxide 1.8% (3% of 60%) and the ammonium nitrate 58.2% (the remainder of that 60%).

For 2-ethylhexyl acrylate or other ester plasticizers, you're probably safe to substitute dioctyl adipate or dibutyl phthalate. Most such plasticizers are fairly similar in structure and will give similar results in Propep.

For Isonate 143, use the "PAPI" entry. IPDI is in the file already. DDI-1410 is listed under "DI-ISOCYANATE (DDI)." Oxamide is listed as "OXAMID (B.LEE)".

How do I get burn rate coefficient and exponent from GUIPEP?

One more time: You don't. Sorry. GUIPEP gives thermodynamic (heat, energy) results. Burn rate coefficient and exponent are kinetic (rate) data. The two are largely unrelated.

To get burn rate coefficient and exponent, the propellant must be burned, and the burn rate measured.

THE PROPEL NOTEBOOK

This book was accompanied by a diskette with Excel or Quattro Pro version of ProPel 2.0. This "notebook" has a dozen or so pages designed to make propellant and motor calculations easier. It's assumed that you already know how to use a spreadsheet. If not, you'll find it's not hard to learn.

Run Excel or Quattro Pro, then select "FILE" and "OPEN". Select your floppy disk as the source, and open the ProPel notebook that comes up.

Important: save ProPel on your *hard disk* immediately, and remove the floppy disk from your drive. It's quite possible to accidentally erase or overwrite some of the formulas in the notebook, and if you don't have the original notebook you're up the creek.

Using these notebooks is largely a matter of entering data in the boxes ("cells") that have blue text, and reading the results the spreadsheet calculates.

THE BATCH SHEET

This sheet allows scaling up (or down) of a successful batch of propellant. As an example, let's assume that four "sticks" of the simple propellant are to be made. Two sticks will be 0.93" inside diameter and 17" long each, and a ⅜" mandrel will be used to form a core in each. One stick will be 1.28" in diameter and 14" long, with a ½" mandrel. The last will be 0.93" diameter, 17" long, and will be solid, to be made into D-slot grains.

Moving from top to bottom: start by typing in a propellant designation; "Simple" is ok, or any other name you want to give the propellant. Then enter the propellant density in lb/cubic inch (don't put the units in the box, just the value). For best results, use the density for *your* propellant. Non-vacuum-processed propellant generally has a density about 90% of the density calculated by PropEP. Let's assume that you obtained a density of 0.054 lb/in^3 without vacuum processing on the first batch, so enter a density of 0.054.

Now enter the size of the grains to be cast. For grain #1 enter 0.93 for the diameter, 17 for the length, 0.375 for the core (mandrel), and 2 for the number of grains. For grain #2 enter 1.28 for the diameter, 14 for the length, 0.5 for the core solid grain, and 1 for the number of grains. For grain #3 enter 0.93 for the diameter, 17 for the length, 0 (zero) for the core, and 1 for the number of grains.

The "Expected waste, %" is a guess as to how much propellant stays in the bowl or on the mixer blade, etc. For first attempts 2% waste may be reasonable. If you're really neat and take great care, 0.5% may be ok[43]. For this exercise, enter 1 for the expected waste percent.

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[43] Being a good Scot, I rarely leave more than a couple of grams of unused propellant mixture in the bowl...

Several ingredients have already been listed on the sheet. You may want to delete the extra ingredients to avoid confusion. Go to the first "Ingredient" cell ("Ammonium perchlorate 400 um") and press the "delete" key. Move below the "Ammonium perchlorate 200 um" entry, and delete the names of all the ingredients after it, since we won't need them.

Now type "Lampblack" in the cell just above "Ammonium perchlorate 200 um". Move down eight cells (to cell A22), and type "PBAN". Move down one more cell and type "Epoxy DER331".

Actually, the spreadsheet will give the right ingredient amounts if the four ingredients are simply typed in the first four cells below "Ingredients". But the "Percent solids" won't be correct. So do it the way I told you to.

Move to the far right column labeled "Original Batch: Weight". In this column, data from a successful batch of the propellant is entered. We'll assume that the first run of the simple propellant cured properly (as given in Table III). Enter 0.2 in the first cell of this column; that was the percentage of lampblack. In the second cell, enter 79.8 for the percentage of AP. Enter 0 (zero) in each cell below that one, until you come to cell E22; it's in the same row as your PBAN entry. Type 16.4 in that cell, and press "Enter". Move down to cell E23 and enter 3.6. Delete the entries in cells E24 to E29.

Essentially, you're done.

In the column labeled "Needed this Batch" you will find the amount of each ingredient to weigh. The "Percent Solids" cell (B33) will be correct *as long as* you entered only solids in cells E14 through E21, and liquids in E22 through E29.

If you've done everything correctly the sheet should look like the one in Table VI.

It is not necessary to use numbers that will add up to 100 in the "Original Batch" column. Suppose that in your first successful batch of propellant you used 0.7 grams of carbon black, 277.2 g of 200 micron AP, 59.4 g of PBAN, and 10.1 g of epoxy. Simply enter those numbers in the "Original Batch" column. Once these values are entered, you will find the percentage of each ingredient at the right of the "Original Batch" column.

The "Actual used" column is useful for a printout. Some workers print such a sheet and tape it into the permanent notebook. The amounts of the ingredients used are then entered in the "Actual used" column as they are weighed. That provides a permanent record of each batch. The "Preparation Steps" are there to be filled in as well, if you want to indicate the mixing time, temperature, changes in procedure, etc. Of course you can change those preparation steps as you like.

Propellant designation	Simple	
Propellant density	0.054	lb/in^3

GRAINS TO BE CAST

	Grain #1	Grain #2	Grain #3
Diameter	0.93	1.28	0.93
Length	17	14	17
Core (mandrel) dia.	0.375	0.5	0
Number of grains	2	1	1
Expected waste, %	1		

Ingredient	NEEDED THIS BATCH	Actual Used:	Original batch: Weight	Percent
Lampblack	2.28		0.20	0.2%
Ammonium perchlorate 200 um	910.73		79.80	79.8%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
PBAN	187.17		16.40	16.4%
Epoxy DER 331	41.09		3.60	3.6%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
	0.00			0.0%
Total wt.	1141.26		100	
Percent solids	80.00%			

PREPARATION STEPS	DATA AND COMMENT
Mix liquid ingredients	
Add metals	
Add curative	
Vacuum process	
Cure	

Table VI: Sample of BATCH spreadsheet from ProPel

THE COREROD SHEET

If you use the technique described in this book for inserting mandrels into the propellant, you will need to know how full to fill the propellant tubes. The "Corerod" spreadsheet tells how full to fill the tubes. This way they will not overflow when coring rods are inserted.

For example, if you enter the two cored grains noted above (0.93 dia, 17 long, 0.375 core, and 1.28 dia, 14 long, 0.5 core) you should see the following:

Grain diameter, in.	0.93	1.28
Total grain length, in.	17	14
Core rod dia., in.	0.375	0.5
Fill this tube to the following depth (in) before inserting core rod	14.2	11.9

Table VII: Sample of the "Corerod" spreadsheet

which means that the 0.93" diameter tubes should be filled to about 14" deep (3" short of the top) while the 1.28" tube is filled about 2" short of the top. It's probably easier to fill a little less than to overfill. It isn't hard to add a little bit of propellant to the top of a cored grain, if needed to fill it completely.

THE K_N SHEET

This calculates the *INITIAL* value of K_n for a given motor design, or it can calculate the nozzle throat needed for a particular K_n. Again, just fill in the spaces with blue text.

The sheet below shows nozzle throats for three grain motors, 0.93" × 1.5" × 0.375" core, for K_n of 180 and 220.

Number of grains	3	3
O.D. of propellant	0.93	0.93
Dia. of core	0.375	0.375
Length of each grain	1.5	1.5
Desired K_n	180	220
Nozzle throat (inches)	0.2483	0.2246
OR in 64ths inch	15.89	14.37

Table VIII: Sample of the K_n spreadsheet

The "64ths inch" result tells that the first nozzle could be drilled 15/64", then reamed to size. CAUTION: K_n calculated by this spreadsheet is the *INITIAL* K_n. For neutral grains K_n will not vary much over the burn. BATES grains that are more than about 1.5 times longer than their diameter may produce an increase in K_n, which produces a progressive motor (depending on the nozzle and on erosive burning). Grains that are too long can cause a CATO due to increasing K_n during the burn.

THE DENSITY SHEET

The density of propellant is a measure of quality control and satisfactory procedure; the better the procedure, the more dense the propellant will be, and the more uniform its density will be. Also, vacuum-processed propellant will have a higher density than non-vacuumed propellant.

The direct way to find density is to cut up propellant into small chunks that will fit into a small (25 mL) graduated cylinder. At least 25 grams of propellant should be used for accuracy. Weigh this dry propellant and enter the weight in "Weight of propellant added to cylinder".

Now fill the graduated cylinder partway with water, to around 10-15 mL. Enter this initial volume in the "Volume of water initially" cell. Carefully drop in the pieces of propellant; don't splash or you'll lose water and accuracy. Tap the cylinder to remove any air bubbles. Now enter the new volume reading in "New volume of propellant and water together". The density of the propellant will appear as shown below:

Volume of water initially	7.2	milliliters
Weight of propellant added to cylinder	25.5	grams
New volume of propellant and water together	24.8	milliliters
Density	1.4489	grams/mL
	0.05234	lb/cu.in.

Table IX: Sample of the upper part of the "Density" spreadsheet

There is an error associated with this sort of density determination. The AP on the surface dissolves in the water. This reduces (slightly) the volume that should be seen. Professionals often use carefully-prepared liquids of various known density for density determination. Bits of the propellant are dropped in the different liquids; they will float in more-dense liquid, sink in less-dense liquid.

For the experimenter, an alternative that is easier and nearly as accurate is provided in the lower part of the "Density" spreadsheet. It requires only the weight and dimensions of a propellant grain, and the weight and dimensions of an empty casting tube. In the example below, a 24" length of casting tube was found to weigh 27 grams. A grain made in this casting tube, 0.93" id, 2" long, 0.375" core, weighed 30.62 grams.

Length of paper casting tube	24	inchesTubing weight is	1.125	grams/inch
Weight of paper casting tube	27	grams		
O.D. of propellant (i.d. of tube)	0.93	inches		
Diameter of core	0.375	inches		
Length of grain	2	inches		
Weight of grain	30.62	grams		
Density	1.522	grams/mL		
	0.05497	lb/cu.in.		

Table X: Sample of the lower part of the "Density" spreadsheet

There is an error inherent in this type of calculation, too. Some of the binder will soak into the paper tubing during processing. That binder, of course, isn't actually in the propellant anymore. Thus, the propellant in the grains is actually a little *higher* in solids than it was when it was made. So the density of the propellant will actually be a bit *higher* than is calculated here. However, this underestimation of density is probably preferable to *overestimating* density. A propellant with too-low density may cause a CATO.

THE BALLISTIC SPREADSHEET

This spreadsheet does the tough work of calculating burn rate coefficient (a) and exponent (n) of a propellant. It requires the burn times of two or more neutral motors at different K_n. The greater the difference in K_n, the more useful will be the ballistic parameters obtained.

Professionals usually use endburning ballistic evaluation motors for this purpose. For the experimenter, this is rather difficult. Small endburning motors are subject to clogging of the (very tiny) nozzle, so that endburners for ballistic evaluation must be quite large (4" dia or larger) for reasonable nozzle throat size. Such motors are expensive to make. However, the grain need not be extremely long; a 4" diameter motor with a 1-2" long endburning grain is sufficient for a fair bit of testing. So if you're planning to make and characterize a bunch of different propellants, an investment in hardware suitable for this purpose might be a good idea.

The BATES grain motor is an alternative to endburners for this sort of characterization. For best characterization, the grains should be as large in diameter as is practical; this maximizes burn time. At the same time the core should be rather large, to eliminate erosive burning and to "flatten" the burn as much as possible. The author has found the values for a and n obtained by this method to be accurate enough for motor design, though they are likely to be less accurate than those obtained by more conventional technique.

A camcorder is used to record burn time. Don't even think about using a stopwatch; it's just not accurate or precise enough. Most camcorders record 30 frames per second. That gives a resolution of about ±0.03 second. The burn is timed from the frame that shows almost-full thrust, to the frame that shows a tail about half that length or a bit less.

For best accuracy the values of K_n for the test motors should be spread over the widest possible range.

As with the other spreadsheets, it's just a matter of filling in the cells with blue text. The run below was from two single-grain motors using the simple propellant. The first motor was a 38mm motor with 1.28" grain 2 ¼" long, with 0.5" core and 0.200" nozzle throat. It burned for 1.45 seconds. The second motor was a 54 mm motor with 1 7/8" grain 3" long, with 0.5" core and 0.21" nozzle throat; it burned for 2.05 seconds. The measured propellant density was 0.055 lb/cubic inch.

Note the value of propellant I_{sp} in this spreadsheet. The value to use is the so-called *characteristic* I_{sp} (I_{sp}*) given by PropEP. See the appendix for PropEP results for the simple propellant (see the last row of the Propep printout).

TEST MOTOR DATA		Motor 1	Motor 2	
	Grain dia	1.28	1.875	inches
	Grain length	2.25	3	inches
	Core dia	0.5	0.5	inches
	Number of grains	1	1	
	Nozzle throat dia	0.2	0.21	inches
	Propellant Isp	187.2	187.2	seconds
	Density	0.055	0.055	lb/cu.in.
	Burn time	1.45	2.05	seconds
PROPELLANT RESULTS				
	Burn rate	0.269	0.335	in/sec
	Kn	181.9	284.2	
	Chamber pressure	503.8	981.2	lb/sq.in.
	Burn rate coefficient		0.0343	
	Burn rate exponent		0.3310	

Table XI: Sample of the "Ballistic" spreadsheet

There is an error inherent in this spreadsheet, too. As you now know, specific impulse depends on chamber pressure. The value of I_{sp}* used here is the value for 1000 psi chamber pressure. But the spreadsheet *uses* I_{sp}* to *find* chamber pressure, and it is unlikely that *that* chamber pressure will be precisely 1000 psi.

The calculation here assumes that I_{sp}* at 1000 psi is a reasonable value for I_{sp}* at other chamber pressures. To avoid the assumption would be a bit difficult. However, the error of measurement of burn time (by the user) is generally greater than any error introduced by this assumption. In other words, don't worry about the error in the calculation until the error in measuring burn time is minimized.

For more reliable values of coefficient and exponent, more motor tests are required. The lower part of the spreadsheet allows entry of up to ten motor tests.[44] To do this, you must know how to use the "regression" part of your program. There are different directions for this with Excel and with Quattro, so I won't go over them here. Suffice it to say that the values that are calculated for "log pressure" are used as the *independent* (X) variable, and the values calculated for "log rate" as the *dependent* (Y) variable. Consult your Quattro or Excel manual or "Help Menu" for further information.

THE BATESBURN SPREADSHEET

This spreadsheet is designed to model (approximately) a coreburning or BATES motor. The burn rate coefficient, burn rate exponent, I_{sp}*, propellant density, and motor dimensions are required. If a nozzle erodes during the burn, that erosion should be entered as well.

The density should be the measured density of the propellant, rather than the theoretical density from PropEP. For nozzles that erode, the throat erosion can be found by measuring the nozzle

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[44] The tests may be of different motors, or several may be duplicated. But the wider the range of K_n used for the tests, the more accurate the final results will be.

throat, timing the burn, and measuring the nozzle afterward (insert drill bits until one is found that just fits the eroded nozzle). For example, a nozzle which is 0.193" dia initially, and 0.219" dia after a 0.85 second burn has an erosion rate of:

0.219 - 0.193 = 0.026 inches / 0.85 seconds = 0.031"/second

For nozzles (graphite) that do not erode significantly, enter zero for the nozzle erosion.

This spreadsheet does not automatically calculate the correct values. A bit more action is required by the user. In the Quattro version of ProPel, the "F9" key is pressed several times after entering the parameters. Watch the value of initial pressure (or initial burn rate); when pressing F9 no longer changes this initial pressure, the values are correct (Quattro allows "circular" calculations and if this procedure is followed, it will calculate the initial pressure and other factors).

Excel does not allow circular calculations, and so the Excel version requires that an initial pressure be entered. This isn't hard. Just pick a pressure (say 500 psi) and enter it in the first space below the "Pressure psi" column. The sheet will calculate the remaining values. Now compare the initial pressure you picked to the pressure value just below it. If your initial guess is much lower than that second value, try a new, larger value for the initial pressure. If your initial guess is much higher than the second value, try a smaller value for the initial pressure. Keep changing the initial pressure until the pressure that follows is about the same (perhaps 5 psi larger, for a BATES motor). Then the values that follow should be reasonably accurate.

The sheet in Table XII shows the result from a four-grain 29mm motor with an eroding nozzle. The "middle" of the sheet has been cut out. Move down to where the "core dia" is 0.930" (that row is in italics). At this point the propellant core has reached the wall -- the burn is over. At the right you will see the burn time, 1.30 seconds. Moving right you will see the final nozzle throat size (0.350"), final K_n (175.5), ending thrust (33.9 lb), final burn rate (0.195 in/s), and total impulse in lb-s (46.8) and in N-s (208.3) for this motor.

The thrust and total impulse deserve some mention. Both have been calculated for a motor with no exit cone. As noted earlier, we use I_{sp}* in these calculation to insure that the pressure is correct. If you want to see the *approximate* contribution of the nozzle, enter an approximate value for the correction factor. If your propellant tends to deliver I_{sp} = 210 s, and I_{sp}* for the propellant is 187, then

Correction = 210 / 187 = 1.12

The corrected thrust and total impulse are shown at the right of the spreadsheet.

Keep in mind that this spreadsheet is meant only as an approximation. It will not show, for example, the tailing-off that really occurs in most Bates motors. Nor does it model erosive burning; the motor shown in Table XII would probably deviate from the predicted performance due to erosion. For proper thrust curves, a better model or a thrust stand is required.

The last few pages of ProPel are the same as the "Batch" page. These are provided that you may save your own commonly-used formulations.

Isp*	187	sec	Grain dia	0.93	in
Density	0.055	lb/cu.in.	Grain length	2	in
Burn rate coeff.	0.025		Core dia	0.375	in
Burn rate exponent	0.35		Number of grains	4	
			Nozzle throat dia.	0.285	in
			Nozzle erosion rate	0.05	in of dia. per sec.
			Correction factor	1.12	
			Propellant weight	113.53	grams

Time sec	Pressure, psi psi	CORE DIA (in)	GRAIN LENGTH (in)	NOZZLE THROAT (in)	Kn	THRUST lb, uncorrected	BURN RATE (in/s)	TOTAL lb-s	IMPULSE N-s	(corrected) N-s	THRUST (corrected) lb
0.00	494	0.375	2.000	0.285	219.1	31.5	0.219	0.0	0.0	0.0	35.3
0.01	494	0.379	1.996	0.2855	219.4	31.6	0.219	0.3	1.4	1.6	35.4
0.02	495	0.384	1.991	0.286	219.7	31.8	0.219	0.6	2.8	3.2	35.6
0.03	496	0.388	1.987	0.2865	219.9	32.0	0.219	1.0	4.2	4.8	35.8
0.04	497	0.393	1.982	0.287	220.2	32.2	0.220	1.3	5.7	6.4	36.0
0.05	498	0.397	1.978	0.2875	220.4	32.3	0.220	1.6	7.1	8.0	36.2
0.06	499	0.401	1.974	0.288	220.7	32.5	0.220	1.9	8.6	9.6	36.4
0.07	500	0.406	1.969	0.2885	220.9	32.7	0.220	2.3	10.0	11.2	36.6
0.08	500	0.410	1.965	0.289	221.1	32.8	0.220	2.6	11.5	12.9	36.8
0.09	501	0.415	1.960	0.2895	221.3	33.0	0.220	2.9	12.9	14.5	36.9
0.1	502	0.419	1.956	0.29	221.5	33.1	0.220	3.2	14.4	16.1	37.1
~~	~~~~~~	~~~~~~	~~~~~~	~~~~~~	~~~~~~~	~~~~~~	~~~~~~	~~~~~~~	~~~~~~~	~~~~~~~	~~~~~~~
1.24	365	0.906	1.469	0.347	179.8	34.6	0.197	44.7	199.1	223.0	38.7
1.25	363	0.910	1.465	0.3475	179.1	34.4	0.197	45.1	200.7	224.8	38.6
1.26	361	0.914	1.461	0.348	178.4	34.3	0.196	45.4	202.2	226.5	38.5
1.27	359	0.918	1.457	0.3485	177.7	34.2	0.196	45.8	203.7	228.2	38.3
1.28	357	0.922	1.453	0.349	177.0	34.1	0.196	46.1	205.2	229.9	38.2
1.29	354	0.926	1.449	0.3495	176.3	34.0	0.195	46.5	206.8	231.6	38.1
1.3	***352***	***0.930***	***1.445***	***0.35***	***175.5***	***33.9***	***0.195***	***46.8***	***208.3***	***233.3***	***38.0***
1.31	350	0.933	1.442	0.3505	174.8	33.8	0.194	47.1	209.8	234.9	37.8
1.32	348	0.937	1.438	0.351	174.1	33.7	0.194	47.5	211.3	236.6	37.7
1.33	346	0.941	1.434	0.3515	173.4	33.5	0.193	47.8	212.8	238.3	37.6

Table XII: Sample of the "Ballistic" spreadsheet. Middle rows deleted. Burn time is 1.30 seconds

A SIMPLE CURING BOX

For curing propellant, a container is required that will hold the temperature of about 140°F for several days. Such a box need not be elaborate or expensive. The curing box shown here was a "scrounge" job, made largely from material on hand. The box itself is ⅜" plywood, 16" square and 30" tall. It is covered on all four sides with 2" styrene foam insulation, glued in place with expanding polyurethane foam ("Great Stuff" is one such brand). The top is ¼" acrylic and is the "door"; it is merely lifted off for access.

In each corner a 1" square furring strip was glued for nailing. Polyurethane glue was used for assembly to avoid the potential problem of white glue softening from the heat.

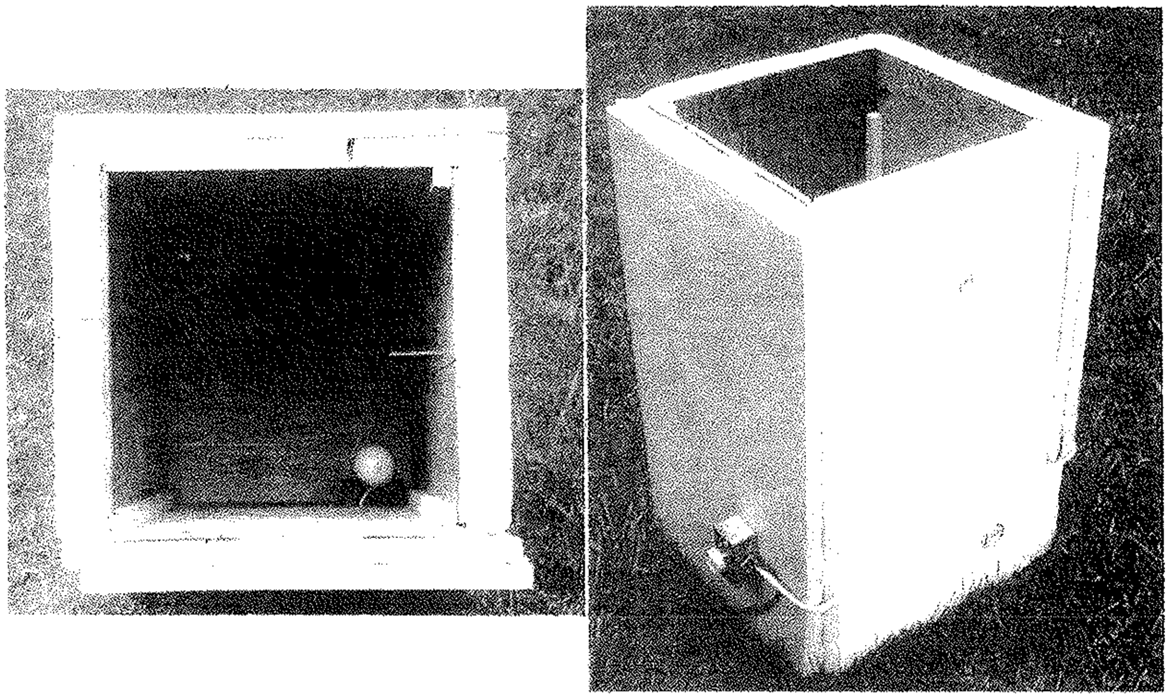

Figure 36: Top and side views of a curing box constructed by the author.

The "heating elements" are an ordinary 40 W incandescent bulb near the top, and a 100W bulb near the bottom, mounted in *ceramic* sockets. Each bulb is surrounded by a piece of 4" phenolic tubing, to minimize the possibility of a hot bulb contacting propellant (one such piece was accidentally broken off in the photo above). In the box constructed, these heating elements result in a "low" temperature around 120°F and a high of over 180°F. If that range is too high, 25 and 75 watt bulbs might be substituted.

An ordinary light dimmer switch is used to control temperature. A thermostat would undoubtedly be better, but the setup shown keeps a constant temperature (within 5°F) over a four-day period. Two meat thermometers are mounted, near the top and near the bottom. Temperature variation top-to-bottom is about 5°F or less, but this depends in part on insulation on the top and bottom. In fact, if the bottom is too cool, a layer of foam could be added there or removed from the top as needed. A small *sparkless* fan would likely keep temperatures more uniform. A couple of layers of aluminum foil may be placed in the bottom of the curing box, to catch drips.

This box requires a lengthy warmup time. It should be turned on at least 48 hours before it is to be used, and the control adjusted as needed to produce the desired temperature. Since the box as shown doesn't use a thermostat, there will be variations in internal temperature with outside temperature. Once a satisfactory setting for the dimmer switch is determined, that setting should be marked (though it may vary somewhat with the outside temperature) and it should not be changed unless absolutely necessary.

CAUTION: although the author has used such a curing box for over a year, there is no guarantee that it will not start a fire (i.e., if a bulb bursts or a short circuit occurs). To minimize danger, the curing box should be located in a remote area. Do not place material that will "dust" (powdered metal, oxidizer, etc.) in the box. Appropriate caution should be exercised to avoid overheating propellant.

USING CORING RODS

In well-cured, firm composite propellant, a drill can produce a beautiful round smooth core. But drilling is time consuming and the shavings present an easily-ignited hazard, not to mention the loss of propellant as scrap and the possibility of friction ignition. And the hard propellant needed for drilling is more likely to crack than a flexible propellant. Molding the core using a coring rod or mandrel is an attractive alternative to drilling. It will be assumed here that round cores are being used, though other shapes can be molded as well.

Coring rods *MUST* be made of a non-sparking material; aluminum or brass are good choices. Teflon isn't as good; in diameters under ½" it bends and flexes too much and the core is often off-center. Also, Teflon is often marred by the knife used to cut grains in the technique described here. For larger coring rods, heavy-wall PVC pipe is recommended by some workers. If a precise core diameter is required the core may be molded undersize and drilled to the correct size.

The coring rod must be at least an inch or so longer than the tube to be filled. One end of the rod is filed or turned to a tapered round point, like a very blunt pencil. The taper length should be about the diameter of the coring rod.

For each casting tube of propellant to be filled, a special plug will be needed. Figure 37 shows a plug for a casting tube 0.93" id and 0.95" od. Plug length is not critical; about an inch in smaller diameters is sufficient. Aluminum and graphite are useful materials for these plugs. Graphite can be cleaned afterward simply by "burning it off" in the propellant scrap box. The inside of the plug is tapered (using a countersink) so that the coring rod will slide into place more easily. The drilled hole must be slightly larger (perhaps a few thousandths) than the coring rod.

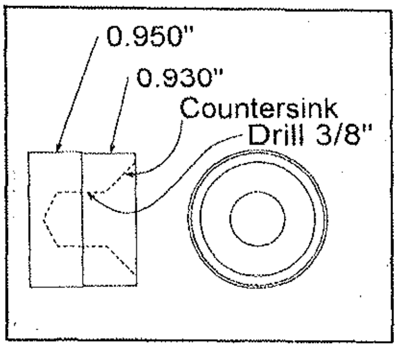

Figure 37: A coring-rod plug for 29mm casting tubes 0.93" id, 0.95" od.

One-hole rubber stoppers have been successfully used as plugs, but the bottom of the hole must be taped or plugged carefully to avoid leaks. Turned metal or graphite plugs are more convenient.

For propellant grains to fit 54mm motors and larger, the coring rod can be placed in the hole of the plug, and propellant may then be packed around the rod with a small packing stick. For smaller motors a different technique is necessary. The following can be used only with propellant that will "give" sufficiently when the coring rod is inserted (all the formulations given in Table V have been cored using this technique). It is probably best to practice with fairly short tubes of propellant first, gradually working up to longer tubes.

1. The casting tube is slid onto the plug (it should be a fairly tight fit). Two layers of masking tape are wrapped TIGHTLY around the joint between plug and tube, to prevent leaks.

2. The coring rod is inserted in the casting tube and into the hole of the plug. The rod is marked where it comes out of the casting tube, as shown in Figure 38. That's about the depth to which the coring rod will need to be forced.

3. The tube is packed with propellant as usual, except that it is not filled completely. The "Corerod" spreadsheet of ProPel will calculate about how full to pack the tube. When in doubt, pack less; it's not hard to add a little more to the top of the tube once the rod is in place.

4. The tube of propellant mix and the coring rod are placed in the cure box for an hour or so, until they've come up to temperature (note: for faster-curing propellant this may be too long).

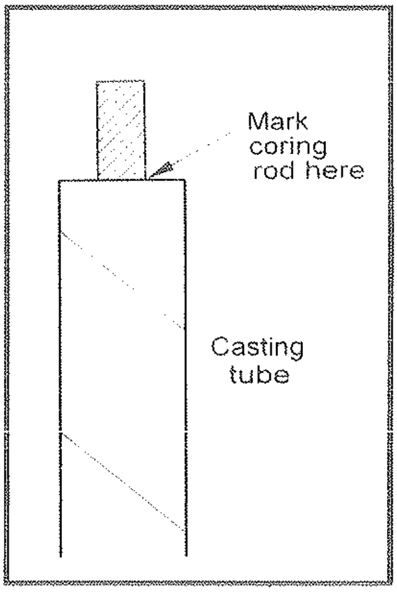

Figure 38: Marking the coring rod for depth.

5. The end of the coring rod is held with locking pliers and the rod quickly coated with release agent. Some workers use "Pam" or other nonstick cooking spray. Others use silicone spray, a very thin coating of silicone grease, or a commercial release agent.

6. The propellant tube is removed from the box and stood on the floor or bench (depending on its length), holding near the top with the left hand. The locking pliers are held in the right hand.

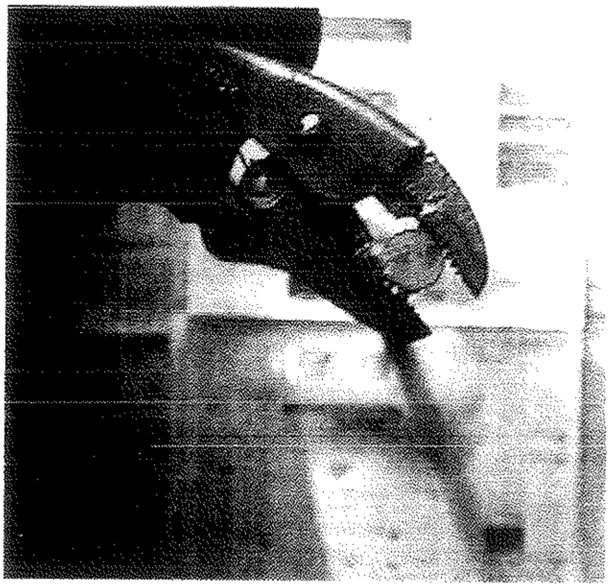

Figure 39: Sighting down the coring rod to keep it centered. The propellant tube is not visible here because the coring rod is centered over it.

7. While sighting down the coring rod, the rod is *slowly* slid into the center of the propellant, as in Figure 39. The objective is to get that rod into the hole at the bottom, while keeping the coring rod centered or nearly centered at the top. It sounds impossible but it just takes some practice. Do not force too hard, or the casting tube may split. If the propellant mix is up to temperature, the rod slides down fairly easily using a little more than the weight of the hand and arm.

8. When the rod hits the plug at the bottom, it may not go into the drilled hole at first. The tube is stood on the bench and the locking pliers are turned back and forth slightly to twist the rod back and forth. If the tube is fragile it is held at the bottom

(it may split or tear if held in the middle). Usually within a few moments, the rod will slip into the hole. You will know when this happens as the rod will drop just a bit, (almost) reaching the mark that was made earlier. Again, practice with short tubes of propellant will make things easier.

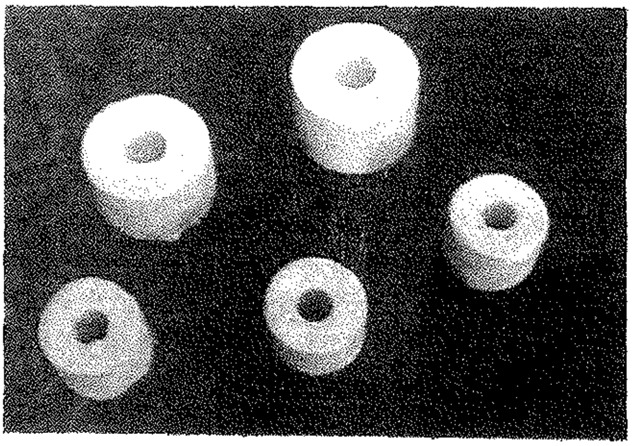

Figure 40: A centering plug can be used to keep the top of the coring rod centered after the rod is in place.

9. The coring rod is centered at the top and taped into place. Centering fixtures (Figure 40) that are nothing more than "one-hole rubber stoppers" can be made by casting a length of stiff PBAN-epoxy in a casting tube, with coring rod taped carefully and neatly in place. After cure the piece is cut into short lengths which are soaked in water to strip off most of the casting tube. These slide nicely over the coring rod and into the casting tube.

10. The propellant is cured as usual. With less epoxy, cure time generally will be longer.

11. When the propellant is cured, it is removed from the box and allowed to cool to room temperature. The propellant is cut into grains while still on the coring rod. Try not to score the rod too badly. After the cuts have been made, the end of the rod can be clamped into a vice and the grains removed one by one, by twisting each grain back and forth, a little at a time, until the grain breaks free. The grain is then slid slowly off the rod (see the cautionary statement at the end).

If your hands are as weak as mine, you may need something better to grab & twist the grains. A pair of gloves with rubber gripping surface on the palms may help. For small grains that are hard to grip, silicone caulk may be molded into a tube, using ¾" PVC pipe as a mandrel. The pipe is wrapped with polyethylene plastic wrap first, the silicone is applied and smoothed out a bit, then this objet d'art is allowed to cure several days. It is then sliced down the side with a sharp knife and used as a gripper.

Don't get too macho while twisting the grains. Thin casting tubing may tear under rough treatment.

Some workers like to cool the propellant to ice temperature (not in the home refrigerator, please!) before removing the grains from the coring rod. This reduces the sensitivity of the propellant to ignition.

In the author's experience, PBAN propellant containing iron oxide, copper oxide, or aluminum tends to be a bit "cleaner". It is easier to cut, and comes off the coring rods more cleanly.

Very long tubes of propellant may bend a little with this technique, causing the core to be off-center in the middle of the tube, and centered at the ends. To alleviate this, shorter sticks of propellant may be cast, or the casting tube can be slipped into a liner tube and/or motor casing to keep the tubing rigid during the curing process.

FORMULATIONS AND CORING RODS

Generally, a formulation which is to be cored with coring rods can be somewhat more flexible than a formulation that is to be drilled. For the initial trial of the simple propellant, a ratio of 32 parts PBAN to 7 parts DGEBA epoxy was recommended because the propellant was to be drilled. When using coring rods, a ratio of 32 parts PBAN to *5* parts epoxy (or possibly less, depending on individual results) may be more satisfactory. This corresponds to 17.3% PBAN and 2.7% epoxy for a propellant that is 80% solids. If System 3 epoxy is used instead of DGEBA epoxy, a good starting point might be 32 parts PBAN to 7 parts System 3 epoxy (with coring rods). Some experimentation may be helpful in establishing the cure ratio.

CLEANUP

A thin layer of propellant may stick to the coring rod in spite of all efforts. A good steel-wool soap pad will remove it, though it may take some work. A slight odor of ammonia from the core rod while cleaning is normal.

SAFETY NOTES

Removing propellant grains from a coring rod creates a *lot* of friction. It is possible for sensitive propellant to ignite[45]. Commercially, core-stripping is performed remotely. For the experimenter, welding gloves are not an unreasonable precaution.

Some experimenters use coarse titanium in propellant formulation. For such propellant coring rods MUST be used. Drilling propellant that contains titanium is a recipe for disaster; titanium can throw sparks when mixtures containing it are drilled.

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[45] This has never happened to the author. On the other hand, the most sensitive mixture this author has made contained about 1.5% copper oxide, 5% aluminum, and mostly 200 and 400 micron AP -- not particularly sensitive by some accounts. Use caution...

NOZZLE CONSTRUCTION

First and foremost: generally speaking, making nozzles without a metalcutting lathe may be an exercise in frustration for many. Tolerances for nozzles are rather tight in small sizes. The individual who does not own a lathe may want to buy the nozzles instead.

For machined or reuseable nozzles the #1 choice is *graphite*. Graphite is messy to machine and tends to stain that which it touches, but it stands chamber temperatures and hot exhaust with little or no erosion. This author generally loses a graphite nozzle by CATO or by cracking before it is worn out. There are several grades of graphite, labeled with strange characters that don't seem to mean much. AJT grade graphite seems to be something of a standard, but most grades of graphite will work for nozzles, though some are less durable than others.

Graphite may be purchased in soft or hard grades. Soft will erode more rapidly but is much easier to machine. Hard will last longer but requires carbide-tipped tools. If you lose nozzles by CATO or by rocket loss as often as this author, soft graphite may be preferable.

A proper dust collection system is REQUIRED when machining graphite. Not only is the dust hazardous to breathe, but graphite is conductive, and graphite dust can short out a lathe motor in jig time (ask me how I know...). There is a system sold in some large hardware and home-supply stores that is used for collecting dust from drywall sanding. It is essentially a 5 gallon bucket with two holes in the lid. One hole connects to a vacuum cleaner; the other is connected to a hose and from there to the lathe. The bucket is filled with water (add a few drops of soap) which traps dust. Such a system ought to be easy for the experimenter to set up, though a heavy-duty blower would be preferable to a (noisy) vacuum cleaner.

When setting up such a system, lightweight metal dryer hose may be used to make the connections. The system must hold the end of the hose *securely* near the cutting edge of the lathe bit, without touching the work. You do *NOT* want the hose end to accidentally hit the work being turned.

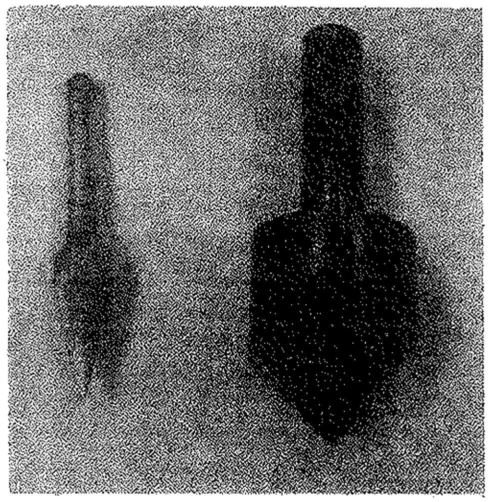

Figure 41: Carbide burr for exit cones up to ½" diameter; countersink for entrance cones up to 1½" diameter.

MACHINING GRAPHITE NOZZLES

The proper tools will save a lot of hassle when machining nozzles. For the entrance cone in small nozzles, an ordinary 82° countersink of the appropriate size (up to 1½" diameter are readily available) is quick and easy to use; see Figure 41. A countersink cuts the entrance cone in a single pass. For the truly anally retentive, 90° countersinks are available at most tool supply houses, but remember that the entrance cone half-angle is arbitrary and need not be exactly 45°.

For the exit cone, most large tool supply houses sell *carbide burrs* in various shapes. The *cone* or *tree-shaped* (radius end or pointed end) burrs are available up to ½" diameter, with a ¼" shank. A ½" diameter burr 1" long produces a half-angle of almost exactly 15°. These burrs run about $20-35 and will last practically forever even with hard graphite. Special burrs for aluminum are more expensive but have wider grooves and clog less.

For larger entrance and exit cones, a boring bar may be used, with the compound slide of the lathe usually set to 45° for the entrance cone and 15° for the exit. There are also tapered end mills and some types of pipe reamers that can be used for the exit cone of a large nozzle.

The following is machining procedure for the 29 mm nozzle shown, which uses an o-ring that is 3/32" thick, and a liner (insulating) tube 0.95" i.d. and 1" o.d. It is designed for readily-available 1⅛" o.d. aluminum casings with 0.058" thick walls (1.009" i.d.). It is readily adapted to other nozzles if the lathe has the necessary capacity.

> [If you are sufficiently unfamiliar with machining that you cannot follow this procedure, it may be best to let another do the machine work. Rocket parts should not be one's introduction to machining]

1. A stick of 1" graphite is chucked into the lathe, with a little more than one nozzle length protruding from the chuck. For large diameter nozzles, billets of graphite of the proper length for one nozzle may be sawn and chucked individually. Leave allowance for cleaning up the ends and for sawing off the nozzle.

2. The end of the job is faced flat. Turning speed is about that used for aluminum.

3. The outside is turned to 0.988-0.993" diameter.

4. Using a bit with a radius a little less than 1/16" (see Figure 47), the diameter is relieved to 0.835-0.840" for a length of 0.34"±0.01". Note that most of the "lengths" are not critical and may vary depending on the nozzle throat and exit cone.

5. Using the same bit, this diameter is relieved to 0.600" for 0.28" of length. Although the length is not highly critical, it should vary in the *same direction* as the length turned of Step 4. This is so that the recess for the o-ring will be 0.06-0.07" long. The recess is shorter than the thickness of the o-ring, and the o-ring is compressed by the internal pressure to create the necessary seal. The same bit is used so that the inside corner will be rounded (sharp inside corners tend to crack).

   If several nozzles are being made, the 0.600" diameter is kept as precise as possible (±0.001" or better) so that when each nozzle is re-chucked, it will be properly centered.

6. A hole is started using a center drill, then a 3/16" nozzle throat is drilled about 1" deep.

7. A tree burr or cone burr is used in the tailstock chuck to form the exit cone. The burr is forced into the nozzle until the cone is about 0.4" in diameter at the exit. My experience with carbide burrs is that they run well at fairly low speed and with heavy pressure; your experience may be different. For a larger nozzle throat a larger exit will be needed, and the nozzle itself may be somewhat longer.

8. The lathe is run at high speed and a piece of 800 grit sandpaper is used to sand the outside and inside of the nozzle. Pressure will give a shiny surface that is cleaner to handle.

9. The piece is cut off to about 1" long.

At this point, if a large number of nozzles are being made, the first one may be set aside and the next started upon. Once the exit cone has been finished on each nozzle:

10. The exit-end of the nozzle is chucked (0.600" diameter). If the exit ends are precise and the first is properly centered, the remaining nozzles should be well-centered too. To avoid the chuck jaws applying too much pressure and breaking the nozzle, some workers use a short piece of aluminum tubing bored to 0.600" i.d. The tubing is slit down the side, placed over the end of the nozzle, and the chuck jaws tightened down onto it. The nozzle is faced off and reduced in length to 0.91"

    A 4-jaw independent chuck will center the work more accurately than a typical 3-jaw.

11. A tool bit with very slightly rounded tip is used to reduce the diameter to 0.950" for 0.12". This is the recess for the liner tubing, and may be omitted if no liner is to be used. Its diameter may be altered if a different dimension of liner tubing is used.

12. A countersink in the drill chuck is used to form the entrance cone. Don't go too far! The finished nozzle should have a throat about ⅛" long or a bit less (roughly half the diameter of the throat). About ⅛" or so of width may be left as a "lip" at the forward end of the entrance cone. If the countersink is run too deep the edge of the cone becomes sharp; it will chip and crack easily. Also, a too-deep entrance cone may leave the nozzle throat too large.

13. Medium grit sandpaper is used to round the entrance cone where it meets the throat. Then finer sandpaper is used to smooth it, and finally the surface is polished with 800 grit as before. The entrance cone and throat should join smoothly without a trace of a ridge.

Professionally, in large motors, the radius of the joint between entrance cone and throat may be made about equal to the throat diameter. For larger nozzles the region where the exit cone meets the throat may be rounded slightly as well.

Some workers make a large number of nozzles at one sitting, all with large exit cones and with standard nozzle throats (perhaps 3/16" for 29mm, ¼" for 38mm). The nozzle throat is then enlarged with a drill or a reamer for a particular motor. Tapered hand reamers are readily available to enlarge throats from ⅛" to ½".

For a single-use motor, the o.d. of the nozzle should be made to fit tightly in the casing, and the o-ring groove may not be necessary. Alternatively, a nozzle that is a loose fit in a single-use casing may be built up with a layer or two of masking tape. Take care that the nozzle remains centered properly, since an off-center nozzle will cause off-center thrust.

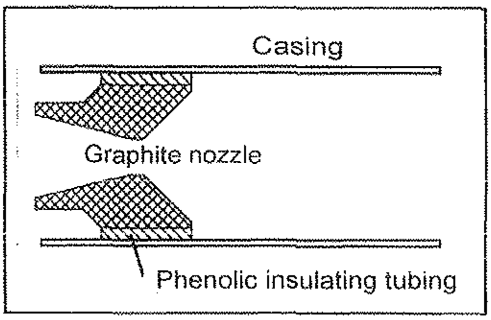

Figure 42: Insulating the casing from the nozzle in a longer-burning motor.

Graphite conducts heat well, and those who use thin phenolic casings and graphite nozzles may find the casings partly carbonized over the nozzle after a long burn. For longer-burning motors a graphite nozzle may require additional insulation so that it does not cause case failure. One way to insulate the nozzle is to use a short, thick piece of phenolic tubing between nozzle and casing, as shown in Figure 42. The tubing is selected to fit the inside of the casing tightly, and the nozzle is made to fit tightly inside the tubing. A ⅛" thick wall on the phenolic insulating tubing has been found to be adequate for motors burning up to eight seconds.

REUSING NOZZLES FROM SINGLE-USE MOTORS

Of course, most workers will want to re-use graphite nozzles. To remove a graphite nozzle from a single-use phenolic cased motor, the motor is held with pliers and the bottom inch or so of the casing is burned with a propane torch. Some workers place the assembly in a good hot fire to burn off the phenolic. It's time consuming, and be prepared for lots of stink. The excess epoxy is melted off and the nozzle heated well with the torch, to convert any residue to a powdery ash. When cool, the nozzle is wiped with a paper towel to remove any remaining gunk, and is ready for re-use.

Aluminum cases will need to be sawn carefully to avoid ruining the nozzle. First saw off the end holding the nozzle. Then saw through the side of the casing up to the nozzle. This piece is then heated; when the epoxy melts, the casing usually springs open and the nozzle drops out. If not, a bit of judicious pulling with a pair of pliers is often fruitful.

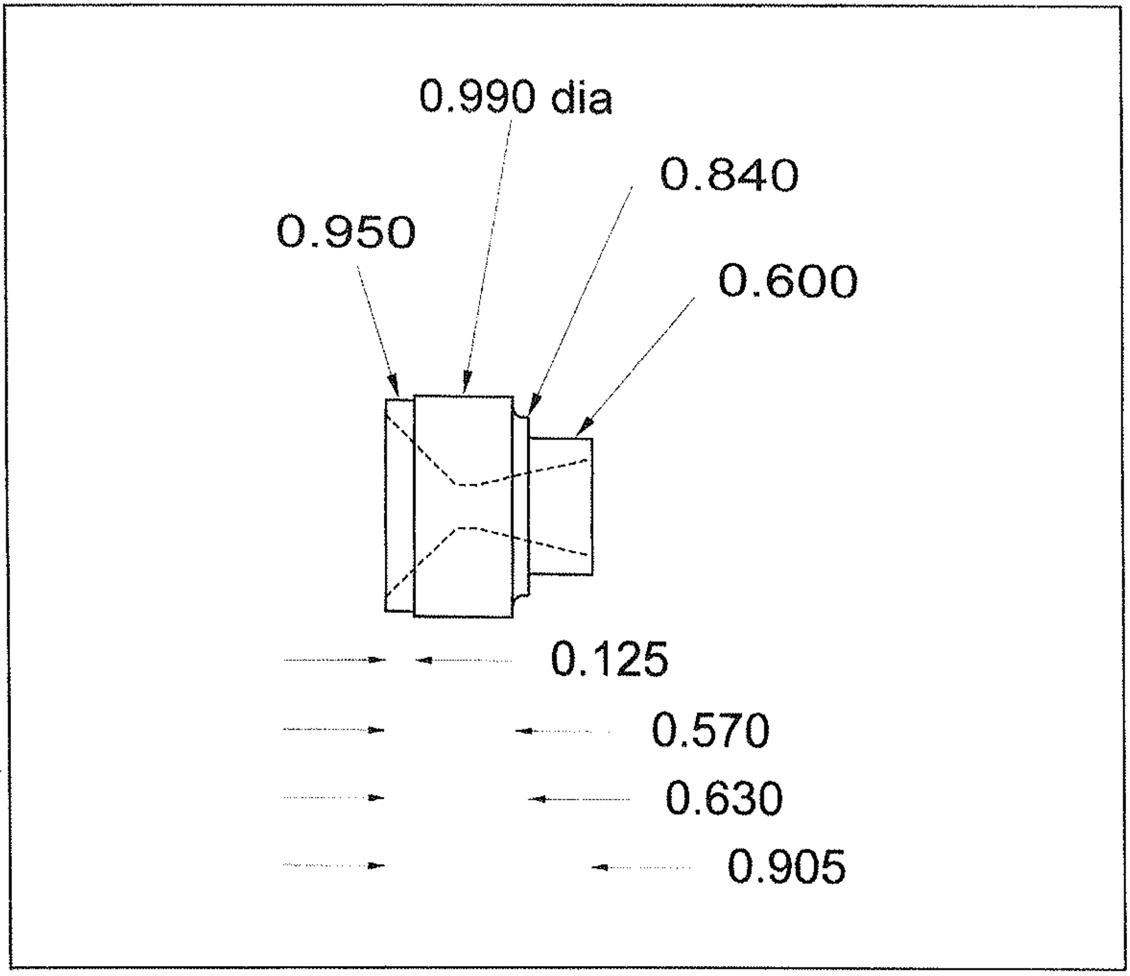

Figure 43: Graphite nozzle suitable for single-use or reloadable motor, 29 mm

Comments:
Nozzle throat is about 3/16", exit cone is about 0.4" diameter.
This design is adequate for nozzle throats up to about ¼".
For nozzle throats from ¼" to ⅜", the exit cone diameter should be increased to 0.6", and the "tail end" of the nozzle diameter increased from 0.600" to 0.750".
Problems may be encountered in using this design with larger nozzle throats in *reloadable* motors, due to inadequate support by the snap ring and washer (see the section on reloadable motors).

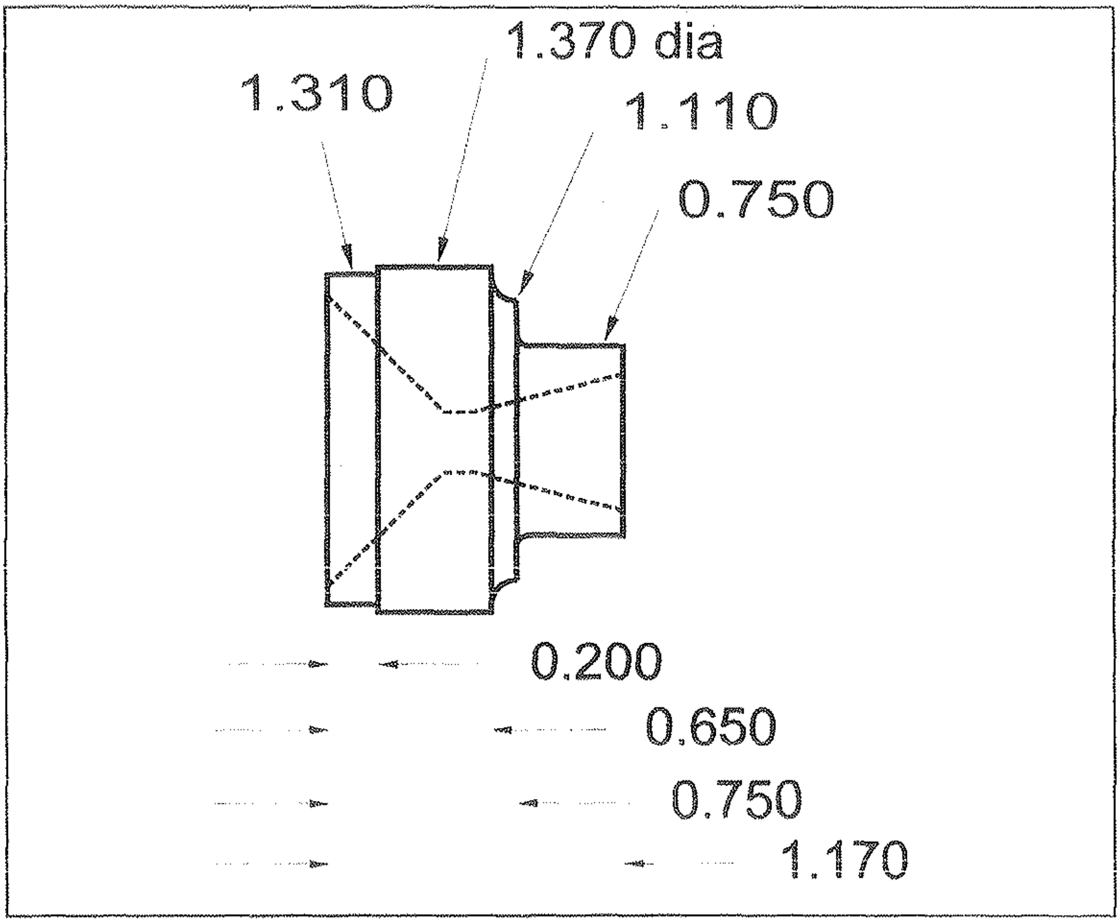

Figure 44: Graphite nozzle for single-use or reloadable motor, 38mm

Comments:
Designed for casings 1.500" od, 1.384" id (0.058" wall). Different casings may require altering the external dimensions.
Nozzle throat is ¼", exit cone is ½" diameter.
This design is adequate for nozzle throats up to about 5/16".
For nozzle throats from 5/16" to 7/16", the exit cone diameter should be increased to 0.75", and the "tail end" of the nozzle diameter increased from 0.750" to 1".
Problems may be encountered in using this design with larger nozzle throats in *reloadable* motors, due to inadequate support by the snap ring and washer (see the section on reloadable motors).

THE RELOADABLE MOTOR

Once single-use motors can be produced with reproducibility and proficiency, the worker may want to consider reloadable motors. There are several makers of commercial reloadable motors at this time. Unless machining facilities (a modest-sized lathe at a minimum) are available, it probably will be easier and cheaper to buy, rather than machine, reloadable motors.

Anyone planning to design and construct a reloadable motor from scratch should be able to engineer the motor properly. Many experimenters are unaware of the enormous forces that exist within a rocket motor, and how those forces change with motor size. For example, a 29mm motor operating at a chamber pressure of 800 psi exerts a force of about 650 lb on the forward closure. In a 54mm motor that force jumps to over 2500 pounds! If you don't know how to design the motor to resist at least twice that amount of force, it would be better not to try.

The author of this book is not an engineer and will not attempt to describe such engineering. However, CP Technologies sells a book on experimental rocketry that includes a section on motor engineering and design, including analysis of heat flow. That book is highly recommended for the individual wishing to design and build reloadable motors. The DARK publication (see the Bibliography) is also very useful.

A reloadable motor typically consists of a casing, a forward closure, and an aft closure. The forward closure often includes an arrangement for a delay charge and ejection charge. A series of o-rings is usually used to seal the casing from damage against the high chamber pressures and corrosive gases.

Probably the best-known commercial reloadable motor is the *Aerotech* motor. It uses threaded closures and can be assembled without tools. The aft closure is ring-shaped to hold a phenolic nozzle in place. The forward closure has a recess for a delay grain and ejection charge.

Aerotech motors have proven to be highly reliable and tens of thousands of them have been flown. However, they are slightly more complicated than some other designs, requiring a number of specialized parts: fiber washers, several o-rings, and spacing tubes. This reduces their desirability for experimental use. Also, the phenolic nozzle is intended to be used once. Some workers re-use these nozzles but the throat will erode significantly during each burn. That means that subsequent uses of the nozzle will give different thrust characteristics to the motor.

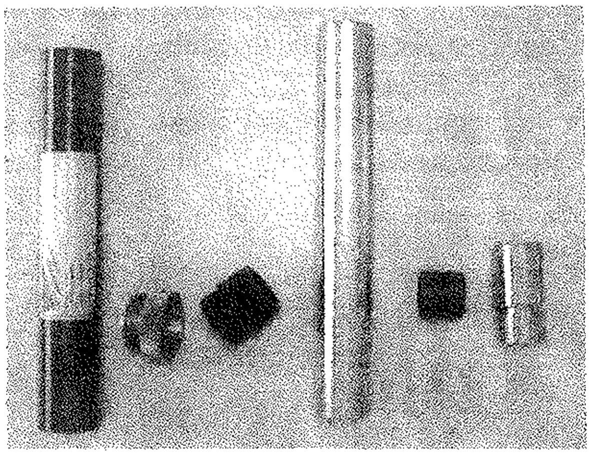

Figure 45: From left: Aerotech 29mm reloadable motor casing; aft closure; forward closure; Kosdon 25mm casing; nozzle; forward closure.

Kosdon motors use snap rings to hold the forward closure and nozzle in place. A pair of snap ring pliers is required for assembly/disassembly. The forward closure has a recess for delay and ejection charge, and can be "plugged"; that is, a bolt can be inserted to fill the ejection charge well and prevent burn-through into the rocket body. This is a good idea for a rocket which will use an electronic device for ejection.

The Kosdon nozzle is solid graphite and can be reused a number of times (though it will eventually erode).

APS motors are no longer made, but some are available on rocket-related websites and elsewhere. These motors are very good for experimental use, combining desirable features of Aerotech and Kosdon motors. The nozzle is graphite, and the closures thread into place, making assembly easy. The forward closure is designed to use a delay grain cast into a short piece of aluminum tube; there is an o-ring inside the forward closure to make the necessary seal. The hole can be plugged with a short piece of smooth aluminum rod of the proper diameter, if a delay grain is not to be used (important: do not attempt to use cardboard-cased delay grains in APS motors; they may lead to failure).

Ellis Mountain motors are also very good for experimental use. There is no delay or ejection charge well to contend with. In 38mm sizes the nozzle is single-use, but a graphite nozzle may be purchased from a third party, or machined. In 75mm size, the nozzle is solid graphite and can be reused.

There are several suppliers that make reloadable motor hardware for experimental use, at very reasonable prices. Be forewarned that when you purchase hardware for use in experimental motors, *YOU* (and not the motor maker) are likely to be held liable for anything untoward that happens. That may be true even if you use your propellant in TRA/NAR certified hardware.

A 29MM RELOADABLE MOTOR DESIGN

For the individual who wishes to make reloadable motors and has machining facilities, the design shown may be useful as a starting point. In the author's work this design has been found to be quite reliable, with over a hundred test firings and no failures at normal chamber pressures (up to 900 psi). This design has no integral delay well, nor does it have provision for an ejection charge. It might be possible to use a full-diameter delay charge, but this has not been attempted by the author.

CASING

The casing is 6061-T6 or similar alloy seamless drawn aluminum tubing, 1⅛" od, 0.058" wall, 1.009" id. Check with local aluminum suppliers.

1. The casing is sawn to length. Needed length will be the total grains length plus allowances for: forward closure (¾") and nozzle (¾"), as well as 1/16" each for the retaining washer, snap ring grooves, and extra length below the nozzle snap ring groove and above the forward groove. All this comes to 1 13/16" plus grain length. So a motor with four 1½" long grains should (theoretically) use a casing 7 13/16"

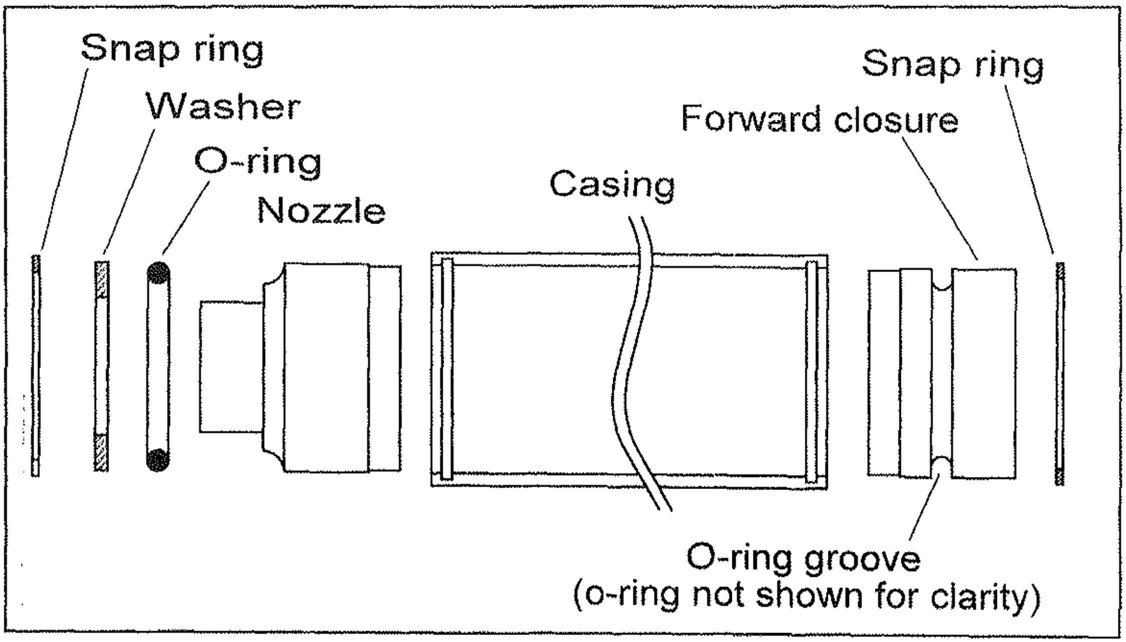

Figure 46: A reloadable motor design in 29mm size. There is no provision for delay or ejection in this design.

long. A little extra (about 1/16" or so) should not hurt[46]. So plan on the casing being 7 ⅞" long, and saw it about 1/16" over this length to allow for machining.

2. The tube is chucked in the lathe with about ½" extending past the chuck jaws. A *good* 3-jaw chuck is needed, or an independent 4-jaw chuck may be used (center carefully). Off-center grooves may cause uneven stress and possible motor failure. Don't chuck too tightly or the tubing may be distorted. Clean up the end, then chamfer the corners slightly, just enough to debur (or use a hand deburring tool).

3. Grind a short piece (¾") of tool bit to a 1/16" wide flat, and relieve slightly past the cutting edge to minimize chatter (see Figure 47). The heel of the bit may need to be ground away so that it does not rub against the work. Hold the bit in a boring bar to cut the snap ring groove. The edge of the groove should be 1/16" from the end of the casing, and the groove should be half of the casing wall thickness -- in this case, 0.029" deep. Debur the edges of the groove carefully. If they are not deburred they will tend to cut the o-rings, leading to possible motor

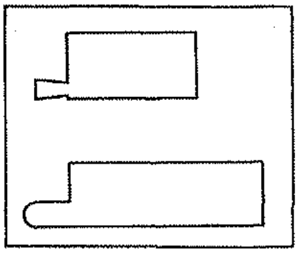

Figure 47: Top: bit for cutting snap ring grooves. Bottom: bit for cutting o-ring grooves (approx. 1/16" radius).

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[46] Some workers are a little unsettled by the use of a casing that is "too long". Contrary to what might be thought, it is not necessary for the propellant grains to fit end-to-end tightly in the casing. A little extra space between grains ordinarily will not hurt anything. However, any direct path between propellant flame and metal case should be minimized, else the case may burn through. O-rings are sometimes used to fill gaps between propellant grains or at the end of a grain.

failure. If they are deburred *too much* (i.e., deeply chamfered) they may lead to slippage of the snap rings -- and motor failure.

4. Remove the casing and mark 7 ⅞" from the finished end. Chuck in the lathe with the unfinished end extending about ½". Trim to the mark, and debur the edges as before.

5. Cut the second snap ring groove as before, and debur.

The casing (and forward closure) may be anodized to make them easier to clean after use. However, anodizing is not required if the motor is disassembled immediately after use and cleaned properly. The hydrochloric acid produced by AP is corrosive, and aluminum parts will get the "gritty grays" if they are allowed to stand for long after firing. Many metropolitan areas have an anodizing facility, and anodizing is not prohibitively expensive (it is about the same price to anodize half a dozen casings as it is one).

FORWARD CLOSURE

The forward closure is machined from a solid piece of 1" aluminum (6061-T6) round bar.

1. The bar is chucked in the lathe with about 1" extending beyond the chuck jaws.

2. The end of the bar is faced off. The diameter is reduced to 0.990" for its exposed length.

3. If a liner is to be used, the diameter is reduced to the i.d. of the liner (0.95" is typical) for about ⅛" or so. If no liner is to be used this can be omitted.

4. Using a tool as shown in the lower part of Figure 47, a groove is cut for the o-ring. The depth of this groove should be 0.835-0.840", and it should be a bit wider than the width of the o-ring. The groove should begin about ¼"- ⅜" from the faced-off end, though exact placement of the groove does not appear to be critical. Chattering of the cut is to be strictly avoided, else the o-ring may not seal. It may help to work the tool back and forth as it is driven into the groove. Alternatively the groove may be cut almost to depth and finished smooth with a ⅛" round file.

5. The piece is cut off to a length of slightly over ¾".

6. The piece is chucked in the lathe with the rough end out, and this end is faced off to make the piece 0.80" long (length does not appear to be critical). This end is then drilled and tapped ⅜×16 to a depth of about ½" or a bit more (not too deep! Drilling completely through the piece will ruin it!).

7. All sharp edges are deburred. An eyebolt is inserted into the threaded hole and screwed home, as a handle or to attach the recovery system. If the recovery system is to be attached to this eyebolt it *must* be a *welded* eyebolt. Common hardware store eyebolts that are merely bent into shape can fail on deployment of the recovery system, with disastrous results.

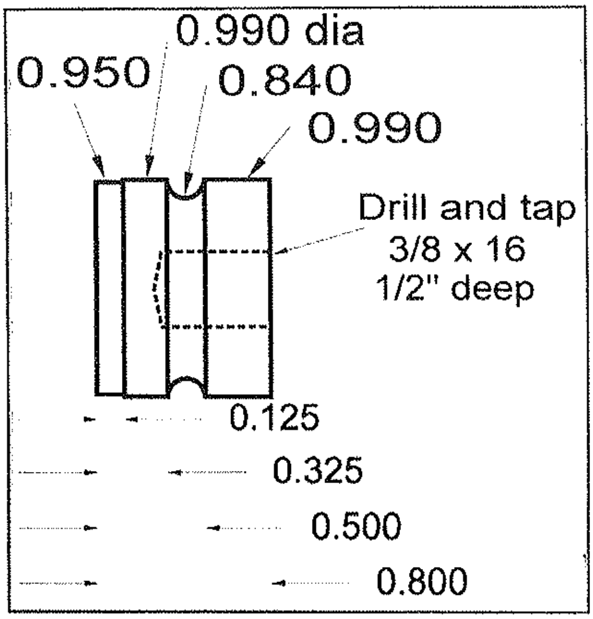

Figure 48: Forward closure, 29mm. Length dimensions are noncritical.

OTHER MOTOR PARTS

Snap rings for 1" i.d. tubing are readily available at most hardware stores. Larger quantities can be had from McMaster-Carr (internal retaining rings, for 1" bore diameter).

The o-rings used in this design are 3/32" wide by 1" o.d. (13/16" id) Buna-N from McMaster-Carr; these also are available at most hardware stores.

The flat washer against the nozzle is 1" od, ⅝" i.d., 1/16" thick, and is available at most hardware stores (look for the small boxes of specialty hardware; these may be called "steel bushings"). If the nozzle is allowed to bear directly against the snap ring, the nozzle is likely to break and cause a cato. Thinner washers may bend excessively.

Directions for nozzle machining are given in the previous section.

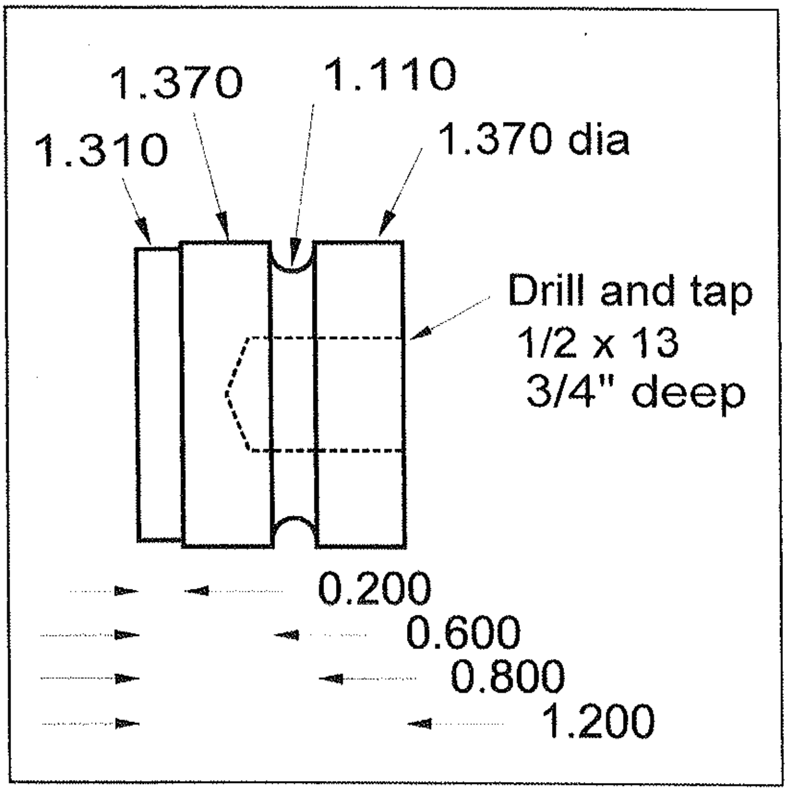

Figure 49: Forward closure, 38mm. Length dimensions are noncritical.

MOTOR ASSEMBLY

1. The propellant grains are selected. A liner is cut ¼" longer than the total propellant length.

2. The grains are slid into the liner and this assembly set aside.

3. An o-ring is greased lightly (Vaseline or silicone grease) and slipped into the recess of the forward closure. The outside of the forward closure is also greased (this is not required but will aid in cleanup).

4. The liner is greased lightly on the outside (again optional, for easy cleanup). The casing is held horizontally and the liner and grains are slid most of the way into the casing.

5. The aft (rear) end of the forward closure is slid into the liner. Now the closure is pushed into the case until it clears the snap ring groove. A bit of twisting may be required as the o-ring passes into the casing, so that the ring may clear the snap ring groove.

6. The aft snap ring is inserted. Examine the snap ring carefully; the metal has a "sharp" side and a "rounded" side (from manufacture) as shown in Figure 50. It should be installed with the sharp side *out* (away from the propellant) for maximum holding power. Be sure the snap ring is properly seated in the groove.

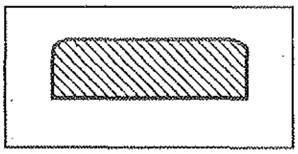

Figure 50: Cross-section of snap ring.

7. A second o-ring is lightly greased. Grease (optionally) the outside of the nozzle that will contact the casing. The nozzle is slid into place at the opposite end of the casing, twisting it so that it goes into the liner properly.

8. The nozzle o-ring is dropped into its recess in the nozzle. It need not be forced into place at this time.

9. The steel retaining washer is installed on top of the o-ring and nozzle. The second snap ring is installed, sharp side out.

   If clearances are "tight" and the casing is just the right length, or maybe a little bit short, it may not be possible to insert the snap ring; the washer is not far enough forward to expose the snap ring groove. If only a millimeter or so of clearance is required, the forward snap ring may be removed and the aft washer pushed forward enough to install the aft snap ring. Then the forward closure is forced into place against a suitable immobile object (the corner of the workbench, a vice jaw) while simultaneously forcing the snap ring into place.

If this does not work, one grain may be removed and cut slightly shorter (⅛"), then reinstalled. A small portion removed should not affect motor performance drastically.

9. Grab the casing in both hands and press the forward closure hard against the floor. This should force the grains against the nozzle, and will press the aft o-ring into its groove and seat it properly. Now hold the casing in one hand and pull back on the eyebolt in the forward closure so that it is once again seated against its snap ring.

   The motor is ready for use.

DISASSEMBLY

1. The snap rings are removed. The steel retaining washer will probably drop out.

2. The eyebolt is twisted clockwise and pulled to remove the forward closure. If it does not move, the casing is gripped carefully in a vice to remove the closure; do not distort the casing in doing so. Or grip the eyebolt in a vice and grasp the casing with both hands, twisting it.

3. A broomstick or ¾" dowel is inserted to push the nozzle out of the casing (a 1" dowel will probably jam).

4. After the nozzle is out, a 1" dowel may be used to force the remains of the liner and casting tubes out of the casing. Ordinarily they will come out easily if the liner was greased. If they do not slide out, an icepick or similar tool is slid between liner and casing to pry the liner loose. Be careful not to scratch the casing excessively.

5. Wipe the nozzle with a paper towel to remove soot, etc. There may be a layer of oxide slag on the entrance cone and throat. Pry it out with a dull spatula (a sharp object may score the nozzle and cause it to crack later). The casing and forward closure may be cleaned in a variety of ways. The author's preference is orange-pumice hand cleaner with a nylon brush (toothbrush). The casing is then rinsed thoroughly with water and dried with paper towels.

   If the motor is to be reloaded and used immediately, and the parts were greased properly before the initial use, it may be practical simply to wipe the o-ring grooves and snap ring grooves clear of grease, wipe all parts with a paper towel, and reuse immediately. O-rings should be replaced with each use, not reused.

OTHER SIZES OF MOTORS

The author has constructed similar reloadable motors in 38 and 54mm sizes. Dimensions and *calculated* working pressures for various thicknesses of aluminum casing are provided in Table XIII. As a rule of thumb, the forward closure should be about the same length as the i.d. of the casing, else it may tend to bind. Depth of snap ring groove is one-half the wall thickness; the groove should begin about 1/16"-1/8" from the end of the casing.

Size	Wall thickness	Yield pressure	Maximum (burst) pressure	Maximum (use) chamber pressure**
1.125" od, 1.009" id (29mm)	0.058"	4599 psi	5173 psi	2300 psi
1.500" od, 1.384" id (38mm)	0.058"	3353	3772	1676
1.500" od, 1.370" id (38mm)	0.065"	3796	4270	1898
2.125" od, 1.995" id (54mm)	0.065"	2607	2932	1303
2.125" od, 1.935" id (54mm)	0.095"	3928	4419	1964

Table XIII: Strength (calculated) of 6061-T6 alloy seamless aluminum tubing. Assumed values: ultimate tensile strength =45,000 psi, yield strength = 40,000 psi.

****Pressure given here is one-half of the yield pressure. However, forward closure and nozzle strength must also be considered in motor design. A motor is likely to fail well below this "recommended" pressure if the *entire motor design* has not been considered. For the reloadable motor described in this book, it might be well to keep the design chamber pressure below 1000 psi.**

IGNITERS

How many will be used? If fewer than about 50 are used in a year, it may be less expensive and annoying to buy them. The so-called *electric matches* used for pyrotechnics are excellent for rocket motor ignition if the match is fortified with a bit of easily-ignited composite propellant. Such matches are available for about $60-80 per hundred, and are extremely reliable, much more so than most ordinary rocket igniters. They are also an excellent alternative to flashbulbs for ejection charges, requiring very little current for ignition. In fact, current requirement is so low that some caution must be exercised; in some launch systems the "continuity" light permits enough current flow to fire the e-match.

An e-match has only a tiny bit of pyrogen at the tip, and by itself may not be enough to ignite some propellants. To "boost" an e-match, easily-ignited composite propellant scraps may be cut into slivers about ⅛" square and 1" long (propellant containing a burn rate catalyst is a good choice). If the e-match has a plastic cap (often the case with such devices), it is slid down the wire. Masking tape is used to attach the propellant to the match as shown at the right. Glue may work for this purpose but taping confines the flame for more certain ignition.

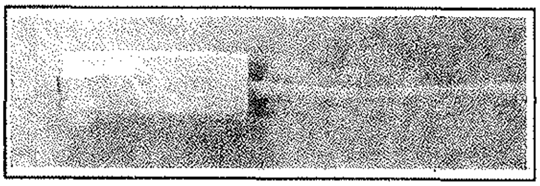

Figure 51: A boosted e-match for use as an igniter. Tape confines the flame better and is preferable to glue for attaching the boost.

For large motors, more and/or larger strips of propellant may be used. A single strip is enough for most 29 and 38mm motors; two to four strips may be used for 54mm motors.

The igniter is inserted into the motor nozzle so that it touches the propellant at the forward end. A kink in the igniter wire about 2" from the head will help it press against the propellant for positive ignition. Some users tape the lead of the igniter to the nozzle, to keep it in place until the motor ignites.

ROLLING YOUR OWN

A number of igniter kits are on the market. Although the author has not used any of them, reports of their reliability abound.

If you're determined to make your own igniters, there is a bit of an investment in materials and chemicals. The igniters described here have a shelf life of only a few months, though some have worked well after a year or more. Apparently the connection corrodes after a while, and reliability drops. It would be well to test older igniters for resistance; if the resistance exceeds four or five ohms the igniter may not work properly.

The pyrogen described here uses a *poisonous* barium compound. Take appropriate precautions. Other compositions using less toxic oxidizers may work as well, though the success of this mixture is such that the author has not attempted other mixtures.

IGNITER LEADS

Lead wire commonly used for igniter leads is 22 or 24 gauge solid copper duplex (2-conductor) cable. In the pyrotechnic community this is known as "shooting wire" and is commonly available in 500 foot rolls for about $15 (see http://www.seminolewire.com). Used igniters from a NAR or TRA launch are a fruitful source of this kind of wire. Telephone cable or twisted-pair communications cable will work (when my workplace was wired for a network, I picked up over a thousand feet of cable as scrap)

The element wire used was 36 gauge (0.005") nichrome. Slightly heavier wire will have a lower resistance and will require more current, but will provide more heat to ignite the pyrogen. Some users have had success with 32 gauge "silver bead wire" found in craft stores, and used for stringing tiny beads for jewelry. At a guess this wire would have a rather high current requirement, but it is much more readily available than nichrome.

A good pair of wirecutters and a good wire stripper are required.

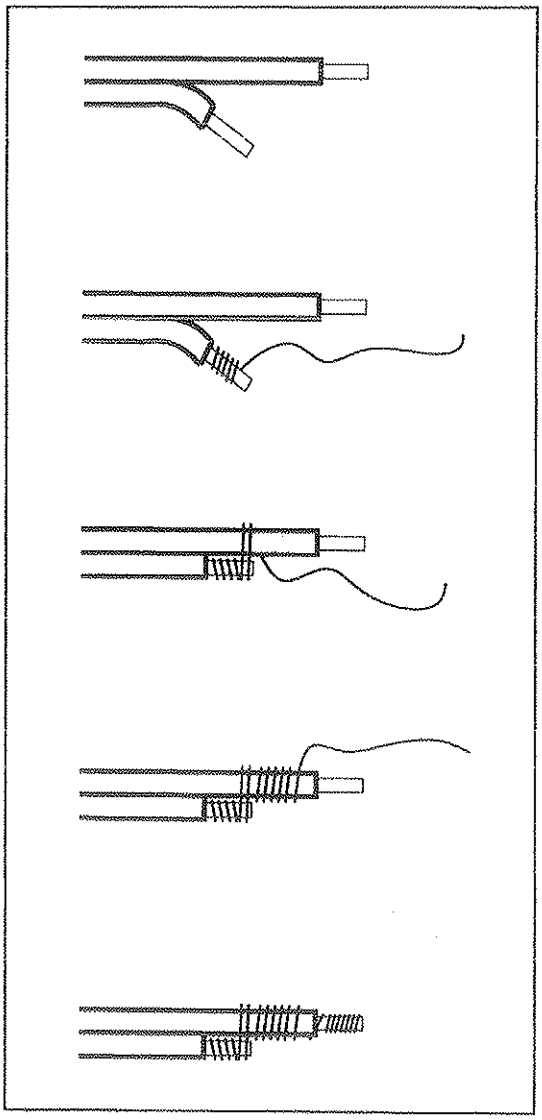

Figure 52: From top to bottom: split and strip the wire; anchor the nichrome tightly on the short wire; wrap the nichrome around both wires; spiral the nichrome up the insulation; anchor the other end with half a dozen turns and snip.

PREPARING IGNITER WIRES

1. Lengths of two-wire cable are cut as needed for the igniters. In general the cable should be at least 3" longer than the motor, to allow enough extra for good connections. Don't skimp.

2. The cable is split or untwisted for about ¾", and one wire is snipped about ½" shorter than the other. About ⅛" of insulation is stripped from each wire.

3. About 8-10 turns of nichrome is wound tightly around the shorter bare copper. The wires are pressed together again and

2-3 turns are wound around both wires, to anchor that end of the nichrome properly.

4. The nichrome is spiraled up the insulation of the longer wire until it reaches the bare copper. About 4-8 turns is adequate for thin nichrome. Some experimentation may be necessary with thicker element wire; fewer spirals may be adequate.

5. About 8-10 turns of nichrome are wound tightly around the other bare copper wire, and the nichrome is cut.

Soldering the nichrome to the copper may help if the igniters have poor continuity as indicated by high resistance. Soldering fluid (acid flux) is needed to solder nichrome, and it's very time consuming.

PYROGEN

The amount here will dip approximately 100 igniters.

1. 10.0 grams of magnesium (200-325 mesh was used for this work) is weighed into a small paper or polyethylene cup. A poly film canister works well. About 5-6 grams of 5% nitrocellulose lacquer is added, and the mixture is carefully stirred with a craft stick until the magnesium is thoroughly wetted.

2. If desired, about 0.5 gram of dibutyl phthalate is added to the mixture; this will make the igniter pyrogen a bit less brittle (do not use 2-ethylhexyl acrylate for this, as it will react with the oxidizer).

3. 5.0 grams of barium peroxide (BaO_2) is weighed into the mixture. The barium peroxide is mixed thoroughly into the mixture with the craft stick. The mixture may be rather dry at this point.

4. A bit more NC lacquer is added. The total amount of NC lacquer can be as much as 10 grams, but too much will make for a less reliable mixture.

5. Acetone is added, a few drops at a time, until the mixture is about as thick as medium pancake batter or cold corn syrup.

6. The mixture is stirred thoroughly and the igniter heads are dipped. The bare wires must be completely covered by the dip. As the igniter is removed, blow on it gently then turn it upright to minimize drips and sags. The igniters are placed in a proper rack to allow them to dry. Add more acetone as needed during the process[47].

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[47] There is a reaction of acetone in the presence of magnesium that causes the mixture to thicken significantly over time. Do not attempt to make more than the recommended amount because it will likely thicken too much to be useful. Smaller amounts can be made, but there must be enough to permit the entire head of the igniter to be dipped properly.

Barium peroxide and magnesium are both rather expensive, \$10-15/lb plus HazMat fee. But as can be seen by the quantities, a pound of each is a lifetime supply for most workers.

Do not double-dip the igniters. The layer should be about the diameter of a wooden match, depending on the type of cable used. In general, a thick coat of pyrogen does not ignite as easily as a thinner coat. There is only a limited amount of heat produced by the nichrome wire, and if the pyrogen is thick there's more material to be heated. Plus, a thick layer tends to cause localized heating. You'll know when this happens; the igniter will make a tiny "pop" and you'll find a hole in the pyrogen where the nichrome burned through. If a more robust igniter is needed, these igniters may be boosted with a strip of composite propellant, as described earlier.

On the other hand, if the layer is *too* thin, the fire may not propagate along the entire pyrogen. Again, a bit of experimentation may be necessary.

A very useful precaution is to strip the other end of the igniter wires and twist them together. This minimizes the possibility of the mixture being ignited by static discharge. Untwist when ready to connect the clips from the launch system.

Changing the proportions of Mg and BaO_2 should be done only with extreme caution. Some limited experimentation has shown that less Mg and more BaO_2 makes the mixture more sensitive (and somewhat more dangerous!), and it burns faster. A mixture of one part Mg to two parts BaO_2 was found to "snap" when the launch button was pressed. It ignited good propellant very quickly indeed, but failed to light some other propellants. The 2:1 $Mg:BaO_2$ burns more slowly and the author has found it to work even for ammonium nitrate and other difficult-to-ignite propellants.

PROPELLANTS AND POLYMER CHEMISTRY

It's not absolutely necessary to understand polymer chemistry in order to make propellant. But an understanding of some of the principles will make it easier to design and change formulations. This is especially true with HTPB propellant, for which there are crosslinking agents, cure catalysts, bonding agents, etc.

The information and explanations given here are simplified to a considerable degree (yeah, I know, it doesn't seem that way...). For those masochistic enough to wish detailed information, consult a good polymer textbook.

The earliest composite propellant (*Galcit*) was a mixture of potassium perchlorate and asphalt, with oil added to produce a mixture that could be formed into a propellant grain. The propellant was much more powerful than blackpowder and did not crack as readily as BP, but.... one difficulty was the fact that it wasn't elastic. It *was* soft enough to deform rather than crack, but it didn't return to its original shape after deformation. Tensile strength was rather low, too

So a search began for a propellant binder that could be *cured* by chemical reaction and produce an *elastomer* with these desired elastic properties. Such polymerization reactions can be (generally) represented as:

$$\underset{\text{resin}}{X{-}R{-}X} + \underset{\text{curative}}{Y{-}R'{-}Y} \rightarrow X{-}R{-}X{-}Y{-}R'{-}Y$$

Figure 53: Typical polymerization reaction

In this reaction, X and Y represent *functional groups*, chemical groups that react with and link to one another. The R and R' represent long parts of the molecule that don't really enter into the reaction (though they can change its speed, etc.). Note that the product of the reaction has an X at one end and a Y at the other end. The *terminal* X can react with another curative molecule, and the terminal Y can react with another resin molecule. So the process may continue until either the resin or the curative is used up.[48]

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[48] The terms *curative* and *catalyst* are sometimes used interchangeably in this context, but they are quite different. A *catalyst* causes a reaction to occur rapidly; the catalyst can be recovered unchanged at the end of the reaction. A *curative* actually becomes part of the polymer during the reaction; epoxy (for PBAN) and isocyanates (for HTPB) are curatives. Note that some polymerization reactions *do* use catalysts. For example, most auto body putties and "boat resins" are cured by adding methyl ethyl ketone peroxide, which catalyzes the reaction of resin molecules *with each other*. The MEKP does not become part of the polymer, it just causes the resin molecules to react rapidly. Polymers that use catalysts rather than curatives may have a limited shelf life because the molecules will eventually react with one another--albeit slowly.

It should be clear that resin and curative must be mixed in a particular ratio. In this example, one resin molecule reacts with one curative molecule. However, that one-to-one ratio isn't always the case. Also, the two molecules may be (usually are) of different sizes. And so they may not weigh the same. This means that the *weights* of resin and curative needed to react will not necessarily be identical.

EQUIVALENT WEIGHT

So the question arises: how much curative is needed for a given amount of resin? or "what's the *cure ratio*?" There are two general ways to determine cure ratio. If you've made propellant according to the directions given in this book, you've used the *empirical* method, i.e., trial and error. Ordinarily, the propellant chemist will begin with a more calculated approach -- literally. The amount of curative needed is first *calculated*. Then, proportions "in the ballpark" of this ratio are tested, to determine the precise amount of curative needed.

Let's introduce a new term: *equivalent weight*. The equivalent weight of a resin or curative or other component is the weight of resin (or whatever) that contains exactly *one zillion* functional groups. In this case, the actual number for "zillion" is what chemists call a *mole*, 6.02×10^{23} groups[49]

This means that one equivalent weight of resin contains one mole of resin-type functional groups (this means one mole of "X" groups in Figure 53). One equivalent weight of curative contains one mole of curative-type functional groups (in Figure 53, that means one mole of "Y" groups).

One resin group reacts with *one* curative group. A mole is just a specific "big number". Thus *one mole* of resin groups will react with *one mole* of curative groups. Since one mole of resin/curative groups is one equivalent weight, it follows that one equivalent weight (or just "one equivalent") of resin will react with one equivalent weight of curative. In fact, the definition of equivalent weight[50] is such that *one equivalent weight of anything reacts with one equivalent weight of anything else with which it will react.*

The concept of equivalent weight makes calculations fairly straightforward. Let's say that the equivalent weight of a resin is 1200, and that of its curative is 400. This means

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[49] If you want to know where this goofy number comes from, find a chemistry book and look up "Avogadro's number".

[50] Polymer chemists often use other terms, such as "hydroxyl equivalent", "acid number", and "percent isocyanate". Many of these terms are very closely related to equivalent weight. In some cases they're the same thing, just labeled differently. Equivalent weight was chosen for this discussion because it is virtually universal.

that 1200 grams of resin will react with 400 grams of curative[51], or 3 grams resin with 1 gram curative.

CHAIN EXTENSION AND CROSSLINKING

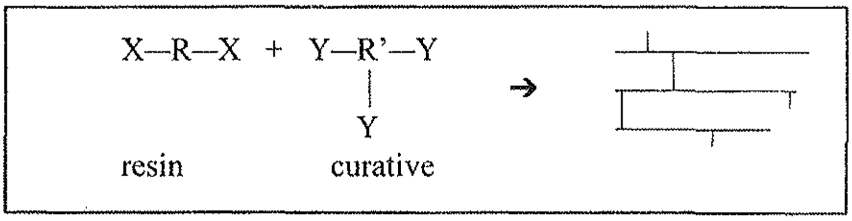

Figure 54: Resin has two functional groups, curative has three. The product of this reaction will be *crosslinked* with a three-dimensional structure (see Figure 55)

The reaction in Figure 53 shows functional groups at the ends of each molecule. They don't have to be located at the ends; the groups may be along the chain of the molecule, depending on the type of resin or curative. As each molecule of resin or curative reacts, it attaches itself to the end (or possibly the middle, depending on location of the functional groups) of a chain. This reaction is called *chain extension.* When all the resin and curative have reacted, the product is a few (very long) molecules.

The forces that hold a molecule *together* (chemical bonds) are much stronger than the forces that attract molecules to *one another* (called intermolecular forces). This means that the product, with many bonds, is much stronger than the resin or curative alone.

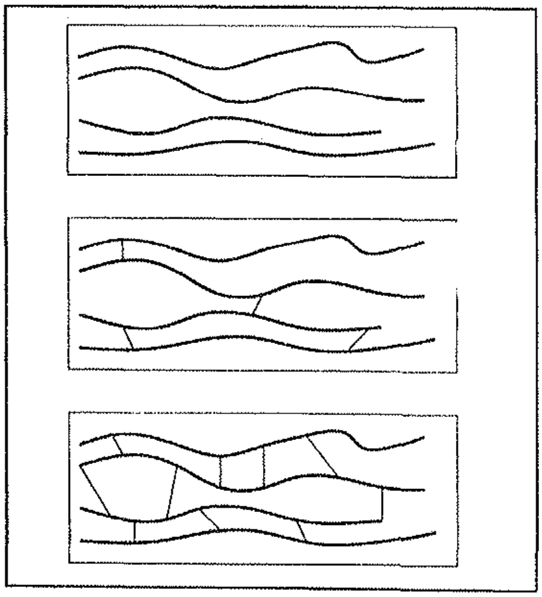

Figure 55: Top: A *linear* polymer formed by chain extension; the molecules consist of long chains. Center: A lightly *crosslinked* polymer has side-to-side connections between molecules, and is stronger but less flexible. Bottom: a highly crosslinked polymer may be very strong but also may be brittle, depending on the degree of crosslinking.

Linear polymers made of long, separate molecules (see Figure 55, top) tend to be soft, waxy solids. Polyethylene is a common example of a linear polymer. For greater strength, the chains can be *crosslinked.* Imagine a reaction between

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[51] The literature often uses the term "phr" for cure ratios. This means "parts per hundred of resin". For example, the epoxy curative TETA is often used at 11 phr, which means 11 grams of TETA per 100 grams of epoxy resin. In the simple propellant, DGEBA epoxy is suggested at 22 phr (that's a ratio of 7 parts epoxy to 32 parts PBAN) to cure PBAN when cores are to be drilled, about 15.6 phr (5:32) when coring rods are used.

the two substances in Figure 54[52]. The curative here has *three* sites at which it can react. This means that side-to-side linkages *between* chains can occur.

Some crosslinking (Figure 55) is necessary for propellant polymers; it joins the individual units and makes for a stronger polymer. Excessive crosslinking can make the polymer less flexible. A propellant that is inflexible may tend to crack rather than yield under stress, inviting a CATO. Excessive crosslinking may also cause the product to shrink too much on curing.

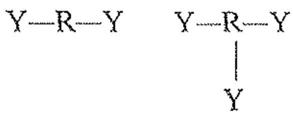
A balance must be worked out in formulating propellant. The degree of crosslinking should be enough for adequate strength, but there should not be so much crosslinking that the propellant tends to crack. For the experimenter, such a balance ordinarily is worked out by trial and error.

FUNCTIONALITY

Functionality simply expresses the number of functional groups in one molecule. In Figure 53, resin and curative each has a functionality of two. That is, there are two X (or Y) groups per molecule. Another way of saying this is that the molecules are *difunctional*. In Figure 54, the curative molecule has a functionality of three (*trifunctional*). It should be apparent that for polymerization to occur, the resin and curative each must have a functionality of at least two. That is, each must connect at two or more places to extend the chain. It should also be apparent that the molecules in Figure 54 will require a ratio of two *curative* molecules to three *resin* molecules for complete cure -- six functional groups of each type.

A single *molecule* can only have a *whole-number* functionality; 2, 3, 4, etc. That is, there can only be a whole number of functional groups on the molecule. However, a bottle of resin or curative has zillions of molecules, and the bottle may contain a mixture of several resins or several curatives, rather than a single compound. Such a mixture may be prepared so as to have a functionality other than a whole number.

For example, consider a mixture of one mole of each of these two curatives:



$$\mathrm{Y{-}R{-}Y} \qquad \mathrm{Y{-}\underset{\substack{|\\ Y}}{R}{-}Y}$$

The first molecule has a functionality of two, the second has a functionality of three, and the molecules are present in equal numbers. This means that the *mixture* has a functionality of 2.5. When used as a curative, the product will be more rigid than if the first curative alone was used, less rigid than if the second one alone was used. A

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[52] Brain exercise relating to Figure 54: in what ratio (moles or molecules) must the curative and the resin be mixed for this example? The answer is under "Functionality".

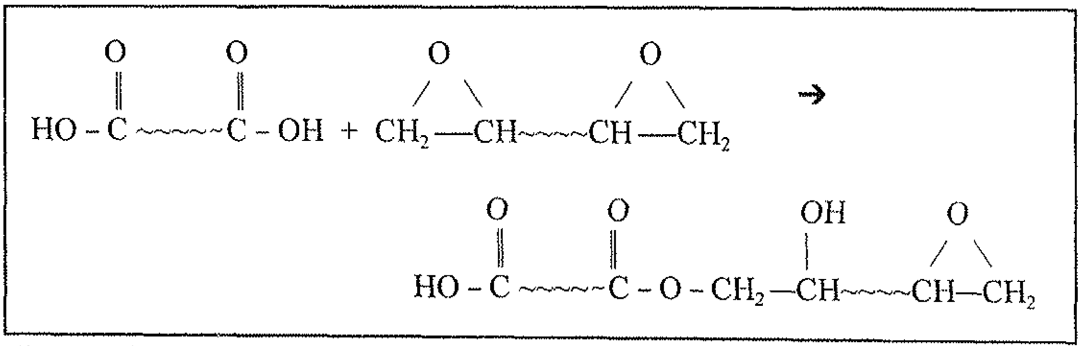
functionality of 2.25 could be obtained by mixing three moles of the first with one mole of the second, and so on.

The functionality of a curative or resin will determine the degree of crosslinking. The higher the functionality, the greater the degree of crosslinking, which (up to a certain point) increases strength, but reduces flexibility and increases brittleness. Physical properties of a propellant, and a good balance of strength and flexibility, can be obtained by selecting resins and/or curatives of the appropriate functionality.

Now this general knowledge of polymer chemistry can be related to specific polymer ingredients used in propellant formulation.

PBAN

PBAN is a resin made from polybutadiene, acrylic acid, and acrylonitrile. The *polybutadiene* (many carbon-carbon double bonds) part of the molecule provides much of the "flex" of the product and is in part responsible for the high specific impulse. The acrylonitrile is a side group that also contributes to I_{sp} and improves physical properties of the cured polymer. The acrylic acid provides the functional group, which is called a *carboxylic acid* or *carboxyl group*, -COOH. For you chemistry geeks, the curing of a carboxylic acid with an epoxide (epoxy group) forms a *polyester*. The general reaction is shown in Figure 56.



$$HO-\overset{\overset{O}{\|}}{C}\sim\sim\sim\sim\overset{\overset{O}{\|}}{C}-OH + \overset{\overset{O}{/\ \backslash}}{CH_2-CH}\sim\sim\sim\overset{\overset{O}{/\ \backslash}}{CH-CH_2} \rightarrow$$

$$HO-\overset{\overset{O}{\|}}{C}\sim\sim\sim\sim\overset{\overset{O}{\|}}{C}-O-CH_2-\overset{\overset{OH}{|}}{CH}\sim\sim\sim\overset{\overset{O}{/\ \backslash}}{CH-CH_2}$$

Figure 56: General reaction of a carboxyl group with an epoxide group. Each molecule has two such functional groups and so the chain can extend. PBAN is a carboxyl-terminated type of resin; DGEBA is an epoxide-terminated curative.

PBAN as it comes from the manufacturer has a functionality of about 2.2 and an equivalent weight of roughly 1500. The functionality of 2.2 means that on average, about one in five molecules has a third carboxyl group. It also means that a difunctional curative is adequate to cause a reasonable degree of crosslinking. To the best of the author's knowledge, there is only one source of PBAN at this time (American Synthetic Rubber Company, Louisville KY) so that PBAN has the benefit of consistency.

Freshly made, PBAN is almost colorless, but turns dark brown over time or on exposure to sunlight. It is very viscous and sticky, similar to cold molasses in consistency. There is a slight acrid odor that may be due to a bit of residual acrylic acid. The author has used PBAN that is four years old with no apparent problem.

EPOXY RESIN

A curative commonly used for PBAN is "DGEBA epoxy resin" or "diglycidyl ether of Bisphenol A". Epoxy resins are compounds that have *epoxide* groups on the ends of the molecule (see Figure 56 for an example of an epoxide group). Dow manufactures several types of DGEBA under the trade names DER330, DER331, and DER332[53]. Similar products are Shell EPON826 and 828, Reichhold Epotuf 37-140, and Ciba Araldite 6004, 6005, and 6010. The equivalent weight of most DGEBA resin is about 180-200, and the functionality is very slightly greater than 2. Theoretically the functionality should be exactly 2 because there are two groups on the ends of the molecule, but most DGEBA sold is a mixture that includes small amounts of some higher functionality compounds. Also, under some conditions each epoxide group can react with more than one functional group.

Military and space program have stringent requirements for propellant physical properties. For hobby work, the requirements may be somewhat less stringent. Consequently, other epoxy resins have been used in place of DGEBA to cure PBAN. The major difficulty is said to be due to side reactions with ammonium perchlorate, which occurs with some of the higher-functionality epoxy resins.

System Three (http://www.systemthree.com) markets an epoxy that is much thinner than DGEBA, but otherwise appears to have much the same chemistry. Although the composition is proprietary, the equivalent weight of System Three's epoxy resin is reported to be about 201, and the functionality is about 2.1.[54]

When using epoxy other than DGEBA for propellant work, some experimentation may be required to arrive at the proper cure ratio. The author has found that a ratio of 32:7 PBAN:SystemThree gives satisfactory properties for cured propellant (when using coring rods). The author has not experimented with other epoxy resins, and caution should be used when employing epoxy resins of unknown composition, as they may react unduly with ammonium perchlorate.

HTPB: R45 AND R20

HTPB is *hydroxyl-terminated polybutadiene*. Again, the polybutadiene provides flexibility and impulse; the functional group in this material is the hydroxyl group. The reaction between HTPB and isocyanate compounds produces a *urethane*, as shown in

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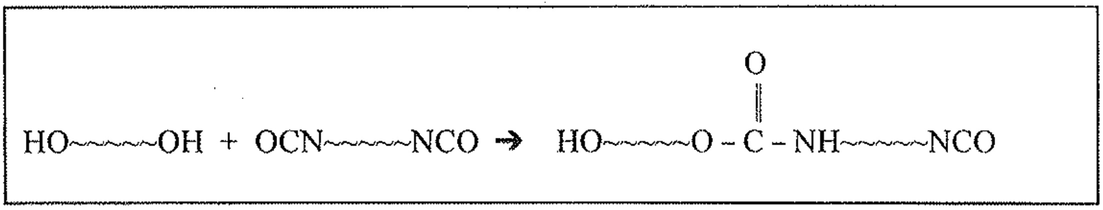
[53] Differences between grades of DGEBA are largely in purity and viscosity. DER 332 has about half the viscosity of DER331.

[54] Epoxies such as System Three's epoxy, that are used for composite construction often have *reactive diluents* added. These are low-equivalent-weight substances that have *fewer* than two functional groups per molecule. Reactive diluents make the epoxy resin thinner, but also reduce the functionality somewhat and may reduce the potlife and cure time slightly.

Figure 57 (when the chain extends, the product is, naturally enough, called a *polyurethane* -- "many urethanes").



$$HO\sim\sim\sim\sim OH + OCN\sim\sim\sim\sim NCO \rightarrow HO\sim\sim\sim\sim O-\overset{\overset{O}{\|}}{C}-NH\sim\sim\sim\sim NCO$$

Figure 57: Reaction of a hydroxyl compound and an isocyanate produces a urethane.

Elf Atochem and Arco are sources of bulk amounts of HTPB. R45HT is a designation for HTPB with no antioxidant added. R45M is the same material with about 1% antioxidant. The antioxidant allows it to be stored longer without deterioration (water will react slowly with the carbon-carbon double bonds and create additional hydroxyl groups). However properly-stored HTPB has quite a long shelf life, at least as long as most of its curatives.

Another type of HTPB is called R20. It has a lower equivalent weight than R45 (a shorter chain between the -OH groups), which means that it requires *more* curative for a given weight of resin. Also, R20 products may shrink slightly more than will R45 products when cured. However, R20 is seeing increasing use because of its lower viscosity.

Both R45 and R20 have the consistency of honey, though R20 is a bit thinner as noted. Both are a light tan in color and have a slight aromatic odor that is not particularly unpleasant.

DIISOCYANATES: MDI

The common curatives for HTPB are *isocyanates*, with -NCO groups on the molecule. Many of the isocyanates used for propellant are *diisocyanates*, although some have a functionality greater than two. All tend to be rather reactive compounds, and will even react with water to some extent. Most are low-viscosity liquids, much thinner than typical epoxy resins. Some isocyanates have no perceptible odor, others have a decidedly unpleasant one.

Isocyanates may act as *sensitizers*, in that repeated exposure may eventually cause an allergic reaction. Once sensitized, even the mildest exposure to an isocyanate may cause a severe allergic reaction[55].

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[55] Epoxy resins also are sensitizers, though they are generally considered to be somewhat less of a problem than isocyanates. In any event, protective gear should be worn when handling binders and their curatives.

One of the better-known isocyanates for curing HTPB is 4,4'-diisocyanatodiphenylmethane. This is better known as *methyldiphenyl diisocyanate* or *MDI*. Pure MDI is a low-melting waxy solid at room temperature, with a functionality of 2. But the pure substance is rarely used to make polyurethanes, for several reasons. First, mixtures of MDI with other isocyanates often are low-viscosity liquids at room temperature (desirable). The liquid mixtures are less troublesome to prepare than pure MDI and so may be cheaper. And the mixtures often are engineered to have higher functionality as desired.

MDI and related products normally cure HTPB overnight at room temperature. This can be very desirable for quick results. But it also means that MDI has limited use for propellant that is to be warmed for easier working; the potlife will be reduced. Typical potlife in a propellant can be 10-90 minutes, depending on the temperature and on the impurities in the MDI. The author has had the dubious pleasure of preparing a number of batches of MDI-cured propellant that solidified during the mixing or degassing cycles.

MDI-cured propellant is quite strong and resilient, and is more easily drilled for cores than is propellant cured with most other diisocyanates.

All isocyanates react with water to some extent. MDI mixtures have the undesirable property of being more reactive than most (general rule of thumb: the faster the isocyanate reacts, the more reactive it will be with water). The -OH group of water is just as adequate as the -OH group of HTPB for reaction. Unfortunately, the product of reaction of an isocyanate with water is CO_2 -- a gas. The bubbles of gaseous CO_2 lower propellant density and strength, and may increase burn rate unpredictably -- not a desirable result.

Some of the products of reaction of isocyanate with water are reported to increase the cure rate of the isocyanate-HTPB mixture. Thus, many isocyanate curatives has a limited shelf life, especially if improperly stored. Thin-walled polyethylene containers can allow moisture to pass through, over time. One way to minimize the problem is to store bottles of isocyanates in a tightly sealed coffee can with some moisture-absorbing desiccant.

There are several trade names for MDI mixtures; common ones are *PAPI* (polyaromatic polyisocyanate) and *Isonate* (Firefox sells Isonate 143L curative). Many such mixtures contain some higher-functionality isocyanates. The functionality of such mixtures may vary from 2.1 to 2.7 or more, depending on the specific mixture. For more complete information on this, consult the manufacturer's literature. One must exercise caution when using high-functionality isocyanates to avoid embrittlement of the product.

IPDI

Another curative for HTPB is *isophorone diisocyanate* or *IPDI*. IPDI is cheap, readily available, has a low viscosity, and has been widely investigated. Its cure is rather slow but can be speeded up by using *cure catalysts*. Propellant made from IPDI is fairly strong and stiff, though it may be a little "gummier" than propellant cured with MDI.

Unlike MDI, IPDI is a (more or less) pure compound with a functionality of 2. For more rigid propellant, a secondary crosslinking agent may be used with IPDI[56], though it is not necessarily required.

IPDI (also DDI and HDI) is an *aliphatic* isocyanate, while the other common isocyanates contain *aromatic* rings (see an organic chemistry text for more information). Aromatic rings tend to be rather stable, even during combustion. Consequently, the aliphatic isocyanates may produce propellant that "chuffs" less when used with weaker oxidizers such as ammonium nitrate and potassium nitrate. CP Technologies does not recommend Isonate curatives for its PSAN propellant, presumeably for that reason.

DDI AND OTHERS

Dimeryl diisocyanate or *DDI* is a moderate-viscosity diisocyanate. It may be more expensive than IPDI or MDI, depending on the source. If it is used alone as a curative, the resulting propellant may be too rubbery and soft for use. So DDI is often used in conjunction with MDI or IPDI. DDI has the advantage of being much less reactive with water than most other diisocyanates. It is also less toxic. Like IPDI it is a pure compound with a functionality of 2.

DDI has a rather high equivalent weight, which means that more of it (than either IPDI or MDI) is required to cure. This can actually be an advantage, because the resulting liquid mixture of DDI and HTPB may be thinner (due to a higher proportion of thin isocyanate) than a mixture of MDI and HTPB. See the section on cure calculations for more information.

Other curatives are available but are used less often for experimental propellant. Commercial propellant manufacturers often use *tolylene diisocyanate* or *TDI*. This is a very low-viscosity material that cures HTPB even more quickly than some MDI mixtures do. But there are several problems associated with TDI. First, it is more volatile than most isocyanates and is therefore more toxic than most. Second, it has a perceptible and rather unpleasant odor. Third, it should not be used at elevated temperatures. Not only will the cure rate be very high, but elevated temperature releases a significant amount of TDI vapor[57], which can be very harmful.

Hexamethylene diisocyanate or *HDI* is a bit thinner and a bit more toxic than MDI mixtures, less toxic than TDI. However, CP Technologies sells a modified[58] HDI curative (designated N-3200) that is supposed to be much less toxic than ordinary HDI and can be shipped without HazMat charge. HDI and TDI have the lowest equivalent

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[56] Frequently a company will produce IPDI or other pure compound under a particular trade name. For the most part, IPDI is IPDI regardless of the trade name.

[57] On a similar note, most of the isocyanates are sufficiently toxic that the curing process should *not* take place in or near living quarters. Enough vapor can be released, especially when warmed, to cause serious health problems.

[58] Presumably, "modified" means that it has other additives, and will not have the precise characteristics of HDI as listed in Table XIV.

weight of the common curatives. Thus, less of these curatives are required (than MDI, IPDI, or DDI) to cure HTPB. The author has not had experience with actual use of HDI for propellant, but other reports indicate that it is fairly rapid in action (overnight cure at room temperature).

"SOFT CURE"

HTPB and isocyanate may exhibit a rather strange phenomenon with regard to the amount of curing agent. If the amount of isocyanate is too small, the cured material has excess HTPB, and will be rather soft and sticky. When the correct amount of isocyanate is added, the cured mixture is firm but flexible without being tacky. Ordinarily, a slight excess of isocyanate is used, to insure that the reaction is complete. But if a *large* excess of isocyanate is added, the mixture may not cure in any reasonable length of time, and may remain soft or even fluid.

This phenomenon is known as "soft cure", and arises because the hydroxyl groups of the HTPB are largely used up while there is excess isocyanate present. The excess isocyanate has nothing to react with immediately and remains in the polymer, acting as a plasticizer and making the mixture flexible for a while. But after a period of days, weeks, even months, that excess isocyanate reacts with water vapor, forming solids. The result is a rock-hard product[59].

In some cases the outside of the mixture cures hard, and seals the inside from further reaction. A propellant grain of this sort will feel hard, but when cut open the inside is soft. Upon standing, the soft surface cures hard.

All of this means that some care is required in determining the cure ratio for HTPB and isocyanates. "Too soft" may mean too much curative, rather than too little. This is why it is a good idea to start from a calculated amount of isocyanate and work from there (see the section on cure calculations for more information).

CROSSLINKING AGENTS

A crosslinking agent is a compound or mixture that has more than two functional groups, to cause additional crosslinking. The crosslinking agent must have functional groups that are compatible with the particular reaction. For example, a crosslinker for HTPB must have either hydroxyl or isocyanate functional groups. A crosslinker is not actually required in many ordinary HTPB or PBAN propellants, as these binders have functionality that is high enough to cause crosslinking adequate for routine use.

The most common crosslinking agent for experimental HTPB propellant is ordinary *castor oil*, available at any drugstore. Castor oil is a trifunctional compound with hydroxyl functional groups. This means that additional isocyanate curative will be

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[59] The author is more of an authority on "soft cure" than he would like to be...

needed when castor oil is used. Castor oil usually is used rather sparingly. A typical HTPB propellant might contain 10-15% HTPB with 1-1.5% castor oil.

Although crosslinking agents for PBAN are available, they are not readily obtained by the experimenter, and apparently have not been thoroughly investigated.[60, 61].

It should be apparent that a crosslinking agent (like a curative) is specific to the chemistry of that polymer system. Thus castor oil is useless in PBAN propellants; it does not react with either PBAN or epoxy.

BONDING AGENTS

A *bonding agent* is a compound that can bond itself to both the oxidizer and the binder polymer. This can more than double the tensile strength of propellant. Without a bonding agent, the propellant often will "lose" oxidizer particles when cut, and oxidizer particles can easily be rubbed off the surface of the propellant with a finger. The best-known bonding agent for the HTPB system is *Tepanol*, also known as HX-878 (triethanolamine is an alternative reported in the literature that has been used by some workers).

Tepanol and triethanolamine each have three hydroxyl groups. Those hydroxyl functional groups react with isocyanate. Each also has a nitrogen atom in an *amine* functional group, as shown in Figure 58. The amine group can displace ammonia from ammonium perchlorate as shown in the figure.

This displacement reaction leaves the AP particle with "carbon backbones" of *Tepanol* or triethanolamine molecules on its surface. Each carbon chain has hydroxyl groups that can react with isocyanate curative. This means that the AP particles can be chemically linked to the polymer, hence the increased tensile strength of the product.

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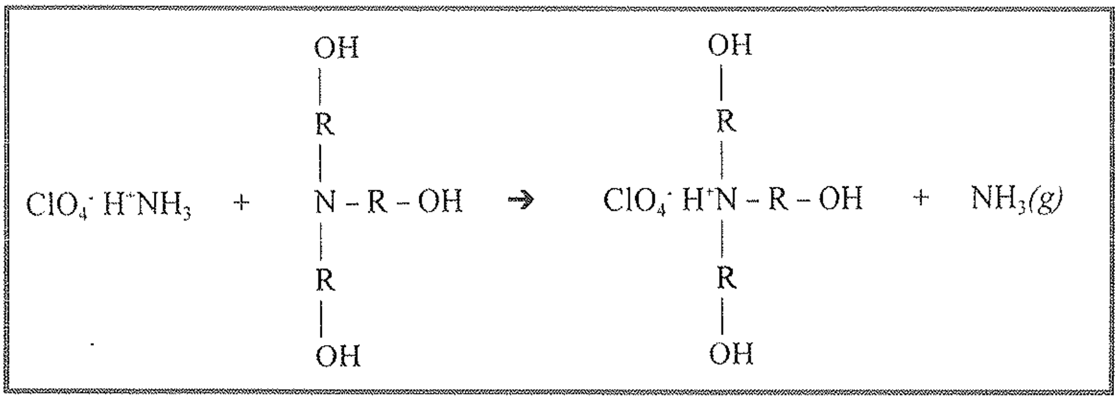
[60] For the diehard experimenter wishing to investigate crosslinking agents with PBAN, DETA and TETA (diethylene triamine, triethylenetriamine) might be reasonable candidates. Both are trifunctional and both will react with epoxy, producing crosslinks. However, these compounds react with PBAN as well. For those wishing to experiment, it would be well to first add a *very* small amount of DETA or TETA to epoxy resin, and allow this mixture to cure. This would give a more viscous epoxy resin that contains trifunctional epoxy links. This mixture could then be used to cure PBAN. The author has not attempted this; it is presented merely as an idea for possible investigation.

[61] One reason why crosslinking agents have not been investigated in PBAN propellant may be related to the fact that some epoxy resins can, under the proper conditions, crosslink themselves. Each epoxide group can react with *two* other groups rather than one. The author does not know whether such crosslinking of epoxy actually occurs in the PBAN-epoxy reaction; if so, it would explain several observations.



$$ClO_4^- H^+NH_3 + \overset{\overset{OH}{|}}{\underset{\underset{OH}{|}}{\overset{R}{|}}}\!\!\!\!\!\!\!\!\!\!\;\; N(-R-OH)(-R-OH)(-R-OH) \rightarrow ClO_4^- H^+N(-R-OH)(-R-OH)(-R-OH) + NH_3(g)$$

Figure 58: The reaction of AP with a bonding agent is an exchange process; ammonia is liberated, and the bonding agent is attached to the AP surface. The NH_4^+ ammonium ion is represented unconventionally here as H^+NH_3, to clarify the nature of the reaction. After reaction the surface of the AP has hydroxyl groups that can bond to isocyanates.

The displaced ammonia must disperse before the propellant is cured, or it will form bubbles in the propellant. When using a bonding agent of this sort, it is common to add the bonding agent to the binder before adding AP. After adding AP but before adding curative, the mixture is allowed to stand, often overnight at elevated temperature. This allows the ammonia that forms to disperse.

It should be noted that Tepanol has a tendency to decompose at elevated temperatures and is ordinarily stored in a refrigerator (NOT the home refrigerator, please!). Some workers mix the uncured propellant for several hours at elevated temperature and (preferably) under vacuum. This minimizes the time that Tepanol spends at elevated temperature. It also causes more of the Tepanol to be attached to the oxidizer particles.

Since the bonding agent need only coat the surface of the oxidizer, very little need be used. As little as 0.05% has been found to be effective, though 0.2% seems to be "traditional" among experimenters[62].

As was noted before, military and commercial requirements are more stringent than those of the experimenter. For some experimental HTPB formulations, Tepanol may be omitted. But it should be used:

(a) in high-acceleration motors where forces are extreme and the propellant must be as strong as possible.
(b) in very high-solids propellant where the amount of binder is at a minimum and strength also is important.

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[62] Some workers report that Tepanol improves processing by acting as a surfactant, reducing viscosity. It has been the author's experience that *hand-mixing* of propellant with Tepanol is more difficult than without Tepanol. Apparently hand-mixing is not vigorous enough to coat all the particles of AP with Tepanol, and the Tepanol increases the viscosity. Following this line of reasoning, too much Tepanol may be worse than too little, due to increased viscosity.

(c) in propellant with a high proportion of coarse AP (400 micron). Coarse AP has less surface area per weight, and so large particles tend to "pop out" of the polymer matrix rather easily if Tepanol is not used.

At this time there is no bonding agent readily available to the experimenter for PBAN propellant. Tepanol can be used in PBAN propellant but the procedure must be different from its use in HTPB. First, the hydroxyls of Tepanol do not bond to the carboxyl groups of PBAN. Second, the amine group of Tepanol *does* react with PBAN, and this reaction would eliminate the ability of Tepanol to bond to the AP. Thus the mixing procedure would have to be arranged so that the bonding agent is not mixed with the PBAN until it (Tepanol) has had opportunity to react with the AP.

However, Tepanol may still have some use in PBAN because it leaves the oxidizer particles with an "organic" surface that has some physical (not chemical) attraction for the organic binder. To the author's knowledge, no investigation of this phenomenon has been reported.

Bonding agents like Tepanol and triethanolamine are virtually useless with propellants that use sodium, potassium, strontium, and barium compounds as oxidizers. The bonding agent cannot displace the (more reactive) metal from the oxidizer as it does with ammonium compounds.

An interesting (and annoying!) phenomenon known as "dry mix" can occur with some bonding agents in HTPB propellant. The forces between the bonding-agent-treated oxidizer and the hydroxyl groups of HTPB are known as "hydrogen bonding" and are quite strong. Before the curative is added, these strong forces can cause the propellant to adhere into a claylike or semi-dry mixture. When curative is added it reacts with the hydroxyls on the bonding agent. This ends the hydrogen-bonding. The worker may then observe that this claylike mixture becomes much more fluid than expected as the curative is added and the propellant is mixed. In fact, this phenomenon can be used to justify small amounts of very reactive isocyanates in a mixture. The reactive isocyanates react quickly with the hydroxyls of the bonding agent, ending the dry-mix phenomenon and making the mixture fluid. The slower-reacting isocyanates cure the HTPB (and crosslinking agent, if used) and give reasonable potlife to the mixture. The dry-mix phenomenon appears to be more of a problem with triethanolamine than with Tepanol.

Bonding agents are not a magical cure to bonding problems. For a bonding agent to be useful, it must bind with the polymer and with the surface in question. For this to occur, one surface must possess a functional group (ammonium ion) that can react with the nitrogen of the bonding agent. Otherwise the bonding agent has very limited utility.

CURE CATALYSTS

A *cure catalyst* is not to be confused with a *burn rate catalyst*. The cure catalyst speeds the curing process, and/or reduces the temperature required for cure. Ordinarily, several days at elevated temperature are required for IPDI or DDI to cure HTPB binder. With a properly selected cure catalyst, an overnight cure near room temperature is possible.

Common cure catalysts for HTPB include organotin, organobismuth, and organocobalt compounds of several sorts. The most commonly available are dibutyltin dilaurate (DBTDL), cobalt octoate, and triphenylbismuth (TPB). Of these, DBTDL is the most effective, often requiring about 0.1% or even less to do the job. This can cause a problem, since it is quite difficult to measure out such small amounts of a liquid. A common technique is to measure 5 mL of DBTDL, then add plasticizer to make a total of 50 mL. To add 0.1 mL of DBTDL to a propellant one simply adds 1 mL of this 10% mixture.

DBTDL[63] (and other cure catalysts) can cause embrittlement of the product if used in too-large quantity. Also, propellant using DBTDL may become brittle in storage if too much is used. For best propellant properties, a rather slow cure is preferred, at least a day or more. In the author's experience, too-rapid cures may cause foaming or bubbling, and reduced density. Cure catalysts should be employed with caution for this reason.

TPB is rather more expensive than DBTDL and is slower in its action. It is somewhat easier to use since it is a solid and can be weighed directly into the propellant mixture. It has been suggested that TPB is less embrittling than DBTDL.

Cobalt octoate is not readily available. It is sometimes provided as a solution in mineral spirits. If used, the mineral spirits should be evaporated off after addition. It appears to be about as effective as TPB, somewhat less so than DBTDL.

All three of these cure catalysts are for the polyurethane (-OH plus isocyanate) system, and work with it specifically. They are useless for the PBAN system. Lee and Neville note that the epoxy-carboxylic acid reaction may be catalyzed with certain organic bases (tetraalkyl ammonium hydroxides or tertiary amines, if you know what those are). The author has not attempted such, and cannot comment on whether such catalysts are effective in the PBAN-epoxy reaction used in composite propellant.

Some epoxy crosslinking *curatives* have been reported as "catalysts" for the PBAN-epoxy reaction. Generally speaking, when such epoxy curatives are added to the PBAN system they speed up the "gelling" of the mixture -- because they react with the epoxy resin. In the author's experience the final cure takes about the same length of time as without the "catalyst", and the product is less flexible than otherwise, owing to the increased rigidity of the epoxy-plus-curative product.

A problem with catalysts and other additives in the PBAN system is that their effects are not entirely predictable. Lee and Neville indicate that the amount of catalyst used in an epoxy system may be very critical and specific to a curing program and to the temperature used. That is, a catalyst which is effective when added in 1% concentration and at 200°F may not be effective at all when used at 2% concentration and a lower temperature. Furthermore, the catalyst may be less effective in the presence of

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[63] Currently there is some question as to the effects of alkyltin compounds on the immune system.. Anyone using DBTDL should exercise caution.

ammonium perchlorate. Finally, the catalyst may have some effect on the sensitivity of the finished propellant. For these reasons, catalysts for the PBAN-epoxy system are probably best left to the experts.

PLASTICIZERS

A *plasticizer* is (usually) a liquid that, when added to a polymer, makes the product softer, more flexible, and reduces the glass transition temperature[64]. PVC can be used to make rigid water pipe; when PVC is processed with a plasticizer, the product is flexible "vinyl" tubing. Properly selected, a plasticizer makes a propellant easier to process, since the plasticizers used in propellant work are lower in viscosity than the polymer mixture. Plasticizers of the sort used in propellant generally do *not* react with the polymer components or affect the final cure.

The increased flexibility obtained by adding a plasticizer is in part due to a lubrication effect. For a polymer to be stretched, the chains must be able to slide over one another. The molecules of a liquid plasticizer fit between the polymer chains and make it easier for those chains to slide over one another.

On the downside, a plasticizer may reduce the tensile strength of the polymer, especially when used in excess. So it is important not to use too much plasticizer. One plan of attack in formulating a propellant is simply to add plasticizer in increasing amounts to small portions of a test batch (similar to the "cure schedule" mentioned in the troubleshooting section). One might prepare a large batch of propellant, split it into small portions, then add no plasticizer to the first portion, 0.5% to the second, 1% to the third, and so on.

To reduce processing viscosity, a method used by some is to increase the amount of curative, using just a little more than required for complete cure. The product of this reaction ordinarily would be harder than desired. To restore some flexibility, plasticizer is added. The finished propellant has sufficient strength and flexibility for use. However, the uncured propellant mixture is significantly thinner (because of the low-viscosity plasticizer and the extra curative) than otherwise, and is easier to mix. Again, it is important not to take this approach too far; too much plasticizer may make the propellant similar in texture to warm chewing gum.

The most common plasticizer for experimental propellant seems to be *dioctyl adipate* or DOA. DOA has a low viscosity compared to most other plasticizers, and it is compatible with both HTPB and PBAN polymer systems. DOA has a perceptible odor, but otherwise is not particularly volatile.

Dibutyl phthalate (DBP) is a plasticizer that is reported to be more compatible with epoxies than most plasticizers. It is more viscous than DOA but not much more so. At

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[64] Below the *glass transition temperature*, a polymer becomes a "glass"; it becomes brittle and tends to crack rather than stretch. Clearly, a propellant must not have a glass transition temperature that is anywhere near the temperature to which it will be subjected.

the time of this writing DBP is less expensive than DOA. The author prefers DBP for PBAN-epoxy systems and has used it at up to 3% by weight with good results[65].

2-ethylhexyl acrylate is a very low-viscosity plasticizer which has been employed by some experimenters. Propellant made with 2EHA has good physical properties, the propellant mixture viscosity is low, and 2EHA is quite cheap. However, 2EHA is more volatile (evaporates more readily) than other plasticizers. This causes several problems. First, 2EHA tends to evaporate during vacuum processing, and it can be difficult to tell when the propellant has been properly degassed. Also, 2EHA tends to evaporate during storage, making the propellant brittle. Propellant which includes 2EHA as an ingredient should be stored in a tightly closed container and used within a very few months. Finally, 2EHA is volatile enough to be something of a health hazard and should be used only in well-ventilated areas.

One potential problem with plasticizers is that of compatibility. A plasticizer that is incompatible with the polymer system may "sweat" out of the polymer, forming a greasy layer on the polymer surface. For example, the author has determined that triacetin has poor compatibility with PBAN except in very small amounts.

Generally, excess plasticizer will make the propellant too soft, like bubblegum. For HTPB propellant, plasticizer should not exceed about 50% of the weight of the HTPB used. For PBAN propellant, plasticizer should not be more than about 25% of the weight of PBAN used. If "sweating" occurs the plasticizer content should be reduced or another plasticizer should be chosen.

SURFACTANTS

A *surfactant* or *surface active agent* coats a particle surface and either minimizes or maximizes interaction of that particle with other substances or particles. Soap is a simple surfactant. One end of the soap molecule is ionic, the other end is "oily" or covalent. When hands are washed with soap, the oily dirt on the hands is attracted to oily end of the soap molecule; the other end interacts with water. The result is oily dirt that can be washed away.

In propellant the idea is to minimize the attraction of AP and metal particles for other such particles. That improves the propellant mixture's ability to flow. A surfactant gives the AP a coating of an organic substance. The organic coating is more weakly attracted to itself than the AP is to itself. The result is that the coated particles slide over one another more readily. Only very tiny amounts of surfactant are needed to coat all the solids in a propellant mixture. About 0.1% or less of a given surfactant will usually be enough. In fact, too much surfactant can increase the viscosity and should be avoided.

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[65] It may be possible to use more plasticizer than this, I simply haven't tried it...

For a surfactant to be useful it must coat most/all the surface of all particles. This can take a long time, up to several hours of mixing. Unless a machine is being used to mix propellant, a surfactant is of rather limited use.

For best results, a surfactant that is specifically designed to coat ionic solids in a high-solids mixture should be used. But many surfactants can be useful. One commonly used by experimenters is *lecithin.* Lecithin is a solid that is isolated from the soy plant. It is available from some baking companies (used as an additive to improve aging characteristics of the bread). Instruction on its use is provided in the section on machine mixing.

The author has found a number of other surfactants to be somewhat useful. Zircoaluminates are used by some, but caution should be observed; some zircoaluminates are supplied dissolved in propylene glycol. Propylene glycol is a hydroxyl compound that will change the cure schedule of the HTPB polymer system. Triton X-100 is nonionic and has some utility, though it does not appear to be as effective as others. There are (expensive) fluorocarbon surfactants that may have very desirable properties. The author has not used these extensively and cannot comment on their utility.

CURE CALCULATIONS

Armed with knowledge of chemistry from the previous section, basic calculations can now be done to find out how much curative and other ingredients to use for a particular mixture. To do such calculations, the equivalent weight and functionality of the different components must be known.

Propellant Ingredient	Equivalent Weight	Functionality
PBAN	1470-1610	Carboxyl
DGEBA epoxy (such as DER331)	180-200	Epoxide
System Three epoxy	201	Epoxide
R45	1040-1370	Hydroxyl
R20	500-600	Hydroxyl
MDI	125-145	Isocyanate
IPDI	111	Isocyanate
DDI	293	Isocyanate
TDI	87	Isocyanate
HDI	84	Isocyanate
Castor oil	164	Hydroxyl
Tepanol	211	Hydroxyl

Table XIV: Common propellant polymer ingredients and equivalent weights. Equivalent weight given are typical, and may vary with source.

Note that several of the ingredients list a range of equivalent weights. Some of these ingredients (such as MDI) may be mixtures of several compounds rather than a single pure compound. For these, the actual equivalent weight depends on the industrial source. Thus the equivalent weight (isocyanate equivalent, hydroxyl equivalent, epoxide equivalent) *provided by the manufacture of the particular product* should be used in calculation. When in doubt, call the manufacturer or distributor. For other ingredients the range given corresponds to the minimum and maximum limits imposed by a particular vendor or customer.

The basic idea in a cure calculation is that

Equivalents of X = Equivalents of Y
or Equivalents of carboxylic acid = Equivalents of epoxide (for PBAN)
or Equivalents of isocyanate = Equivalents of hydroxyl (for HTPB)

To perform a cure calculation, the weights of the components containing one type of functional group is selected, and the amount of the component(s) containing the other type of functional group is calculated from that[66]. If the equivalent weight given is a range rather than a single value, the *low* end value might be used for resins R45 or PBAN and the *high* end value used for curatives (at least as a starting point). This will insure that there is an excess of curative in the mixture to provide proper cure.

Example: A propellant is to use 16.4 grams of PBAN as a binder. What weight of DER331 epoxy will be needed to cure?

Answer: according to the table, the equivalent weight of PBAN is 1470-1610 grams, and that of DGEBA epoxy is 180-200 grams. We will use the values of 1470 and 200 for this calculation.

$$\textbf{16.4 g PBAN} \times \frac{\textbf{1 equivalent of carboxylic acid}}{\textbf{1470 g PBAN}} = \textbf{0.011156 eq. carboxyl}$$[67]

so 0.011156 equivalents of epoxide are needed.

$$\textbf{0.011156 eq.} \times \frac{\textbf{200 g DER331}}{\textbf{1 equivalent of epoxide}} = \textbf{2.23 g DER331}$$

You'll recognize that half again that amount of epoxy was suggested for the simple propellant. This is in part because a faster cure was desired (more curative causes a faster cure), and because a firmer product was desired (for drilling)[68].

It should also be noted that PBAN contains some excess acrylic acid from the manufacturing process. This gives PBAN its slightly acrid odor. This acrylic acid reacts with epoxy too. Thus, the calculation performed here should be viewed as a *starting* point. Experimentation -- and often additional curative -- is almost always required to attain the correct cure ratio.

When more than one resin or curative is needed, the calculations can become a bit more complicated.

Example: A propellant is to use 14 grams of R45 HTPB as the binder. To increase the degree of crosslinking, 1 gram of castor oil will be added. To bond the oxidizer to the polymer, 0.2 grams of Tepanol will be used. What amount of DDI will be needed to cure the mixture?

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[66] For substances that are cured by catalyzing the reaction (rather than by a crosslinking-type reaction or similar) the amount of catalyst must be determined *empirically* -- by experiment. In other words, the amount of DBTDL needed for a given cure rate of HTPB is found by trial and error.

[67] Don't round these small values. Rounding off before the final answer can make the difference between a properly cured mixture and a soft, squishy mix. And after all, it's not like you can't get eight figures from a calculator...

[68] Epoxy resin is capable of crosslinking *to itself*. It is possible that some of the epoxy does just that in the PBAN-epoxy mixture. That would leave less epoxy to react with the PBAN and therefore more would be required for complete cure.

Answer: If the total number of equivalent weights of hydroxyl materials used is found, that number will be equal to the number of equivalent weights of DDI needed.

$$14 \text{ g R45} \times \frac{1 \text{ equivalent of hydroxyl}}{1040 \text{ g R45}} = 0.01346 \text{ eq. hydroxyl}$$

$$1 \text{ g castor oil} \times \frac{1 \text{ equivalent of hydroxyl}}{164 \text{ g castor oil}} = 0.006098 \text{ eq. hydroxyl}$$

$$0.2 \text{ g tepanol} \times \frac{1 \text{ equivalent of hydroxyl}}{211 \text{ g tepanol}} = 0.0009479 \text{ eq. hydroxyl}$$

$$\text{Total equivalents of hydroxy} = 0.020507 \text{ eq. hydroxyl}$$

$$= 0.020507 \text{ eq. isocyanate needed}$$

$$0.020507 \text{ eq. isocyanate} \times \frac{293 \text{ g DDI}}{1 \text{ eq}} = 6.01 \text{ g DDI}$$

A rule of thumb often used with isocyanates is to use about 5% excess (again, as a starting point). So the actual amount used in a first batch might be 6.01 × 1.05 = 6.31 g DDI

Example: A propellant is to use 14 grams of R45, 1 gram of castor oil, and 0.2 grams of Tepanol. The curative will be TDI. How much will be needed?

Answer: This is the same problem as before, except that the curative has changed. The same number of equivalents (0.020507) of hydroxyl is used, so that number of equivalents of TDI will be needed.

$$0.020507 \text{ eq. isocyanate} \times \frac{87 \text{ g TDI}}{1 \text{ eq}} = 1.78 \text{ g TDI}$$

And with 5% excess, that becomes 1.87 g TDI as an initial trial.

It should be noted here that the cure with TDI may be "touchier" than with DDI. Just 0.2 g excess DDI would be about 3% excess, not much of a problem. If 0.2 g excess TDI is added, that's about 10% more than needed, and may make a large difference indeed in the properties of the cured mixture.

Example: A propellant is to use 14 grams of R45, 1 gram of castor oil, and 0.2 grams of Tepanol. Both DDI and MDI (of eq. wt. 145) are to be used to cure. The amount of DDI is to be two times the (mole) amount of MDI, so that the mixture does not "set" too quickly. How much of each should be used?

(Note: with two curatives, there is an infinite number of possibilities for amounts of each to cure. That's why the proportions of DDI to MDI must be specified)

Answer: Again, this is the same problem as before, except that the curative has changed. This time a little algebra must be used:

total eq. wts. of isocyanate needed = 0.020507 eq. wts.

Let: X = eq.wt. of MDI needed,
So: 2X = eq.wt. of DDI needed.
X + 2X = 3X = 0.020507, the total needed

Then: X = 0.020507 / 3 = 0.0068357 eq. wts. of MDI needed
and: 2X = 0.01367 eq. wts. of DDI needed

So: 0.0068357 eq. wts × 145 g/eq. = 0.99 g MDI needed

And with 5% excess, that becomes = 1.04 g MDI

Then: 0.01367 eq.wt. × 293 g/eq = 4.01 g DDI

And with 5% excess, that becomes = 4.21 g DDI

Remember that these cure calculations give starting points ONLY. Exact amounts are determined by experiment. Generally it is best to use the minimum amount of curative that will give a product with the desired properties. Too much curative may give a product that becomes brittle on storage.

You will notice that both plasticizers and cure catalysts were left out of the cure calculations. A plasticizer does not react with either resin or curative and does not affect the cure as such. However, a large proportion of plasticizer acts to dilute the liquid ingredients and may slow the curing process.

A cure catalyst should not affect the product -- *theoretically*. In fact, since a cure catalyst speeds the cure, a large amount of cure catalyst may result in a harder product than if the cure catalyst were not used. If a cure catalyst is to be used, one approach would be to begin with the calculated amount of curative, and determine the cure time. Then cure catalyst may be added to decrease the cure time as needed.

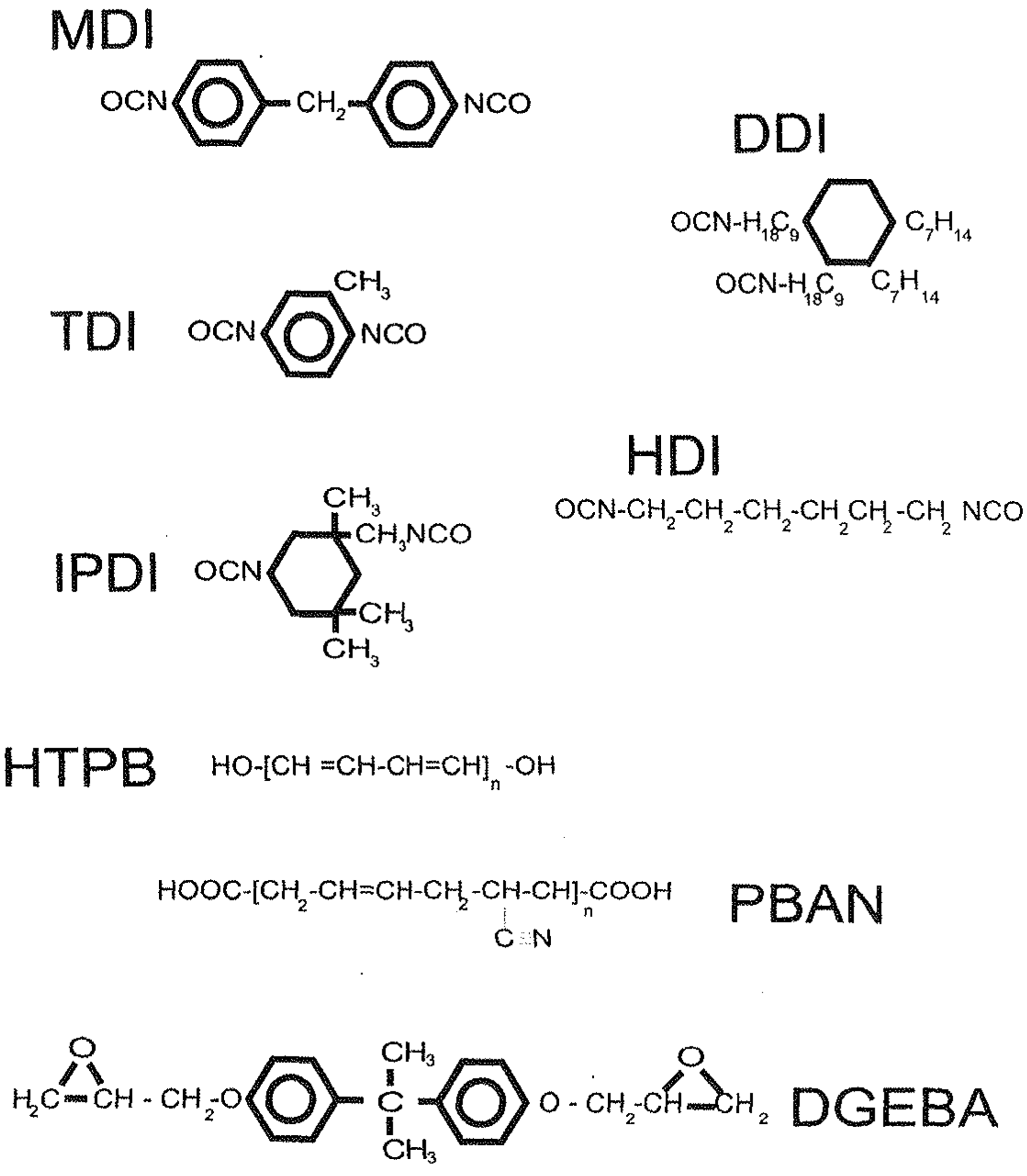

Figure 59: Structures of some of the polymer components used in propellant compounding.

MIXING PROCEDURE WITH HTPB BINDER

If HTPB is to be used as the binder, the procedure is very similar to that used with PBAN. It is assumed here that a bonding agent will be used. If bonding agent is omitted, the period of overnight standing may also be omitted. However, some workers find that an overnight period in the curing box makes the propellant somewhat easier to work.

1. The HTPB, plasticizer, Tepanol, castor oil or other crosslinking agent, cure catalyst, and surfactant are weighed one at a time into the mixing bowl (of course, not all of these may be used, depending on the formulation). These ingredients are mixed thoroughly. If the mixture is to be worked while warm, it is warmed at this time and later as needed.

2. If a burn rate catalyst is to be used, it is weighed into the bowl at this time, then mixed thoroughly.

3. If aluminum or magnesium is to be used, it is weighed into the bowl after the burn rate catalyst, and mixed thoroughly, with care to avoid dusting. Some workers advocate coating magnesium with linseed oil or dichromate[69] before using. Others note that the cured binder acts as a fairly good barrier except at the propellant surface, and suggest simply that the finished propellant and motors be kept in airtight containers until they are to be used.

4. The AP is added in several portions, mixing between each portion as was done with the PBAN propellant. If Tepanol has been used, the odor of ammonia will be noted at this time, and more will probably be noted as the mixture is stirred Stirring brings more of the AP in contact with the dissolved Tepanol.

5. After the AP has been added, the mixture may be allowed to stand at working temperature overnight. This causes the Tepanol to react completely with the AP, and most of the ammonia is liberated, leaving fewer bubbles in the binder.

   However, the mixture should not be allowed to stand longer than this if Tepanol is used. As was noted earlier, Tepanol may decompose if allowed to stand too long at higher temperatures[70].

---

[69] See Shimizu for a procedure for dichromate coating of magnesium. Simple addition of dichromate to the propellant is not recommended. The reaction between magnesium and dichromate is an ionic one, that occurs in water solution but not very well in an organic binder. Thus, the magnesium may remain partially or completely uncoated. Also, the dichromate may cause changes in the burn rate of the propellant, as chromium compounds are often burn rate catalysts.

[70] Troubleshooting hint: if a bonding agent is used and the oxidizer is easily rubbed off of the cut surface of the propellant with a finger, or if oxidizer comes loose when cutting the propellant, the bonding agent may have decomposed. The time for which the propellant mixture stands (uncured) at high temperature should be reduced.

6. If the mixture is to be vacuum processed, the first step of vacuum processing is carried out at this time, as described in the section on vacuum processing.

7. The curative or curative mixture[71] is added and mixed thoroughly. The second step of vacuum is performed at this time. Fast curatives at elevated temperatures may result in a potlife of twenty minutes or less, so time is of the essence. With slower curatives potlife can be adjusted by adding more or less of the cure catalyst.

8. The propellant is packed into casting tubes or casings in the usual way, and cured. Enough trials should be done beforehand so that the potlife is known, so that there is enough time for processing *and* cleanup afterward. A couple of pounds of propellant hardened in a mixer bowl, with the paddle stuck in place is...not gratifying...

Once a formulation has been decided upon, some experimenters prepare a large batch of HTPB, plasticizer, crosslinker, cure catalyst, and bonding agent of the proper proportions. The needed amount of this mixture is weighed out for each propellant batch. This speeds the process (one weighing) and improves reproducibility. If Tepanol is included the mixture should be refrigerated until it is ready for use.

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[71] For mixed curatives it may be convenient to make up a larger batch of curative mixture and add a weighed portion of the mixture to the batch. For example, if DDI and MDI are to be used in a 2:1 ratio by mass, a mixture containing 200 g DDI and 100 g MDI may be prepared and used as needed.

LARGE BATCHES AND MACHINE MIXING

Hand mixing has the virtue of reduced danger. An electric mixer can generate excessive friction and/or sparks. Either of these in propellant can ruin your whole day. Experiments by the author indicate that propellant mixed in small batches by hand can be nearly as uniform, batch-to-batch, as machine-mixed propellant.

But hand mixing is very tiring for more than a pound or so of propellant. Many experimenters have turned to machines for mixing larger amounts of propellant.

Professionally, propellant is prepared in low-shear (low speed) mixers. High speeds tend to reduce the particle size of the oxidizer, and long mixing times at high speed can alter the properties of the polymer. Also, professionally-made propellant is mixed for long periods – up to several hours, to fully incorporate all ingredients. Finally, most professionally made propellant is mixed under vacuum, to maximize density and reproducibility.

Some experimenters use the Kitchen-Aid or Hobart type of mixer for propellant. This is a "planetary" type mixer; the beater spins, and its axis moves around in a small circle (hard to describe; go look at one in a store). The lowest-cost Kitchen-Aid mixer is the 4.5 quart unit, which is about $200 and can mix from about 300-1500 grams of propellant. The slightly larger 5 quart unit is about $300. Some users have noted that the 5 quart unit is significantly more powerful and doesn't overheat as readily. For really big batches, restaurant supply houses sell larger versions (10, 20, 50, and 80 quart) but they're pricey, starting around $2000.

As noted earlier, a mixer can generate sparks and friction. If AP or aluminum dust gets into the motor, it is highly likely that there will be a fire or even an explosion. Extreme precautions must be taken to avoid this. One of the most elementary precautions is to mix the oxidizer and metals in *by hand*, until they are fully moistened. Then the mixer is run to make the mixture uniform.

Never use a makeshift power mixer. A "bread machine", blender, etc. has the potential to "pinch" propellant at the mixing shaft. This is not a recipe for propellant, it is a recipe for disaster; propellant pinched between shaft and bearing can ignite. One professional has reported two accidents caused by friction or pressure on propellant. The Kitchen-Aid mixer has a small amount of clearance between bowl and beater, which is one reason for its choice by many experimenters.

The following is a general procedure for machine-mixing of the simple propellant.

1. The mixer is adjusted for proper clearance between the bowl and the beater. Consult the mixer manual for instruction.

2. PBAN is weighed into the bowl. The lampblack is added, working at an area of the workbench that is at least several feet removed from the mixer[72]. The mixture is stirred slowly *by hand* to mix. The paddle blade of the mixer may be held in the hand to do this. A fixture (½" steel rod with a cross pin) to be inserted as a handle may be helpful to hold the paddle blade.

3. The bowl is installed on the mixer, the paddle blade inserted and the mixer is run for a few minutes, until the mixture is uniform.

4. The mixer is stopped and the bowl again removed to the "safe" area. About a third of the AP is added. The mixture is stirred *by hand* until completely wetted; no white AP should show.

5. The bowl and contents are warmed to the working temperature. It may not be absolutely necessary to warm the mixture, but the mixer will labor less, run cooler, and last longer. The mixer is run for 5-10 minutes.

6. The bowl is again removed to the safe area, and the next third of the AP is added, worked in by hand, then mixed by the mixer for 5-10 minutes, warming as needed.

7. The last third of the AP and the epoxy are added (again at the safe area) and worked in by hand.

8. The bowl and paddle are installed and the mixer is run for 10 minutes or so. If a large batch of propellant is being prepared, the paddle blade may "bog down" and the dough hook may be used instead. The dough hook is not as thorough as the paddle, and may require considerably longer to mix.

9. The mixer is stopped and the paddle/hook scraped off. The bowl is removed (a piece of foil may be useful under the paddle to catch drips).

10. A stiff rubber spatula or flat wooden stick[73] is used to scrape down the inside of the bowl. Be sure that the mixture at the very bottom of the bowl is scraped up; it tends to be difficult to incorporate.

11. The bowl is returned to the mixer and run for about 15 minutes. The mixture is warmed again as needed.

12. The mixer is stopped and the bowl scraped down, then mixed again for another 15 minutes.

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[72] All solids are added *away from* the mixer; this is especially true for AP. Adding solids and mixing them in by hand creates some dust. That dust must not get near the mixer.

[73] A tongue depressor with one end cut off flat makes a useful scraper that can be discarded in the scrap can after each batch.

13. If the propellant is to be vacuum processed, this is performed at this time. If the propellant is to be poured, it is often easier to control by transferring it to a large paper cup.

Note again that a Kitchen-Aid mixer is NOT an explosion-proof mixer and can cause a fire if any dust or propellant gets into it. Some workers prefer to place the mixer at a distance from the work area, and turn it on (off) by plugging (unplugging) an extension cord. Others argue that if something goes wrong there is no way to see from a hundred feet away; they instead run the mixer in an open workshop, keeping it under eye constantly.

If metals, burn rate catalysts, or other solids are to be added, this is done *before* adding any of the AP. Metals especially must be thoroughly incorporated and fully wetted with binder before adding AP.

The exception to this rule is titanium; it is added LAST, after the curative has been added and the mixture has been machine-mixed. The titanium is stirred or worked in *by hand* just before packing or pouring the propellant into the tubes. Titanium scraped against stainless steel can cause sparks. Transfer of the propellant to a plastic bowl before adding the titanium is one method of decreasing this danger.

When machine-mixing, a surfactant can help a great deal in reducing viscosity. One commonly available surfactant is *lecithin.* This is available in granular form, and should be dissolved in a suitable solvent before use. One way to dispense lecithin is to make a 20% solution of it in dioctyl adipate (20 grams lecithin and 80 grams DOA; this will take a long time to dissolve, and some may not dissolve), and add a small amount of this solution to the PBAN before the initial mixing. About 0.1-0.2% lecithin is sufficient for most propellant, so 5-10 grams of the 20% solution would be needed for one kilogram of propellant.

For a surfactant to do its work properly, the propellant must be mixed for an extended period. The length of time to mix may vary with the surfactant and the propellant mixture. To keep the mixture warm during this time, some workers use a heated bowl. http://www.tiac.net/users/bluesky/rockets/ shows a Kitchen-Aid mixer with heating element and vacuum chamber, for mixing under vacuum (gives higher density). One note of precaution: if this type of mixer is operated in a vacuum, it may burn out more quickly than otherwise, since the mixer relies on airflow for cooling.

VACUUM PROCESSING

The single technique that most improves the reproducibility and reliability of experimental propellant is that of vacuum processing (degassing). Examination of a grain of the simple propellant will reveal that it has bubbles. With good technique these bubbles should not be too numerous, but they do decrease the propellant density and change the nature of the burn. The author has found that bubbles tend to make the initial part of the burn somewhat progressive, due to increased surface area with each bubble exposed. Toward the end of the burn, the area at the bubble is the first to reach the wall, and this makes the end of the burn rather regressive and introduces excessive tail-off, as shown below.

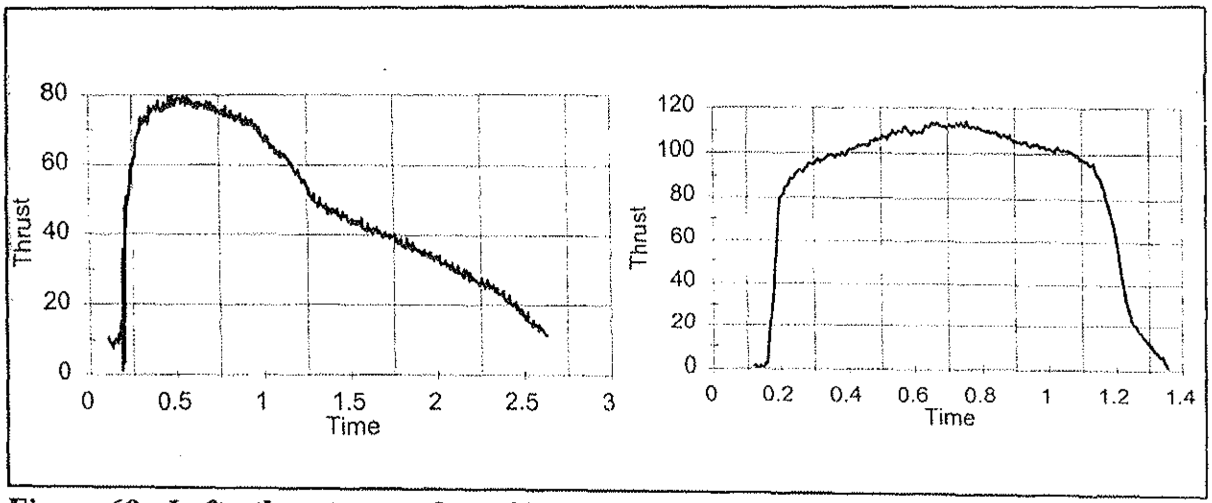

Figure 60: Left: thrust curve from 29mm motor with undegassed propellant. Right: thrust curve from motor with degassed propellant (the different burn times are due to the fact that the propellant compositions are slightly different). Note the more neutral curve and the reduced tail-off.

With vacuum processing, most of the bubbles can be eliminated. The propellant density increases, so the propellant will be correspondingly more powerful volume for volume. And results of motor burns will be more predictable.

One important advantage of PBAN over HTPB is that the curative for PBAN does not react with water. Isocyanates react with water, producing carbon dioxide, which forms bubbles. The formation of CO_2 continues as long as there is any water present. The author's experience has been that degassing of HTPB propellant may take anywhere from ten minutes to two hours. By contrast, the bubbles in PBAN propellant are those which are mechanically trapped in the propellant, from mixing. Five to ten minutes of degassing is often sufficient to remove them.

THE VACUUM PUMP

Of course, a proper mechanical vacuum pump will be needed. Pump requirements are rather modest. The main requirement is *capacity*; it should be able to move at least half a cubic foot per minute *at the desired pressure*. Capacity decreases as pressure drops; a pump that moves 3 cubic feet per minute at normal pressure may only move half a cubic foot at 25" of vacuum. The larger the capacity the more quickly the propellant will be degassed.

Vacuum is often reported as "inches of vacuum". Thirty inches of vacuum is a full vacuum[74]. A pump that produces 29" of vacuum should be quite sufficient, though some workers have reported good results with as little as 25" of vacuum. In fact, too-high vacuum may cause problems in propellant degassing. Some plasticizers will evaporate more readily at low pressure and the propellant appears never to "settle down".

Scientific vacuum pumps often are available as surplus; check the Internet for suppliers. Such pumps are often rather expensive, several hundred to several thousand dollars. And they may be "overkill" for the experimenter. The online auction sites may carry used pumps at much more reasonable cost.

Surplus Center (800-488-3407) sometimes sells vacuum pumps. They also sell compressors that require a motor; a compressor may be used as a vacuum pump by connecting the intake of the compressor to the vacuum chamber.

An old refrigerator compressor or air conditioner compressor may be pressed into service as a vacuum pump. The larger the compressor, the better. Details of setting up such a compressor may be found at http://web2.airmail.net/redmonj/sucker.htm.

An automobile air conditioning compressor may be used as well. A pulley is attached to the shaft and the compressor is run from a washing-machine-type motor at about 600-1800 rpm.

In all such compressors, remember to change the oil frequently. Since the compressor takes in gases from the propellant, any such gases that are corrosive will damage the pump. If you don't like the idea of replacing the pump, keep the oil clean. Special compressor oil is available for about $50 a gallon. Some workers use ordinary motor oil; the author has no opinion on this practice.

THE VACUUM PLATE

The heavy stainless steel bowl used for mixing may be used as the vacuum chamber, for modest amounts of propellant. It is very important that the bowl be very heavy (thick) for this purpose; the bowl must be tested with the vacuum pump *before* trying it with

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[74] Atmospheric *pressure* is about 30 inches of mercury, and perfect *vacuum* is zero inches of mercury. Take note when reading the pump specifications. Often these specs are given in mmHg. Thirty inches of mercury is 760 mmHg.

propellant. A plate for the top of the bowl, a seal, and a connection to the pump are needed. Figure 61 shows such a setup.

The plate must be ½" or thicker polycarbonate ("Lexan" is one such brand). Do NOT use acrylic. Acrylic has about one-fifth the strength of polycarbonate. If the plate cracks there will be a catastrophic mess and may be injury. The plate shown in the figure is 1" thick; the author values his safety.

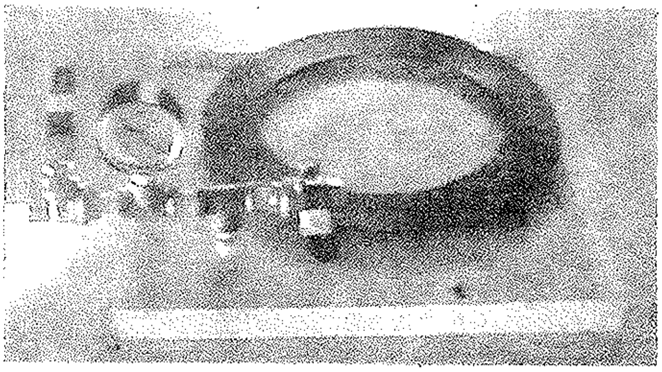

Figure 61: A vacuum plate to fit the mixing bowl.

In the figure, a ¼" pipe thread was drilled and tapped into the plate near the edge. A short brass pipe nipple was Teflon-taped and screwed into the hole. A T was screwed on to this nipple. On the left of the figure, a second nipple and T were attached. One opening of this T was connected to a ball valve (from the hardware store; this valve will be called the "pass" valve) which in turn was connected to the vacuum pump. A vacuum gauge was screwed into the other opening.

On the right of the figure, a second ball valve (called the "vent" valve) was connected. It is open to the air. This is necessary because under vacuum, propellant can foam to twice its initial volume or much more, depending on the solids content. Propellant going into the vacuum hoses is a very bad idea, as might be imagined. The vent valve allows the chamber to be opened to the air almost instantly[75].

On top of the plate is a sealing ring cut from black sheet rubber. Silicone caulking can be used to make such a ring, if sheet rubber is not available. A sheet of heavy polyethylene (drop "cloth") is taped flat onto a smooth, flat surface, such as a countertop. A ring of silicone about the size of the bowl's rim is squirted onto the polyethylene. A second sheet of polyethylene is taped securely to a smooth, flat piece of wood. The silicone is flattened between them to about ⅛" thick. The tape is removed and the wood carefully slid off. The silicone will harden in a few days. After that, the polyethylene is peeled off, the bowl placed on top of the silicone, and a gasket about 1" wide is cut from the silicone. With silicone, there is no need of a grease seal for the gasket unless the pump is very small.

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[75] A safety trap is a good idea. In laboratories, a safety trap is made from a special heavy-walled flask with a two-hole rubber stopper. A tube in one hole is connected to the pump, the other to the vacuum chamber. If propellant does flow out of the chamber, it goes into the trap first before it can get to the pump. The two tubes in the stopper are of different lengths so that the ends will not be close together.

Heavy-wall tubing should be used for vacuum connections. Thin vinyl tubing usually collapses. Heavier semi-rigid polyethylene tubing or heavy-wall rubber tubing can be found at most hardware stores.

THE DEGASSING OPERATION FOR PBAN PROPELLANT

1. The seal is placed on the rim of the bowl. The tubing is connected to the pass valve and the plate is laid on top of the seal. The vent valve is opened to the air.

2. The vacuum pump is started. The vent valve is slowly closed, while watching the propellant through the plate.

3. As the pump runs, the propellant will rise in the bowl. How much it rises depends on the solids content. Very high-solids propellant will rise just a little; propellant that flows or sags when the bowl is tilted can rise and foam a great deal. It is ***critical*** that the propellant not enter the tubing that leads to the pump. So as the propellant rises, the plate is held in the hands and the bottom of the bowl is tapped firmly and repeatedly on the bench top (an alternative is to place the bowl on a vibrating platform). That will tend to break bubbles and settle the propellant.

4. It's quite possible that tapping the bowl won't slow the foaming down enough; the propellant may rise near the plate. If this happens, the vent valve is opened immediately, enough to stop the rise. Watch out for spattering of the propellant near the inlet when the air rushes in. When the propellant level drops, close the valve again. Keep opening and closing the valve as needed to keep the propellant foaming a little (but not too much).

5. As this continues, the propellant gradually "settles down" and eventually almost stops bubbling. With PBAN propellant this may take about 5-10 minutes, depending on the size of the vacuum pump and on the solids content.

6. When the propellant appears to have settled down and very little gas is coming from it, close both valves, then shut off the pump. Now tap the bowl on the bench to settle the propellant as much as possible, then allow the setup to stand until enough air has leaked in so that the plate can be lifted off. The slow leakage allows additional bubbles time to rise and burst, and leaves fewer bubbles in the finished product.

The propellant can be rolled and packed at this time. However, some workers prefer to tamp the propellant down into the bowl with the mixing stick, then vacuum a second or even a third time, to insure that as many bubbles are removed as possible.

Once the propellant has been vacuum-processed, care should be taken not to re-introduce bubbles in the rolling and packing. Degassed propellant does not flow as easily as non-vacuumed propellant. Bubbles tend to act like tiny ball bearings and make the propellant flow more readily. Thus, a mixture that was pourable without vacuum processing may not be pourable when it is vacuum processed.

Very high-solids propellant often behaves a bit differently; it rises a bit, settles back some, and stays that way. However, it is still better to vacuum such mixtures than not.

THE DEGASSING OPERATION FOR HTPB PROPELLANT

The mechanics of degassing are similar for PBAN and HTPB. However, potlife of HTPB mixtures is usually shorter than for PBAN mixtures. To provide enough time to cast the mixture, some workers elect to degas HTPB propellant in two steps.

In the first step, the mixture is thoroughly degassed *before* the curative is added. This degassing helps to remove water, which can react with isocyanate curative. It also removes ammonia[76]. This first degassing step may be done for an hour or two.

In the second step, the curative is added and mixed in for a relatively short time, then the mixture is briefly degassed again. The length of time for this mixing and degassing depends on the curative used. If MDI-containing curative (PAPI or Isonate) is used at elevated temperature, there may be only a few minutes before the mixture begins to thicken perceptibly. Mixing and degassing must be finished within that period. If IPDI or DDI are used, there is more time available. Generally, it is a good idea to mix for about five minutes, scrape down once in the middle of that time, then do the second degas for about five minutes.

Some workers elect to use a vacuum mixer, so that the curative can be added and the mixture mixed while degassing takes place. One such mixer is described at http://www.tiac.net/users/bluesky/rockets/. The author has not attempted to use such a configuration; it is provided for reference only.

SILICONES AS PROCESSING AIDS

Silicone oil (polydimethyl siloxane or PMDS) is a surface active agent used as an antifoaming agent. It causes bubbles to break more easily. This can be a significant advantage in vacuum processing, because the propellant does not foam up as much. Some workers recommend adding about 0.1% or less of silicone oil (one drop to a typical batch) to a propellant mixture for this reason. In practice, the author has not found this to make a great difference; however, the reader's experience may be different.

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[76] When Tepanol is used in AP or AN propellant, ammonia gas is generated. Since ammonia is rather corrosive to the vacuum pump, the mixture may be allowed to stand overnight at atmospheric pressure after the Tepanol and AP are added. Most of the ammonia is given off, so very little comes out in the vacuum processing.

A Simple Thrust Stand

Being a proper thrifty Scot, I hate to pay a buck when a nickel will do the job. So I've spent a fair bit of time working on a small stand for evaluating motor thrust, at the lowest possible cost, that uses stock commercial components. I wanted to avoid surplus items that may or may not be available later.

The one I came up with requires a computer that has a serial port, and runs Windows 3.1 or above. I started with a 386SX 25 MHz laptop, moving to a 486 33MHz when the 386 died. Acquisition rate is up to 200 points per second for as long as you want to acquire data. Maximum thrust must not exceed 40 lb (about 180 newtons) with this cell, but the general design should be adaptable to much larger systems. Best of all from my point of view, the cost for the major parts is as follows:

Data acquisition system	$100 (or less)
Load cell and mount	99
Amplifier parts	20

The stand itself is constructed on a small steel I-beam. With a bit of scrounging, the entire system less computer can be had for about $250.

Theory of Operation

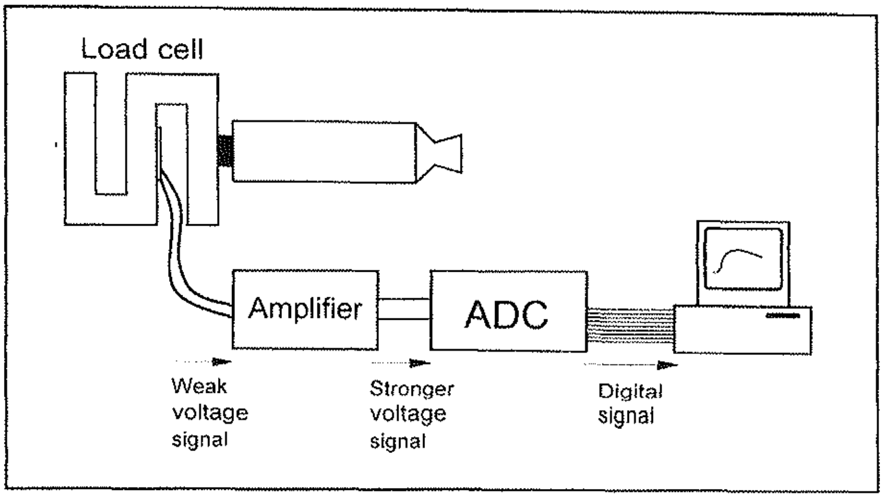

Figure 62: Schematic diagram of an electronic thrust stand

Figure 62 shows a simple thrust stand setup. A *load cell* is a device with one or more *strain gages* on it. When force (i.e., thrust) is applied to the load cell, it bends or distorts slightly. This changes the resistance of the strain gage(s). The resistance of the load cell depends on the amount of force, so measurement of that resistance gives a measure of thrust.

A constant "excitation" voltage is applied to the strain gages. The strain gages then produce an output voltage that is proportional to the applied force. That output voltage is very small, on the order of a few millivolts, and so must be amplified. The amplified signal is sent to an analog-to-digital converter (ADC), which changes the voltage to a digital signal that a computer can understand. The ADC performs its operation many times per second, in effect giving a graph of force as a function of time -- a thrust curve.

LOAD CELL

The Omega model LCL-040 thin beam load cell, with 40 lb capacity ($69) was used for this system. Specifications are available from the company (http://www.omega.com). This load cell does not include a mount; you can make one yourself if you've access to a milling machine, but the Omega LCM-CL1 mount at $30 can hardly be beat. Once mounted, the unit is attached to the stand by a single 10-32 machine screw. A second screw attaches several washers to the cell, against which the motor bears. Other load cells should work as well for this application.

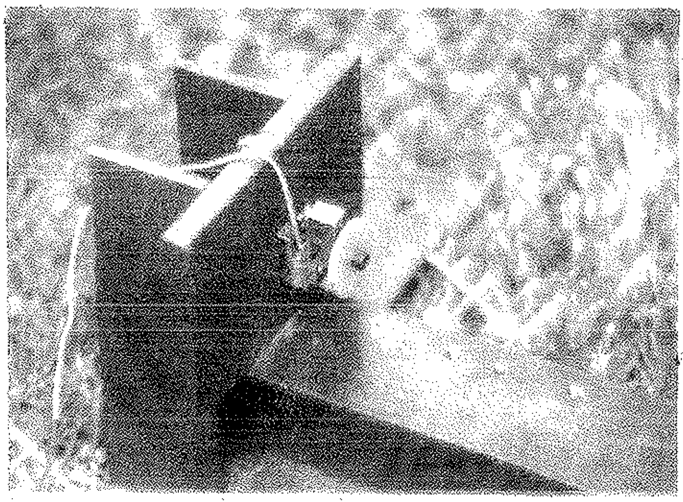

Figure 63: The load cell mounted to the upright plate of the thrust stand. Large washers are attached for the motor to bear upon.

HARDWARE

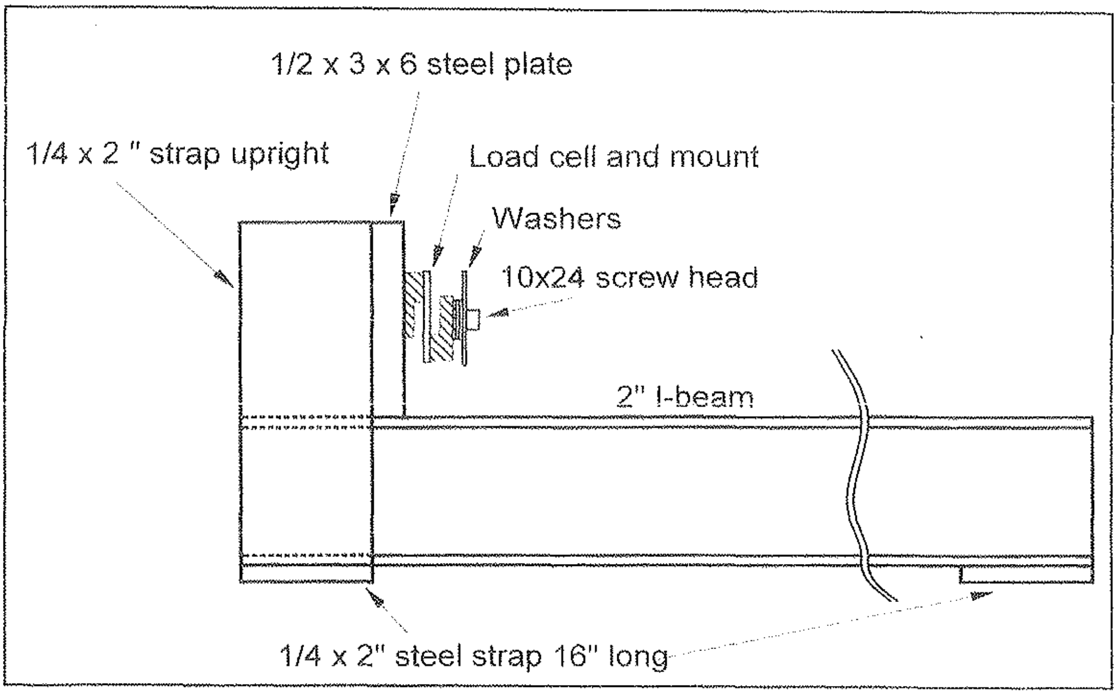

Figure 64: Side view of the thrust stand hardware.

The stand itself uses a 2' long section of 2" steel I-beam which, as it turns out, was rather excessive. For this system a smaller, lighter stand would probably work just as well. Two 16" lengths of ¼ × 2" steel welded to the bottom have drilled holes so that the stand can be anchored. Two more 6" lengths of this steel are welded upright to the sides of the beam, at one end, and a steel plate 3" square is welded to them. The mounting hole for the load cell is in the center of this plate and it is drilled *before* welding the plate in place (it's very difficult to reach with the drill press once the stand is assembled).

DATA ACQUISITION SYSTEM

The DATAQ DI-180 used for this project is a serial data acquisition system with 12 bit precision (means readability is better than 0.05%), and can run at up to 200 samples per second. At that rate a 10 KB file provides 23 seconds of run time. That's enough for almost any motor test, and time resolution is 0.005 seconds. The WinDaq Lite software is free with the system, or can be downloaded at http://www.dataq.com. I prefer spreadsheets, so I convert the data to a text file that can be imported into Quattro Pro. That option is available in the software.

One caveat: if an ejection charge is being used in the motor, use a small amount of BP. A large amount could damage the load cell.

The software is very easy to use; install and run. It's fairly self-explanatory. The DI180 itself is also easy to use. Plug it into the serial port with the included cable, connect the wires from the amplifier, and you're ready to run.[77]

AMPLIFIER

The load cell has a maximum output of about 10 mV. The data acquisition system has a maximum range of 3V. So the signal from the cell must be amplified about 200 times or so for a reasonable input. The Burr-Brown INA125 instrumentation amplifier (available from DigiKey, http://www.digikey.com) is designed

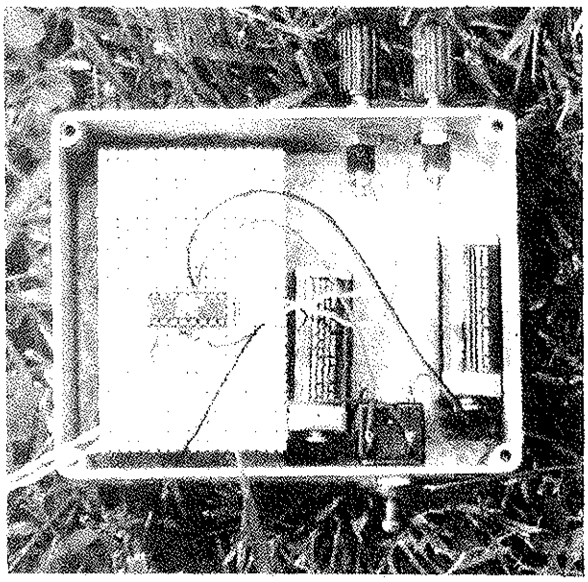

Figure 65: Photograph of the amplifier. The two 9V batteries are visible in the box. At the bottom of the photo is the switch. At top are the banana plug connections to the data acquisition system.

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[77] DATAQ no longer offers the DI-180, but now (March 2000) markets the improved DI-151 ($99). The new model has TWO inputs so one could measure chamber pressure from another sensor. It also has a maximum data acquisition rate of 240 points per second, and input of ±10V. To make full use of this newer system, the resistor on the amplifier may be changed to increase the amplification from 300 to 500 times. Burr-Brown gives information on the resistance to be used at their website.

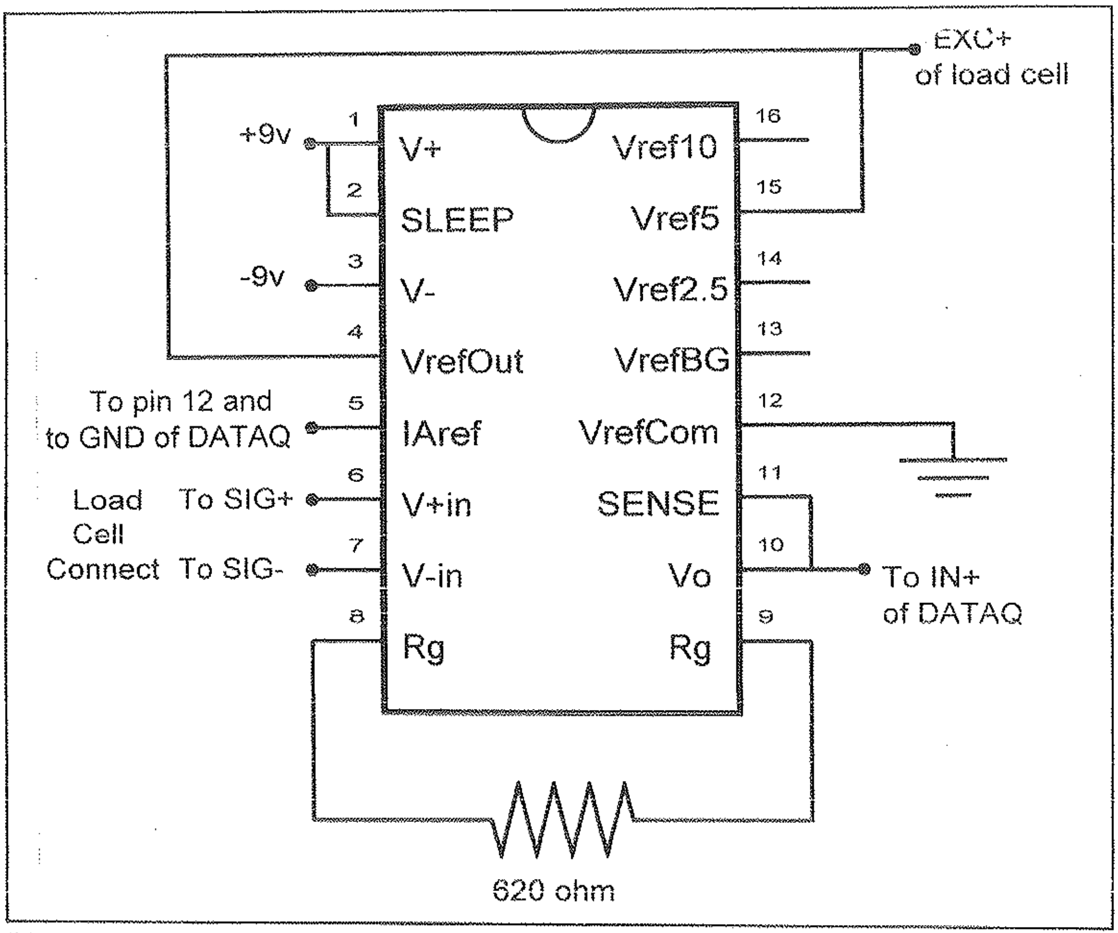

Figure 66: Circuit diagram for load cell amplifier based on Burr-Brown INA125

specifically for bridge resistance applications like this one. The only external components needed are: one resistor (620 ohm) to set the amplification and two 9V batteries for power. The circuit diagram is shown in Figure 66.

Using batteries rather than a power supply provides simple portability and avoids the problems of noise from the power supply. It may be possible to run from only one battery but I elected not to try; I was afraid of frying the data acquisition system if the amp was hooked up incorrectly (not an electrical engineer by any means...)

A double pole switch turns on the battery power. Don't forget to turn it off at the end of a session, or you will be replacing batteries frequently. An "on" LED would probably be a good idea...

The INA125 provides the necessary regulated excitation voltage for the load cell. Since the circuit is designed for ±9 V power, the 5V excitation voltage is selected (if ±12V power was used, the 10V excitation voltage could be selected for improved sensitivity).

The amp is hard-wired to the load cell. Connection to the data system is by dual "banana plugs". They are cheap, easy to use, and can be keyed or color coded to make it difficult to mess up the connection.

MOTOR MOUNT

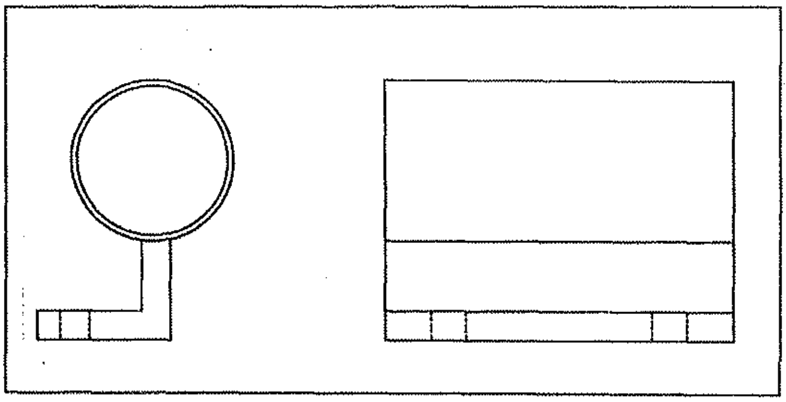

Figure 67: Motor mount for thrust stand, made from a piece of phenolic tubing and an aluminum angle. Dimensions are not critical but the height and location of the mount should be such that the forward end of the motor bears against the button of the load cell.

The motor mount is shown in Figure 67. It is nothing more than a piece of motor-mount tubing mounted on a piece of aluminum angle. The tubing was sanded smooth and deburred inside, to minimize friction. Epoxy and fiberglass was used to mount the tube on the angle. One leg of the angle was cut shorter, to a height such that the center of the motor presses against the center of the load cell. Holes were drilled in the bottom of the angle for mounting to the I-beam with thumbscrews.

The figure shows a 29mm motor mount. An adapter is used for 24mm motors; a second mount was constructed for 38mm motors.

The motor is simply slid into the tube. On ignition, the motor forward closure simply presses against the load cell. To avoid errors due to friction the motor must slide freely inside the mount. For safety, a thin steel cable is attached to the aft end of the motor with a hose clamp. The other end of the cable is staked to the ground. If the motor ejects and starts spinning about, it will be restrained by the cable.

Warning: NEVER test an "unproven" motor on your nice test stand. A CATO may destroy the load cell.[78]

OTHER CONSIDERATIONS

The amplifier is connected to the load cell by a few feet of 22 ga. twisted-pair wire. The same kind of wire connects the (analog signal of the) amplifier to the (input of the) data system.

Four tent stakes about a foot long are used to hold the stand to the ground, through holes drilled in the legs. For a larger test stand a more permanent method of anchoring is necessary, but for 40 lb maximum thrust, tested horizontally, this method has been more than adequate.

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[78] Been there, done that... The LCL-040 is not particularly rugged. Other workers have claimed that better load cells have survived catos on their stands, so this is certainly an argument for spending the money on a better cell.

This stand fires horizontally to minimize error from changing propellant weight. Watch out for fire! Remove any loose grass from the area. For a larger stand it might be preferable to fire vertically and correct for propellant weight changes. I've not decided that one yet...

CALIBRATION PROCEDURE

The calibrating weight used was a short piece of 1" lead-filled copper tubing (slides easily in the motor mount tube), which was epoxied to a large chunk of lead in a can; the entire weight is 60.41 Newtons. Although it looks crude it is correct to better than 0.1%, as it was weighed on a large-capacity digital balance. Theoretically it doesn't matter WHAT the calibration weight actually weighs, as long as you *know* exactly what it weighs. In practice, the calibrating weight should be somewhere in the neighborhood of half of the maximum motor thrust, or more.

1. Turn on the power to the amplifier (the DATAQ is powered from the serial port of the computer, and is on whenever the computer is on).

2. Run the WinDAQ Lite software.

3. Open the EDIT menu and click on "Sample Rate". Enter a Sample Rate of 200 and click OK.

4. Stand the thrust stand on its forward end.

5. Open the EDIT menu again and click on "Low Calibration". Type "0" (zero) in the "Low Cal Value" block. Move down to "Engr. Units" and type "N" or newtons. Click the OK button.

6. Slide the calibrating weight into the motor holder, allowing it to rest on the load cell.

7. Open the EDIT menu again and click on "High Calibration". Type "60.41" (the weight of *your* calibrating weight, in Newtons) in the "High Cal Value" block. Click the OK button.

8. Remove the calibrating weight and stake down the thrust stand.

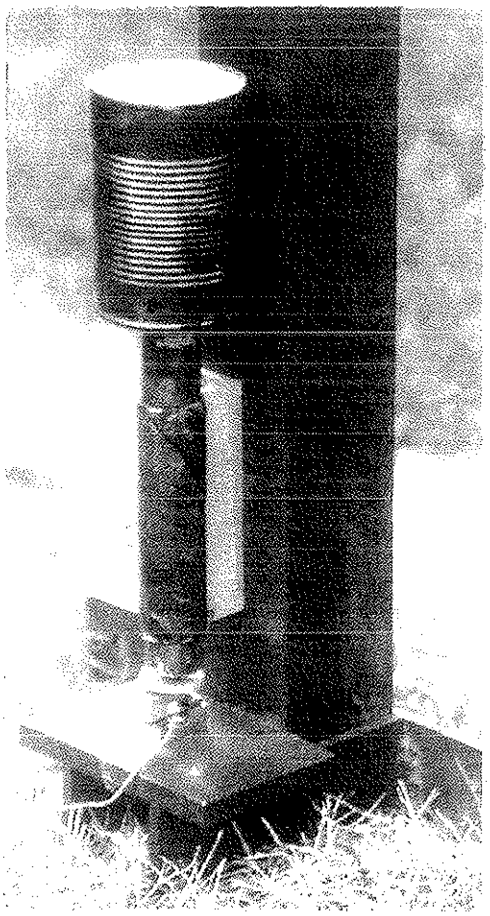

Figure 68: Calibrating the load cell.

Ordinarily it is not necessary to redo the high calibration on a day's run. However, the system may "drift" a bit (whaddaya expect for a cheap system??). From time to time, you may want to re-do the low calibration. It is not necessary to stand the thrust stand on end again for this; simply select "Low Calibration" and enter zero for the "Low Cal Value".

MOTOR TESTING

1. Prep the motor, and attach the restraining cable to the aft end.

2. Slide the motor into the motor mount so it touches the load cell screw. Note that there is a series of washers used on this screw, so that motors of varying forward diameters can bear against the cell.

3. Clip the leads of the launch system to the igniter, and install it in the motor.

4. Click on FILE then OPEN. The OPEN window will appear. Type in a file name WITHOUT an extension (the program automatically adds the .WDQ extension). Click the OK button. (I selected TEST_001 as the first filename; on subsequent runs the program automatically gives TEST_002 for the next filename, etc.)

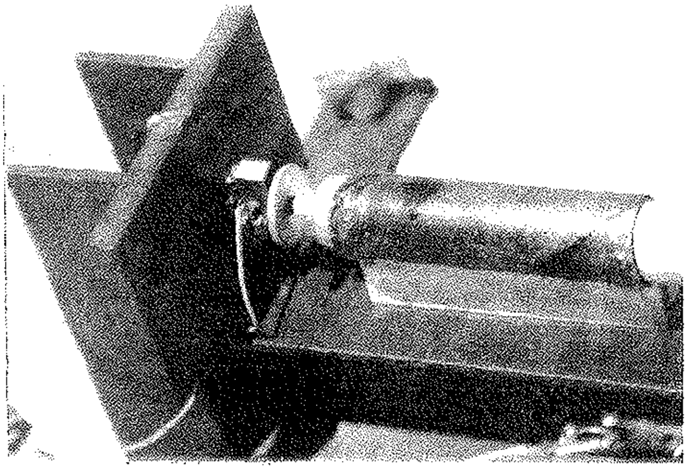

Figure 69: Motor in place on the thrust stand, ready for the test.

5. The FILE SIZE window will appear. Type "10" for the file size selected and click OK. You may get away with a 5 KB file but I wouldn't push it.

6. Arm the launch system.

7. Give a countdown. When the countdown reaches 3 or 2 seconds, press the F4 key of the computer. This starts the data acquisition process, and it will acquire data until the file is full, about 23 seconds for a 10 KB file.

8. When the data file is full, select FILE then CLOSE to save the file.

It would undoubtedly be possible to make the computer start taking data automatically, using a double pole launch switch and appropriate circuitry to connect to the computer. There's a lot to be said for the KISS principle here, though.

I keep a permanent notebook with the test data from all motor firings, including the data file name. Always record everything IMMEDIATELY following the test. Don't wait until later. Don't record it on scratch paper.

REDUCING THE DATA

To convert the data to a spreadsheet requires a little manual work. Unless you're running dozens of tests a day, it isn't very troublesome.

1. Run the DATAQ Playback software. The "WINDAQ Playback Open" window will appear.

2. Double-click on the file you wish to use. You should see the thrust curve on a grid screen; there is a vertical cursor on that screen as well.

3. Use the right arrow to move the cursor to a point just before the motor ignites. Press F4.

4. Use the right arrow to move the cursor to a point past the last data you wish to use.
5. Click on "File" from the menu, then "Save As". The "Save As" window will appear.

6. Type in a filename (you can use the same filename for convenience, as it will be saved with a TXT extension), then click on the "Format" button. Another window will appear. Select "Spreadsheet print", then click the "Save" button.

7. Check the boxes labeled "Sample Rate" and "Relative Time" (you don't really have to do these). If you wish to include comments (such as propellant weight, nozzle throat, type of propellant, etc.) type them in the spaces provided, and check the "Comments" box.

8. Click the "OK" button.

The saved file can be loaded into your favorite spreadsheet for manipulation. A sample file is included on the ProPel disk. Generally:

Start -- thrust exceeds 10% of the maximum thrust.
End -- thrust drops below 10% of the maximum thrust.

The thrust curve shown at the right is raw data, unsmoothed, as displayed by Quattro Pro. This is a three-BATES-grain motor using the 10% aluminum propellant.

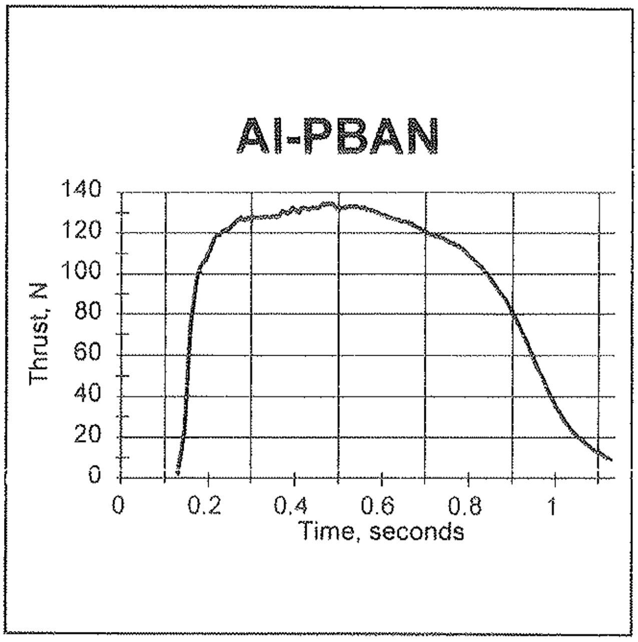

Figure 70: Thrust curve data collected from an experimental motor, using the stand described here.

THE COMBUSTION PROCESS

Exactly what happens at the molecular level when AP propellant burns is a subject that is still being investigated by the big guys, even though the stuff has been in use for about fifty years. However, a fair knowledge of the process is available. The description given here is rather elementary. For more information, consult the references.

A rocket motor is sometimes described as "a controlled explosion". This is erroneous (and gives rise to rather a lot of misunderstandings). Propellant combustion is just that: *combustion*. It differs from combustion of paper, wood, coal, etc. largely by the location of the oxidizing agent. In propellant, that oxidizer is within the propellant; in paper, coal, etc. the oxidizer (oxygen gas) diffuses to the reaction zone from outside.

PREMIXED FLAME AND DIFFUSION FLAME

A *premixed* flame is one in which the oxidizer and fuel are mixed intimately (at the molecular level) before combustion. An example would be a mixture of methane and oxygen gases. Such flames tend to have very high burn rates, on the order of meters or tens of meters per second for gaseous mixtures, and several times higher than AP combustion rates for solid mixtures.

In a *diffusion* flame, the oxidizing species and the fuel species do not mix until they reach the reaction region. A candle (and almost any other combustion ordinarily observed) is a diffusion flame; the oxygen mixes with reactive species from the wax, in the region of the wick. AP composite propellant burns by a diffusion process[79], and the rate at which it burns is partly diffusion controlled. Hence the error in calling a rocket motor a "controlled explosion".

FLAME ZONES

Examine a candle flame carefully; several distinct zones can be seen. A region immediately surrounding the wick is pale blue, almost invisible. That region contains wax vapor, which has (mostly) not yet decomposed. Wax melting, vaporizing and breakdown are *endothermic* processes; that is, the wax (fuel) must *absorb* heat for these processes to occur. That heat, of course, is supplied by the candle flame. This pale-blue zone is non-luminous because the fuel vapor and oxygen have not yet reacted.

Beyond the nonluminous zone is a bright yellow-white region. Between this zone and the pale-blue zone, the wax vapor breaks down and mixes with oxygen. In the bright zone, the products of wax breakdown and the atmospheric oxygen actually react.

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[79] It's true that the oxidizer and the fuel are mixed together, but they are mixed on a "gross" scale. At the molecular level, the oxidizer and fuel in AP composite propellant would be considered to be widely separated. Also, the actual species that undergo reaction aren't AP and fuel, as you will see a bit farther on.

Above the bright region is a darker yellow region. Here the reaction products are recombining, forming other species, and cooling down. The yellow color of a candle flame (and of many other flames) is due to the formation of C_2 molecules which, when heated, give off yellow wavelengths of light.

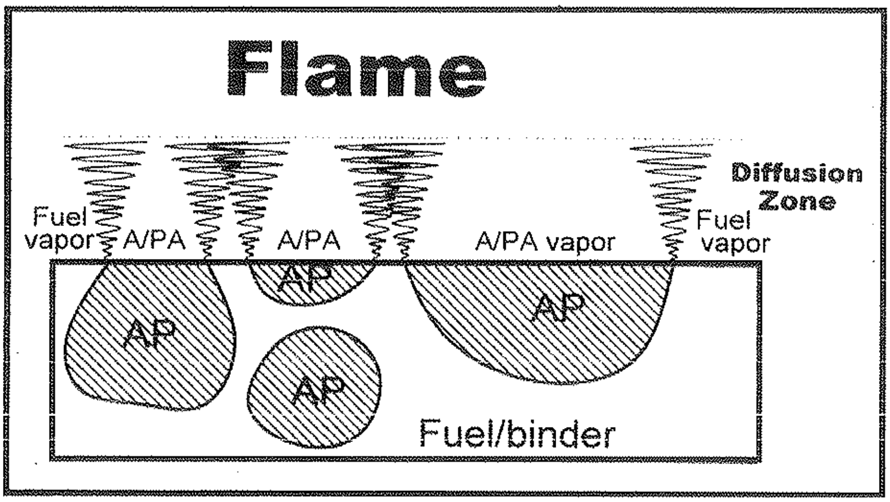

Figure 71: Model of the combustion process for composite AP propellant (not to scale; the diffusion zone is only a few micrometers thick).

At the surface of ammonium perchlorate composite propellant, much the same processes occur, and so there are distinct reaction zones just as in a candle flame. A simplified model of the propellant surface and the processes is represented in Figure 71.

The combustion process begins with the solid propellant being heated from the flame above it, and the propellant vaporizing at the surface. On top of the propellant surface is a thin (few micrometers thick) *diffusion* zone that contains this vapor. The vapor consists largely of ammonia vapor and perchloric acid vapor (A/PA vapor) and fuel vapor (molecules or fragments of molecules). The A/PA vapor forms because solid AP does not vaporize into gaseous AP; rather, it appears that ammonia and perchloric acid *dissociate* molecule-by-molecule from the surface.

The diffusion layer is not uniform. Remember that AP particles and the "chunks" of fuel between them are several tens or hundreds of microns in size, much larger than the dissociation layer's thickness. Instead, within the diffusion layer there will be tiny pockets that consist mostly of A/PA, because each such pocket is right above an AP particle. Other pockets contain fuel vapor; these pockets are above the binder. The pockets shift and change location constantly. When an AP particle is consumed, there is binder just below it, so the A/PA pocket changes to a fuel pocket[80].

---

[80] The "lumpy" or granular nature of the diffusion zone is an important aspect of one of the better-known models of propellant combustion, the so-called Granular Diffusion Model by Summerfield.

As the gases diffuse away from the propellant, several things happen. Temperature rises, because the gases are closer to the reaction zone. Molecules from fuel pockets diffuse into A/PA pockets, and ammonia and perchloric acid molecules diffuse into fuel pockets as shown in the figure.

As diffusion occurs, reactive molecules and fragments of molecules come in contact and of course they begin to react. These are exothermic reactions, and the temperature rises dramatically. The result is a flame above the diffusion zone. Energy from the flame feeds back into the solid propellant, continuing the entire process and producing steady-state combustion.

THE RATE-LIMITING STEP?

Any chemical reaction occurs as a series of "steps" or individual reactions between molecules/ fundamental particles. In each chemical reaction there is a *rate-limiting step*; it is the slowest step, and it determines how fast the overall reaction occurs[81].

In a candle flame, the step that determines the rate at which the candle burns (*rate-limiting step*) ordinarily involves decomposition of the fuel. A candle burns slowly because the wax must melt, then vaporize, then break down slightly into more reactive species. Those processes all take a great deal of time, chemically speaking. After decomposition, the reactive species react very rapidly indeed with oxygen from the atmosphere.

Clearly, to increase the rate of candle burning, it is the rate-limiting step that must be speeded up.

Much the same is true of composite propellant. The solid propellant components must melt and/or vaporize, then partially decompose for the actual combustion reaction (in the flame zone) to occur. One difference between composite propellant flame and other kinds of flame is that in composite propellant the *oxidizer* also must decompose. It is this (relatively) slow decomposition of solid fuel and solid oxidizer that largely determines the burn rate of the propellant[82].

Part of what is not yet known about composite propellant combustion is the actual nature of this decomposition, at the molecular level. It is clear that *decomposition of the oxidizer* is a major step, since burn rate exponents (which describe burn rates) depend on the type of oxidizer. The burn rate exponent of pure ammonium perchlorate has been found to be around 0.3, very nearly the same as that of AP propellant. But several

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[81] Analogy: if a fast food restaurant wants to speed up production of gristleburgers, they have to speed up the slowest (rate-determining) step -- cooking the burger. If they can cook 20 burgers a minute, they can dish up 20 burgers a minute; no more. The guys that assemble the burgers may be able to assemble them at 50 per minute, but that does no good if there aren't cooked burgers to assemble...

[82] The diffusion process itself also has a bearing on burn rate. That process is relatively slow, though not ordinarily as slow as is the propellant decomposition.

researchers have indicated that *binder decomposition* is also a very important factor. And the *diffusion* is certainly a contributing factor as well. The degree of contribution of each of these three processes is still unclear.

To increase the burn rate of the propellant, one or more of these slow steps must be speeded up.

BURN RATE AND PRESSURE

Why does burn rate depend on pressure? One reason is that an increase in pressure makes the diffusion layer thinner. This brings the hot reaction zone closer to the propellant surface. The closer the flame is to the propellant, the faster the propellant can decompose into fuel vapor, ammonia, and perchloric acid. Consequently, the burn rate increases.

BURN RATE AND MODIFIERS

Burn rate modifiers perform a number of different functions in propellant. There is a great deal of uncertainty as to which processes are most prevalent and/or important. Some workers have postulated that AP dissociation is speeded by TMOs because of the formation of metal-ammonia complexes; this helps ammonia to leave the surface of the AP. Others have indicated that unstable metal perchlorates form, helping perchloric acid to leave the surface. Still others suggest that the TMO in the binder collects at the surface. Thus, radiation and heat are absorbed more readily by the binder, increasing binder regression.[83]

It is generally agreed that burn rate suppressants such as LiF, NH_4Cl, and oxamide interfere with the initial decomposition of AP into A/PA vapor.

BURN RATE AND AP PARTICLE SIZE

Here it is the diffusion process that is speeded by decreasing particle size. With large particles of AP, the A/PA vapor must diffuse a large distance to reach reactive fuel vapor. Smaller particle sizes mean shorter diffusion distances.[84] Note that the literature indicates that the rate is not extremely dependent on particle size. Apparently the diffusion process does not provide a major contribution to the overall burn rate.

GRAIN TEMPERATURE AND BURN RATE

It has been known for some time that propellant that is warmed to room temperature or above will burn faster than cold propellant. This may seem counter-intuitive, since this

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[83] Each group has experimental evidence to support their hypotheses. Each group also finds that their predictions have limitations. That's science, and that's why there's still controversy...

[84] Of course this doesn't tell the whole story. As noted in an earlier section, propellant made from extremely fine AP can have a lower burn rate than propellant made with coarser AP.

sort of temperature difference is only a few tens of degrees, while the propellant burns at 3000°F or more. However, remember that the rate-limiting step involves the propellant decomposition or vaporization. These processes begin around 400°F, sometimes lower. So warming the propellant just a few tens of degrees brings it significantly closer to its decomposition temperature and consequently has a significant effect on burn rate.

INCREASING BURN RATE WITH WIRES

Wires embedded in the propellant can increase the burn rate by a factor of seven or more. Again, this arises because the wires conduct heat to the propellant and bring its temperature that much closer to the decomposition temperature. As might be expected, the better the wire conducts heat, the faster the propellant burns; silver and copper wires work best, but aluminum is quite useful here and can add to specific impulse. Some workers have experimented with pieces of aluminum wire or aluminum staples mixed with the propellant, to increase the burn rate. Very fine wire must be used to insure that it will burn properly before exiting the nozzle.

PRESSURE LIMITS AND CHUFFING

At low pressure the combustion region may be so far from the propellant surface that the propellant does not absorb enough energy from it to sustain the decomposition. Under such conditions, the propellant will "go out". For composite AP propellant the critical pressure is about 150-200 psi, though that pressure may vary with additives[85].

Near this critical pressure, *chuffing* can occur. A portion of the propellant decomposes on ignition and generates the reactive gases that undergo combustion. But not enough of the propellant has decomposed to cause the motor to reach "steady state" combustion. The heat from the combustion is insufficient to keep the motor operating. However, it is enough so that when the heat diffuses to the propellant surface and the products of combustion have diffused away from that surface, the propellant re-ignites. These spurts of combustion can continue until the motor either ignites fully, or goes out completely. The proper cure for chuffing is usually an increase in chamber pressure by increasing K_n.

EROSIVE BURNING

Erosive burning can occur when the combustion gases flow rapidly over the propellant surface. The fast gas flow increases the burn rate; the faster the gas flow the greater the increase in burn rate. There are several theoretical models for erosive burning, but one that is accepted by many is that the fast-flowing gas increases mixing of the A/PA vapor and the fuel vapor, effectively bringing the flame zone that much closer to the propellant surface.

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[85] In fact, this is a "safety feature" of AP composite propellant. When a BP motor catoes, the propellant will continue to burn, for BP burns at almost any pressure. When an AP motor catoes, the propellant often goes out. This permits examination of the propellant grain to see what might have gone wrong.

Naturally, gas flow out of the nozzle is very rapid; in fact, gas flow through the nozzle throat is at sonic speed. If the nozzle throat is significantly smaller than the core area, the flow over the propellant is correspondingly slower, and erosive burning is less severe. When the nozzle throat is close to the same size as the core area, flow of gas over the propellant is nearly at the same rate as flow through the nozzle -- very fast -- and erosive burning is more severe.

Erosive burning actually can be useful in a motor designed specifically for it. Consider a motor with BATES grains that are twice as long as their diameter. Ordinarily such a motor would be slightly progressive. Consider that the motor is designed so that the maximum (end) pressure does not exceed case limits, *and* the nozzle throat diameter is such that the motor is erosive at first. In such a motor, the initial pressure will be increased by the erosive burning, until the core has increased in size so that erosive burning no longer occurs. The net result is that the motor may be more neutral, even regressive. Such an approach is almost a necessity for very long motors which use rather large nozzle throats. It is very important that the erosive behavior of a propellant be characterized when making use of erosive burning. The propellants described in Table V have not been characterized according to their erosive burning.

METAL COMBUSTION

The combustion of metal in propellant is not thought to occur in the same fashion as does AP or binder-fuel. Basically, metal particles are thought to undergo several processes in a rocket motor:

1. The metal particle is heated from the nearby flame until it melts; a thin layer of oxide forms on the surface of this particle at some point during the heating.

2. The metal particle detaches from the propellant and continues to be heated in the flame zone. A layer of molten metal oxide surrounds the molten particle of metal.

3. In a steady-state process, the metal vaporizes, the oxide layer expands (forming sort of a bubble) and the metal vapor reacts with oxidizer species, forming more oxide which further coats the surface.

4. At the end of the process a tiny bubble of oxide is carried downstream to the nozzle.

In short motors, the metal particles may not have enough time to vaporize and combust completely by the time it reaches the nozzle throat, so that enhancement of specific impulse may be reduced somewhat (note the lack of difference in specific impulse between aluminum-containing propellant and the simple propellant in Table V).

The process given above may vary with the type of thermic agent. Aluminum and magnesium apparently burn in the vapor phase; silicon burns on its surface, in the solid phase. There are reports of silicon being used effectively to increase burn rate of compositions; if so, this may be the reason for the increased burn rate.

Aluminum (possibly other low-melting metals) is reported to undergo *agglomeration* in propellant that contains monomodal (a single particle size of) oxidizer that is significantly coarser than the aluminum[86]. When the oxidizer is monomodal, the spaces between oxidizer particles are large. Tiny aluminum particles collect in these spaces during processing. During combustion, the aluminum particles melt and this molten aluminum can collect together on the surface of the burning propellant. A single agglomerate is formed that is much larger than the original aluminum particles, and is much less likely to combust completely. A result is reduced delivered specific impulse.

A multimodal oxidizer blend is said to minimize agglomeration by making spaces between oxidizer particles as small as possible. Agglomeration may also be a contributing factor to the relatively poor performance of the aluminum-containing propellant of Table V.

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[86] Presumeably, reduced solids loading may also contribute to aluminum agglomeration, for the same reasons given here.

SOURCES FOR MATERIALS

RCS
1955 S. Palm St., Suite 6
Las Vegas NV 89104
702-641-9478
http://rocketmotorparts.com/

Rosenfield Consulting Service sells the Aerotech line of motor parts, including phenolic casings, fiberglass casings, liner tubes, casting tubes, nozzles, o-rings, fiber washers.

Skylighter, Inc.
PO Box 480-W
Round Hill, VA 20142-0480
(540) 554-4543
(540) 554-2849 (Fax)
http://www.skylighter.com

Source for oxidizers, metals, some burn rate catalysts. For those interested in blackpowder motors, Skylighter also sells the books "Best of AFN II" and "Best of AFN III" that provide useful information for "skyrockets" (note: "Best of AFN IV just came out in April 2000, and is also useful)

Firefox Enterprises Inc
PO Box 5366 Pocatello, ID. 83202
208-237-1976
http://www.firefox-fx.com/products.htm

Vendors of pyrotechnic and rocket chemicals and other supplies. Ammonium perchlorate, aluminum, magnesium, silicon, polymer supplies including PBAN, HTPB, curatives, plasticizers, etc.

Iowa Pyro Supply
1000 130th. Street
Stanwood, Iowa 52337
http://www.netins.net/showcase/iowapyrosup/

Source for oxidizers, metals, some burn rate catalysts

McMaster-Carr
P.O. Box 4355
Chicago, IL 60680-4355
http://www.mcmaster.com/

Industrial supply house for all sorts of hardware: snap rings, O-rings, Garolite (phenolic) tubing, bolts, nuts, etc. Warning: it is very difficult to get a McMaster-Carr printed catalog; web site ordering is recommended.

Aerocon / Dept LT
P.O. Box 432
Los Gatos, CA 95031
831-637-2442
http://www.energyrs.com/aero/aerocon.htm

Sort of a rocketry "surplus" store. They have inexpensive graphite (very suitable for nozzles), load cells, other miscellaneous items, as well as HTPB (not curative).

Nite Lites Pyrotechnics
6009 Sadler Road
Leitchfield KY 42754
Phone/fax 270-879-9340.

Atomized aluminum and some other pyrotechnic chemicals at very good prices. They also have e-matches at very reasonable cost. The "Chinese" ematch they sell (40/$22.50) is not useable for motor ignition but is excellent for ejection charge firing.

Prodyne Inc.
1620 9th St.
Ogden UT 84404-5341
801-392-7205

John Rakhonen is the proprietor, and has been in rocketry for about forty years. Source of AP, HTPB, PBAN, curatives, plasticizers, casings and some other materials. Wholesale quantities only. Minimum order is $250. Call first.

CP Technologies
4010A South Poplar, Suite 23
Casper, WY 82601
(307) 265-5895
http://www.space-rockets.com/Cptechno.html

Phase-stabilized ammonium nitrate, R45 binder, and HDI curing agent

PYROTEK
P.O. Box 300
Sweet Valley, PA 18656
(570)256-3087
http://www.pyrotek.org

Pyrotechnic chemicals and supplies, including HTPB, DOA, and HDI. A bit pricey but more complete selection than some other dealers. They also sell chemicals that may not be readily available to the experimenter.

Taig Tools International
12419 E. Nightingale Lane
Chandler AZ 85249.
480-895-6978
http://www.taigtools.com
http://www.pioneer.net/~felice/taig.html

The Taig is a small metalcutting lathe suitable for turning forward closures and nozzles for up to 75mm motors. Cost is around $300 depending on accessories. The author has a Taig and has found it to be entirely satisfactory for small work. The second URL is a discount dealer for Taig.

http://www.omega.com
Omega sells a variety of load cells.

http://www.dataq.com
A source of low-cost data acquisition systems and software.

GEORDI@c031.aone.net.au
Troy Prideaux, author of "Grains" spreadsheet (for Excel). The spreadsheet models a wide variety of motors including Bates, star, D-slot, C-slot, and others. Calculates burn time, chamber pressure, thrust curve, motor designation, etc. Some limited experimentation has shown the models for Bates grains to be accurate; presumeably the others are too. Highly recommended.

dpsmotor@aeneas.net
Jim Mitchell, Dynamic Propulsion Systems. Mitchell provides custom experimental motor casings, forward closures (including/not including delay well), and graphite nozzles in 22, 29, 38, 54, and 76mm sizes, and will custom-machine other materials at *very* reasonable prices. He often can provide casting and liner tubes as well.

PROPEP RUNS FOR LISTED PROPELLANTS

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CODE                                     WEIGHT    D-H  DENS      COMPOSITION
137 AMMONIUM PERCHLORATE (AP)            79.800   -602  0.07040    1CL  4H   1N
244 CARBON (AMORPHOUS)                    0.200    917  0.06370    1C
779 POLYBUTADIENE/ACRYLONITRILE CO       17.200    314  0.03400  653C 854H  19O  7
1096 DER-331 EPOXY                        2.800   -661  0.04200   24H  21C   4O

THE PROPELLANT DENSITY IS 0.05851 LB/CU-IN OR  1.6195 GM/CC
THE TOTAL PROPELLANT WEIGHT IS  100.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   4.380514 H      1.310677 C      0.802801 N      2.782192 O
   0.679166 CL

****************************CHAMBER RESULTS FOLLOW*****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV     GAS    RT/V
2658. 4325.   68.02  1000.00   -44.31   245.08  1.2377  4.253   15.996

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=   10.343   10.345
NUMBER MOLS GAS AND CONDENSED=   4.2526   0.0000

  1.18507 H2O          1.02890 CO           0.67209 HCl          0.66188 H2
  0.40121 N2           0.28166 CO2          0.00984 H            0.00695 Cl
 4.42E-03 HO          2.68E-04 NO          5.05E-05 NH3         4.15E-05 O
 3.18E-05 Cl2         3.03E-05 O2          1.82E-05 CHO         1.78E-05 COCl
 8.11E-06 HOCl        8.11E-06 CNH         6.36E-06 CH2O        2.53E-06 NH2
 2.16E-06 CNHO        1.58E-06 OCl

THE MOLECULAR WEIGHT OF THE MIXTURE IS   23.515

****************************EXHAUST RESULTS FOLLOW*****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV     GAS    RT/V
1175. 1655.    1.00    14.70  -109.42   245.08  1.2798  4.242    0.236

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    9.088    9.088
NUMBER MOLS GAS AND CONDENSED=   4.2418   0.0000

  0.94263 H2           0.90794 H2O          0.74698 CO           0.67912 HCl
  0.56360 CO2          0.40136 N2           0.00003 NH3          0.00003 CH4

THE MOLECULAR WEIGHT OF THE MIXTURE IS   23.575

**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE**********

IMPULSE   IS EX      T*      P*      C*     ISP*  OPT-EX  D-ISP      A*M    EX-T
  236.0  1.2600   2352.   37.62  4792.1             7.92  382.2  0.14898  1113.
  238.1  1.2324   2383.   37.97  4855.9    188.2    8.16  385.5  0.15096  1175.
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CODE                                      WEIGHT    D-H  DENS       COMPOSITION
137 AMMONIUM PERCHLORATE (AP)             79.000    -602  0.07040    1CL  4H   1N   4O
541 IRON OXIDE                             1.000   -1230  0.18400    3O   2FE
779 POLYBUTADIENE/ACRYLONITRILE CO        17.200     314  0.03400  653C 854H  19O  72N
1096 DER-331 EPOXY                         2.800    -661  0.04200   24H  21C   4O

THE PROPELLANT DENSITY IS 0.05882 LB/CU-IN OR  1.6281 GM/CC
THE TOTAL PROPELLANT WEIGHT IS  100.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   4.353279 H     1.294026 C     0.795992 N     2.773742 O
   0.672358 CL    0.012523 FE

****************************CHAMBER RESULTS FOLLOW*****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY   CP/CV    GAS   RT/V
2642. 4297.   68.02  1000.00   -45.24   243.43  1.2364  4.215   16.140

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=   10.380   10.392
NUMBER MOLS GAS AND CONDENSED=   4.2147   0.0000

  1.19236 H2O        1.01143 CO         0.65652 H2         0.64154 HCl
  0.39782 N2         0.28247 CO2        0.01217 FeCl2      0.00919 H
 6.25E-03 Cl        4.12E-03 HO        2.46E-04 NO        2.04E-04 FeH2O2
 6.67E-05 Fe        5.08E-05 NH3       3.65E-05 O         2.78E-05 Cl2
 2.70E-05 O2        2.64E-05 FeCl      1.87E-05 FeCl3     1.72E-05 CHO
 1.62E-05 COCl      7.86E-06 CNH       7.74E-06 FeO       7.31E-06 HOCl
 6.26E-06 CH2O      2.39E-06 NH2       2.11E-06 CNHO      1.36E-06 OCl

THE MOLECULAR WEIGHT OF THE MIXTURE IS   23.726

****************************EXHAUST RESULTS FOLLOW*****************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY   CP/CV    GAS   RT/V
1171. 1649.    1.00    14.70  -109.47   243.43  1.2786  4.205    0.238

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    9.120    9.120
NUMBER MOLS GAS AND CONDENSED=   4.2046   0.0000

  0.93734 H2         0.91552 H2O        0.72972 CO         0.64730 HCl
  0.56420 CO2        0.39796 N2         0.01242 FeCl2      0.00003 Fe2Cl4
 3.00E-05 NH3       2.64E-05 CH4       4.70E-06 FeCl3

THE MOLECULAR WEIGHT OF THE MIXTURE IS   23.783

**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE**********

IMPULSE   IS EX      T*       P*      C*     ISP*  OPT-EX  D-ISP      A*M   EX-T
  234.5  1.2588   2340.   37.64  4758.5            7.93  381.7  0.14793  1110.
  236.4  1.2317   2370.   37.98  4821.8   186.8    8.17  384.9  0.14990  1171.
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CODE                                     WEIGHT    D-H  DENS       COMPOSITION
137 AMMONIUM PERCHLORATE (AP)            70.000   -602  0.07040    1CL  4H   1N
 63 ALUMINUM (PURE CRYSTALINE)           10.000      0  0.09760    1AL
779 POLYBUTADIENE/ACRYLONITRILE CO       17.200    314  0.03400  653C 854H  190
1096 DER-331 EPOXY                        2.800   -661  0.04200   24H  21C   4O

THE PROPELLANT DENSITY IS 0.05990 LB/CU-IN OR  1.6581 GM/CC
THE TOTAL PROPELLANT WEIGHT IS  100.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   4.046888 H     1.294026 C     0.719395 N     2.448566 O
   0.370645 AL    0.595760 CL

****************************CHAMBER RESULTS FOLLOW***************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV     GAS   RT/V
2999. 4939.   68.02  1000.00   -38.59   237.71  1.2064  4.008   16.973

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=     9.526   11.111
NUMBER MOLS GAS AND CONDENSED=   4.0079   0.1817

  1.21945 CO          1.18644 H2          0.57181 HCl         0.52658 H2O
  0.35941 N2          0.18164 Al2O3*      0.07435 CO2         0.04171 H
  0.01365 Cl          0.00629 HO          0.00304 AlCl        0.00200 AlCl2
 1.05E-03 AlOCl      6.87E-04 AlCl3      3.57E-04 NO         3.05E-04 AlHO2
 2.12E-04 AlHO       1.34E-04 O          9.34E-05 NH3        6.57E-05 CHO
 5.27E-05 CNH        3.47E-05 Cl2        2.96E-05 COCl       2.43E-05 AlO
 2.37E-05 O2         1.41E-05 Al         1.39E-05 CH2O       1.14E-05 NH2
 6.81E-06 HOCl       4.11E-06 AlH        3.75E-06 CNHO       2.93E-06 Al2O
 2.46E-06 OCl        2.01E-06 N          2.01E-06 NH

THE MOLECULAR WEIGHT OF THE MIXTURE IS    23.869

****************************EXHAUST RESULTS FOLLOW***************************

 T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY  CP/CV     GAS   RT/V
1520. 2276.    1.00    14.70  -112.79   237.71  1.2427  3.975    0.252

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=     8.697    9.721
NUMBER MOLS GAS AND CONDENSED=   3.9750   0.1853

  1.27751 H2          1.14336 CO          0.59568 HCl         0.44802 H2O
  0.35966 N2          0.18530 Al2O3&      0.15059 CO2         0.00005 H
 1.87E-05 Cl         1.29E-05 NH3        1.13E-06 CH4

THE MOLECULAR WEIGHT OF THE MIXTURE IS    24.037

**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE********

IMPULSE   IS EX     T*      P*      C*     ISP*  OPT-EX  D-ISP     A*M   EX-
  249.0  1.2172  2705.   38.17  5017.7             8.58  412.8  0.15599  1412
  254.1  1.1897  2746.   38.53  5071.9    195.6    8.87  421.4  0.15767  1520
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CODE                                          WEIGHT     D-H  DENS       COMPOSITION
 137 AMMONIUM PERCHLORATE (AP)                77.000    -602  0.07040    1CL   4H    1N    4O
 731 OXAMID (B. LEE)                           3.000   -1376  0.06020    4H    2C    2N    2O
 779 POLYBUTADIENE/ACRYLONITRILE CO           17.200     314  0.03400  653C 854H   19O   72N
 1096 DER-331 EPOXY                            2.800    -661  0.04200   24H   21C    4O

THE PROPELLANT DENSITY IS 0.05827 LB/CU-IN OR  1.6129 GM/CC
THE TOTAL PROPELLANT WEIGHT IS  100.0000 GRAMS

NUMBER OF GRAM ATOMS OF EACH ELEMENT PRESENT IN INGREDIENTS

   4.421447 H      1.362154 C      0.847098 N      2.754997 O
   0.655336 CL

****************************CHAMBER RESULTS FOLLOW*****************************

 T(K)  T(F)  P(ATM)    P(PSI) ENTHALPY  ENTROPY   CP/CV     GAS    RT/V
2505. 4049.   68.02  1000.00   -46.93   245.15  1.2431  4.329   15.712

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=    10.159    10.161
NUMBER MOLS GAS AND CONDENSED=   4.3294    0.0000

  1.12536 H2O        1.09644 CO         0.75558 H2         0.65183 HCl
  0.42344 N2         0.26560 CO2        0.00564 H          0.00342 Cl
 1.78E-03 HO        8.94E-05 NO        7.18E-05 NH3       1.54E-05 Cl2
 1.34E-05 CHO       1.14E-05 COCl      1.12E-05 CNH       8.59E-06 O
 7.74E-06 CH2O      5.28E-06 O2        3.11E-06 HOCl      2.37E-06 CNHO
 1.76E-06 NH2

THE MOLECULAR WEIGHT OF THE MIXTURE IS    23.098

****************************EXHAUST RESULTS FOLLOW*****************************

 T(K)  T(F)  P(ATM)    P(PSI) ENTHALPY  ENTROPY   CP/CV     GAS    RT/V
1090. 1502.    1.00    14.70  -108.84   245.15  1.2880  4.323    0.231

SPECIFIC HEAT (MOLAR) OF GAS AND TOTAL=     8.888     8.888
NUMBER MOLS GAS AND CONDENSED=   4.3234    0.0000

  1.07857 H2         0.80387 H2O        0.77259 CO         0.65529 HCl
  0.58924 CO2        0.42350 N2         0.00026 CH4        0.00006 NH3

THE MOLECULAR WEIGHT OF THE MIXTURE IS    23.130

**********PERFORMANCE:  FROZEN ON FIRST LINE, SHIFTING ON SECOND LINE**********

IMPULSE    IS EX      T*       P*      C*     ISP*   OPT-EX  D-ISP      A*M    EX-T
  230.3   1.2674    2209.    37.53   4682.1             7.81  371.5   0.14556   1028.
  232.1   1.2410    2236.    37.86   4746.3    184.0    8.09  374.4   0.14755   1090.
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ANNOTATED BIBLIOGRAPHY

Many libraries may not have these books, but most can arrange for an interlibrary loan for a modest fee. Your tax dollars helped pay for the library, so avail yourself of the service. Books without an ISBN may be unavailable through interlibrary loan.

The literature of propellant work is often contradictory, either in fact or in appearance. Be aware that you will likely find statements that appear to be inconsistent in different books and references.

PROPELLANTS MANUFACTURE, HAZARDS AND TESTING. C. BOYARS AND K. KLAGER, ADVANCES IN CHEMISTRY SERIES 88, AMERICAN CHEMICAL SOCIETY, WASHINGTON 1969

Out of print. Essentially a reprint of papers presented at a symposium sponsored by the Division of Industrial and Engineering Chemistry in 1967. Boyars and Klager were the symposium chairmen. Rather technical, but has a great deal of information on double base and composite propellant. Rumbel's section on PVC plastisol propellant is especially useful in that the effect of variables such as oxidizer particle size, metal type and content, and catalyst type and content are discussed. Explanations of phenomena such as dry mix and bonding agents are provided. Probably very difficult to find, but worth searching for.

MILITARY AND CIVILIAN PYROTECHNICS. H. ELLERN, CHEMICAL PUBLISHING COMPANY, NEW YORK 1968

The author of this book has had extensive experience in the match industry and in military pyrotechnics, and much of the book considers pyrotechnics from a military standpoint. It is not specific to composite propellant. Nonetheless it is loaded with so much information that it is highly recommended as a permanent addition to the experimenter's library. Over 200 formulations for the components of everything from strike-anywhere matches to gasless delays. Unavailable for many years, a softcover edition has been published (1999) by American Fireworks News.

ROCKETS AND SPACE SCIENCE SERIES, VOLUME 2, PROPELLANTS. AMATEUR ROCKET ASSOCIATION, HOWARD W. SAMS CO, 1967

Less technical and more readable than most, this book provides basic mathematical treatment of rocket parameters.

ROCKET PROPULSION ELEMENTS. G. P. SUTTON, JOHN WILEY & SONS, NEW YORK

Now in its seventh edition, this book is the single most useful reference for all aspects of rocketry. It is not a how-to book; rather, it covers all aspects of rocketry and space travel from an engineering and technical standpoint. Solid and liquid propellant, grain configuration, etc are covered in mathematical detail. Not for the faint of heart; this is a college level textbook for engineering students.

DESIGNING ROCKET MOTORS. J. LANIER, GAS DYNAMICS LABORATORY

If Sutton's book is too hard for you to follow, Lanier's book may be what you want. Lanier gives a more rigorous treatment of solid motor design than is covered in the book you have in your hands, but it it less rigid than Sutton. Only requires high school mathematics.

BEST OF AFN II, BEST OF AFN III, BEST OF AFN IV

American Fireworks News published a "Best of AFN I" and "Best of AFN II" some time ago, then combined them into one book, and published yet a third book. For the individual who would like to make small blackpowder rocket motors, these books provide down-to-earth details and hints. (Warning: blackpowder motors can be highly hazardous to construct, and may require a different set of safety precautions than composite motors). Most of the books' content is on other types of pyrotechnics but there is also useful safety and testing information. Both are a bargain, available from AFN and from Skylighter. "Best of AFN IV" came out in April of 2000; also very useful.

PLASTIC RESIN BONDED HIGH ENERGY ROCKET FUEL SYSTEMS, GARY PURRINGTON, FIREFOX ENTERPRISES

Gary Purrington is the proprietor of Firefox Enterprises, a source for many of the chemicals used by the experimenter. This book is recommended as a supplementary reference rather than as a starter book. It gives a large number of propellant formulations (including hybrid propellant grains). Many of the formulations use a large number of ingredients. Many may require "tweaking" in terms of cure ratio and effect. The latest edition (1998?) is much more complete than earlier ones.

CHEMICAL ROCKETS. R. T. HOLZMANN, MARCEL DEKKER, NEW YORK 1969

This book explores solid and liquid rocket technology from a (largely) chemical standpoint rather than an engineering point of view. Highly technical, it will answer some of the "why" questions that the advanced experimenter may have.

HOW TO MAKE AMATEUR ROCKETS. J. WICKMAN, CP TECHNOLOGIES

This is meant to be the "second edition" of Wickman's previous booklets on how to make solid rocket motors. I have not seen this newest book, but the previous booklets were well written and illustrated. The first two emphasized the practical aspects of mixing propellant and constructing single-use rocket motors, with little emphasis on theory. The third booklet provided mathematical details of simple engineering design for the non-engineer. The author emphasizes the use of ammonium nitrate as an oxidizer, however, the book will undoubtedly be useful for the individual using ammonium perchlorate as well. The current book is $60 from CP Technologies and includes software to aid in motor design as well as a videotape.

INTRODUCTORY PRACTICAL PYROTECHNICS. T. I. PEREGRIN, FALCON FIREWORKS, 1996

No rocket-specific information is provided here. Rather, this is an introductory lab-type manual for the person working with pyrotechnic chemicals. Written by a Ph.D. with over thirty years in the field, this provides background on the nature of many of the chemicals used in pyrotechnics. Much information is provided on chemical incompatibilities. Some of the techniques described may be of interest to the individual who wishes to make blackpowder motors.

SOLID ROCKET TECHNOLOGY. M SHORR AND A. J. ZAEHRINGER, JOHN WILEY & SONS, NEW YORK 1967

Somewhat more technical than this book, less so than "Chemical Rockets" or "Propellants Manufacture, Hazards, and Testing". Covers both solids and liquids. Includes sections on propellant chemistry, structural analysis of viscoelastic materials, combustion, ignition, nozzle design, motor design. The step-by-step industrial procedure given for preparing propellant and loading a test motor is quite interesting. Out of print.

A SAFETY MANUAL FOR EXPERIMENTAL & AMATEUR ROCKET SCIENTISTS, 3RD ED. L.E. JONES, REFERENCE RESOURCES PUBLISHING CO, NEVADA 1999

Excerpted from "Handbook of Fireworks and Explosives" by the same author (which is in preparation), this book provides a great deal of safety information that is not readily available to the experimenter. Appears to be more technically correct than the average self-published book. Highly recommended.

FIREWORKS: THE ART, SCIENCE, AND TECHNIQUE. T. SHIMIZU, PYROTECHNICA PUBLICATIONS, AUSTIN 1981

A general reference on pyrotechnics, there is a great deal of useful information on the nature of some oxidizers (KP, KN, AP, strontium nitrate, etc.) and fuels.

PRACTICAL DISPERSION: A GUIDE TO UNDERSTANDING AND FORMULATING SLURRIES. R. F. CONLEY, WILEY-VCH, NEW YORK 1996

For the individual with a solid chemistry or heavy technical background, who is looking to maximize solids content, minimize viscosity, etc., this book may be of interest. Primarily directed at the paint and pigment industry, much of what is described is applicable to all slurries including solid propellant mixtures. Not cheap.

HANDBOOK OF EPOXY RESINS, HENRY LEE AND KRIS NEVILLE, MCGRAW-HILL, NEW YORK 1967

For those interested in the chemistry and applications of epoxy resins.

USEFUL URLS AND EMAIL ADDRESSES:

The World Wide Web is a fluid medium, and some/all of these URLs may have changed or be unuseable when you read this.

http://www.rocketryonline.com
Almost everything you wanted to know about hobby rocketry

http://www.atf.treas.gov/pub/xcomplete.htm
Federal explosives law

http://www.atf.treas.gov/pub/listofexp.htm
BATF list of explosive materials

http://www.labx.com
Auction site for lab equipment: vacuum pumps and vacuum chambers

http://www.surplusrecord.com
Used vacuum pumps and machinery (lathes)

http://web2.airmail.net/redmonj/sucker.htm
Describes a vacuum pump constructed from a refrigerator compressor

http://www.systemthree.com
System Three epoxy resin is a useful curative for PBAN

http://members.aol.com/ricnakk/index.html
Richard Nakka's site is arguably the single most useful web site for the experimental rocketeer. He concentrates on potassium nitrate-based propellants, but there is an incredible wealth of general information on rocketry, motor operation and design, equipment construction and use, propellant parameters, etc. Updated frequently.

http://inet.uni2.dk/~dark/TechNotes/JF/Motordesign.pdf
A downloadable document on mechanical design of rocket motors from DARK, the Danish rocketry group. VERY useful.

http://www.ioc.army.mil/dm/dmsweb/4145/ch16.html
Safety information on propellant compounding.

http://www.info-central.org/index_propulsion.html
Information on legalities of rocketry

http://www.lekstutis.com/Artie/PEP/Index.html
Propep and GUIPEP available here

http://www.everett.net/users/bloomer/propelant.html
List of web sites for those interested in propellant and rocket motors; it's longer than the list you're reading.

http://www.tiac.net/users/bluesky/rockets/
Shows a thrust stand, heated mixer, vacuum setup, an HTPB propellant formulation, results of Propep runs, and more.

http://www.cmass.org/uploads/Robert.Galejs/timer.html
A low-cost electronic timer for ejection charges.

http://members.home.net/jelanier/index.html
"Designing Rocket Motors" website, by Jim Lanier. Detailed information on determining burn rate parameters, downloadable software, and info for ordering Lanier's book and for subscribing to the ChemRoc electronic mailing list.

http://members.xoom.com/aRocket/downloads.html
Arocket page: downloadable software for rocketry and information on subscribing to the Arocket mailing list.

http://www.jpyro.com
Home page for the *Journal of Pyrotechnics*. JoP comes out about four times a year and has solid, meaty, scientific articles on pyrotechnics and related subjects. The index of each issue is available on the website.

http://home.iae.nl/users/aed/gdp/gdp.htm
Home page for the Grain Design Program, which will model the ballistic behavior (burn rate, thrust, etc.) of a wide variety of propellant grains. More difficult to use than a spreadsheet, but more versatile. The GDP-lite program is available at modest cost and should be sufficient for all but the most advanced experimenter.

http://siri.uvm.edu/msds/
Site for Material Safety Data Sheets

SERMONETTES

The following essays are opinion only, not necessarily the author's opinion, but someone's opinion, I dunno whose. No libel is intended or should be inferred. Resemblance of any aspect of these essays to any person, company, entity foreign or domestic or interspecies or alien is coincidence and is totally unintended. Any one offended by these essays shall not infer that offense was intended.

"And if you are still pissed off, you are invited to go pound sand up your ass. Conciliation has its limits" – "Uncle" Al Schwartz

DELAY CHARGES IN COMPOSITE MOTORS

The astute reader will notice that although the use of delay charges has been described in single-use motors, a formulation for the delay charge has not been given in this book. There's a reason for that.

Let's look at the delay situation in endburning and coreburning BP motors. Referring to Figure 2, the delay charge in an endburning blackpowder motor is simply placed ahead of the propellant. The charge does not ignite until the propellant is consumed. Since only the delay mixture (and not the propellant charge) is burning at that point, no significant pressure is generated and the burn rate of the delay is nearly constant. If the delay mixture burns at a rate of 2 mm/s, then a charge 10mm long produces a 5 second delay, and a charge 6mm long produces a 3 second delay. Simple.

In a coreburning BP motor, the propellant and the delay charge often are the *same* type of composition. As the core burns and until the flame reaches the wall of the casing, pressure is quite high. When the core reaches the wall, pressure drops, and the remaining "propellant" ahead of the core burns more slowly, acting as the delay charge. Again, it's fairly simple, since propellant and delay are the same composition.

However, in a coreburning composite motor (Figure 3) it is apparent that the delay charge is ignited *at the same time* as the propellant. And we now know that the burn rate of composite propellant (including the delay composition) will vary as pressure changes. Chamber pressure will be high during propellant combustion, so the delay will burn fairly rapidly. When the propellant is completely consumed, the burn rate of the delay will drop considerably. This complicates the situation.

Consider a typical delay mixture that burns at ⅛" per second at a pressure of 1000 psi, and 1/32" per second at atmospheric pressure. If a ½" long delay is placed in a motor that burns for one second at 1000 psi, ⅛" of delay will be consumed during this time. That will leave ⅜" (12/32") to burn at atmospheric pressure, so the delay will be 12 seconds long.

Now place the same length of delay charge in a motor that burns for *two* seconds at 1000 psi. During the burn, ¼" of the delay will be consumed. That will leave ¼" (8/32") to burn at atmospheric pressure, or an 8 second delay.

Not that the situation is that simple! Since the burn rate of the delay may change with pressure, it should be apparent that a motor burning for one second at 500 psi (instead of 1000 psi) may consume *less* of the delay during the motor burn. Which means that such a motor would leave *more* of the delay unburnt at the end, and give a longer delay time.

And as if that weren't bad enough...composite AP propellant tends to go out at pressure below about 200 psi. Which means that the delay may go out when the propellant is consumed, due to the pressure drop.

And as if *that* weren't bad enough...many of the CATOs that occur in commercial motors appear to be the result of flame bypassing the wall of the delay element and reaching the ejection charge. Which suggests a general problem with delays.

All in all, the use of pyrotechnic delays in coreburning composite motors is something of a dicey situation.

Aerotech uses a novel solution to part of the delay problem. The delay mixture in an Aerotech motor has a very low burn rate exponent, approximately 0.05. This means that its burn rate changes relatively little when pressure changes. So the burn rate of the delay is about the same at 300 psi as at 900 psi. The Aerotech delay is also sensitive enough that it ordinarily will not go out when chamber pressure drops at the end of a burn[87].

This minimizes the problem of motors that operate at different pressures. But it doesn't solve the problem of motors with different burn times. However, most Aerotech motors within a given class (say, 29 mm) burn for roughly the same length of time. The difference in burn time between the slowest and the fastest 29 mm motor is roughly a second. That means that differences in delay times for a given length of delay grain and within a given class of motor will be fairly small, on the order of three or four seconds at most. In fact the differences are even smaller than this, since the motors that burn longer usually operate at a lower pressure than the fast-burning motors.

So here's my first suggestion on the use of delays in composite motors: buy commercial delay elements if possible. They're proven, inasmuch as delay elements can be.

DELAY COMPOSITIONS

Commercial delay compositions generally have a high zinc content. The zinc serves the double function of reducing the burn rate exponent and providing the huge amount of smoke desired in a delay composition. Zinc is a problem, though, in PBAN. It tends to react with the carboxylic functional group and solidify the mixture in a matter of minutes. I've attempted to coat zinc so that it could be used in PBAN. That has been unsuccessful to date.

Delay compositions MUST be degassed or otherwise rendered bubble-free. A bubble 1/16" in diameter will advance the flame front by 1/16" in an instant. And the delay burns through -- and ignites the ejection charge -- when *any part* of the forward end burns through to the ejection charge. So that bubble will change a ten second delay to an eight second delay.

Regarding composition of the delay: Rumbel reported that PVC plastisol propellant shows a definite "plateau burning" trend when the AP oxidizer is reduced to 60%. At this level of oxidizer the burn rate tends to stay around 0.1 in/s from 200 to 800 psi. So

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[87] Commercial composite delay mixtures are said to use a high zinc content, 20-40%. This produces the smoke. They may also contain a bit of burn rate catalyst to make the mixture more sensitive, so that it does not go out at propellant burnout.

one way of obtaining a delay that would burn at a constant rate under pressure might be to use a formulation with about 60% AP. Of course, such a mixture would tend to "settle" readily during cure. A fair proportion of fine AP in the mixture may minimize this problem. So a reasonable formulation for an HTPB delay mixture might be 20% zinc, 20% binder (HTPB plus curative plus plasticizer if desired), and 60% AP. To increase the sensitivity of the mixture to ignition and insure that the delay does not "go out" too easily, 1% iron oxide burn rate catalyst might be added.

Some workers have suggested the use of *timing fuse* as a delay element. This material is not the ordinary green or red "Visco" fuse used in consumer fireworks. Timing fuse is about ¼" diameter, with a thin core of modified BP. It burns very reliably at about three seconds per inch *at atmospheric pressure*, and is used as the delay element in pyrotechnic aerial shells. For a composite motor, one might cut the desired length of timing fuse, insert into a punched disk, and epoxy the disk and fuse into the forward closure as usual. The fuse has a rough cloth outer surface, so its use in a reloadable motor would present something of a challenge unless it were embedded in a cylindrical casing.

Two points regarding timing fuse. First, the burn rate given is at atmospheric pressure, since it burns at atmospheric pressure when used as the delay element in a shell. To the author's knowledge, no comprehensive study has been performed to determine the burn rate at typical *chamber* pressures. At least one reference suggests that BP has a fairly low pressure exponent at pressures above 300 psi, which is encouraging. A second minor point is that the delay is physically small and will produce negligible tracking smoke.

An area of study that perhaps has not received the attention it deserves is that of *gasless delays* in composite motors. Ellern lists several delay compositions which are reportedly gasless and therefore should change little in burn rate with changes in pressure. The simplest such delay appears to be a mixture of 20% silicon and 80% "red lead", Pb_3O_4, with 3 to 7% diatomaceous earth added to adjust the burn rate. Chemically, this is very similar to the "thermite" mixture. Other mixtures use chromium, zirconium, manganese, or tungsten metals. Most of these delays are powdered mixtures and presumably would be pressed (hydraulically) into a tube.

ELECTRONIC DELAYS AND ALTIMETERS

Recommended. In the long run, an electronic timer or altimeter will be more reliable than an experimentally-prepared pyrotechnic delay. The website http://www.cmass.org/uploads/Robert.Galejs/timer.html shows an electronic timer that can be built for about $10, and with careful work can be made to fit inside a 13mm airframe tube. So there's no excuse for using a pyro delay in even the smallest rocket.

Ignition of the ejection charge may be performed with a flashbulb or an electric match. The author prefers e-matches (NOT homemade ones; commercial ones are far more reliable). These are not particularly expensive, about 60¢ each in quantity.

Starting a homemade timer is something of a problem. One method is to connect a wire to the "start" circuit. The wire is arranged so it will pull loose when the rocket lifts off the pad, or it burns through when the motor is ignited. Another is a roller switch that presses against the launch rod, and is opened when the rocket leaves the rod. Many commercial timers and altimeters use a starter switch which uses acceleration of the rocket as a "start". Some are quite sophisticated so that they will not be set off by a "chuff".

General opinion: a "delay" element should be used solely to produce tracking smoke. For experimental rocketry, electronic delays appear to be more reliable.

WHY PBAN?

When I started making composite propellant, I looked longingly at PBAN as a binder. After all, it was only $10 a gallon as opposed to $35 for HTPB. And if it's good enough for the space shuttle... Well, instead I heeded the experts and used HTPB as the binder. It's good that I did, because I'd have been quickly discouraged had I tried PBAN. HTPB can be cured quickly and I got feedback on my technique in a reasonable time.

But after I worked with HTPB for a while, I learned that not all is great with it. The main problem was "bubbles". Though the propellant was degassed it still ended up with lots of bubbles. And it was touchy as a result. Out of my first ten motors, not more than two worked properly. So it goes.

I finally decided that part of the problem was moisture. In the part of the country I live in, you can't get away from moisture. And EVERYTHING absorbs moisture. And the curatives for HTPB react with it. And that liberates gases, forming bubbles. So I tried PBAN instead. The results weren't encouraging at first, and it took a long time but eventually it worked.

PBAN has other advantages:

1. It's cheap, about 1/3 the cost of HTPB in small quantities, 1/10 its cost in bulk. That's minor but not inconsequential.
2. HTPB curatives are isocyanates, which may be classified as hazardous materials for shipping purposes. Some isocyanates can cause allergic reactions, and are not too good to have in the air around you. Both PBAN and its epoxy curative are shipped as non-HazMat.
3. HTPB gives a brittle product if too much curative is added, and the cure ratio can be "touchy". Just a bit "under" on the curative and the product stays gummy forever (been there, done that). A little too much and the stuff hardens quickly and is like a rock (been there, done that too).
4. PBAN is simple. A very satisfactory propellant can be made with just four ingredients. It's harder to screw up. With HTPB one typically uses Tepanol, crosslinkers, cure catalysts, and plasticizers. These do improve propellant properties to some extent but...change the amount of one ingredient and you change the nature of the mixture.
5. PBAN gives slightly higher (theoretical) specific impulse for the same solids loading than does HTPB. To be fair, I haven't actually seen noticeably higher impulse, but it should be attainable.
6. PBAN is slow to cure, which gives a long potlife. Nothing is more annoying than a batch of propellant that hardens in the middle of processing. PBAN doesn't.
7. For simple work (hand mixing, no vacuum processing) PBAN propellant gives higher density than HTPB. I routinely get 92% of the maximum theoretical density with PBAN, using hand mixing and no vacuum. With vacuum I can get almost 100% theoretical density. With HTPB, I've not exceeded 96% theoretical density

even with vacuum. Without vacuum I get about 90% theoretical density at best. And delivered impulse is proportional to density.

Of course, there are disadvantages to PBAN as well:

1. PBAN is much thicker than HTPB and is sticky, making it harder to work.
2. The cured material may be somewhat weaker than cured HTPB. It can de-bond from paper casting tubes, especially when plasticizer is improperly used. Sometimes the casting tubes must be coated with epoxy glue or other material to which the PBAN will stick well.
3. It smells bad (well, HTPB doesn't really smell good).
4. High amounts of plasticizer cannot be used with PBAN, which means that propellant mixtures will be much thicker at a given solids loading. Again, they're harder to mix.
5. A curing "oven" is a necessity. PBAN doesn't cure at room temperature, at least not at a reasonable rate.
6. Although uncoated aluminum can be used with PBAN, magnesium and/or zinc must be coated with a nonreactive layer before use. Both of these react with PBAN to form bubbles and harden the mixture very quickly.

If you're not sure of what you're doing PBAN can be forgiving and not terribly hard to work with. Once you've gotten your feet wet, you may want to move to HTPB. Or you may master HTPB from the start; however, I've met too many people who had the same problems I did...

WHY NOT ENDBURNERS?

A common question of beginners is, "Why don't we see endburning composite motors? Doesn't the endburner hold more propellant? After all, there's no hole drilled through the propellant, so it should give more total impulse for a given size." In fact, it's quite possible to make such motors; Aerotech and Apogee both market them. BUT there are problems when the experimenter decides on endburners.

BP burns fast, and so requires a K_n of about 15-25 or thereabouts. A ½" id BP motor has a nozzle of about ⅛". Most composite propellant burns rather slowly, and requires K_n of about 150 or more. In a ½" diameter motor, that corresponds to a nozzle about 0.04" in diameter. Such a motor would be VERY difficult to ignite, and would tend to CATO due to clogging. In such a motor, if the nozzle were 0.06", the motor might chuff. A nozzle 0.03" diameter might lead to a CATO.

Composite propellant can be made to burn faster, remember. All you have to do is increase K_n. Unfortunately, that means an even *smaller* nozzle.

Of course, there are other ways to increase burn rate; finer AP, add Mg, add burn rate catalyst. Still, it is very difficult indeed to get AP propellant to burn fast enough to make a decent endburner. I have seen two formulations for AP propellant designed for endburning motors. Both used 90 micron AP, both were very high in solids. Neither would be particularly easy to mix. The other formulation I have seen was a KP formulation; also difficult to work with (remember, the high burn rate exponent?).

But suppose you do make a faster-burning formulation. What will it be used for? A 29mm motor with 8" of propellant will have about 200 N-s of total impulse. If it is a coreburner it might be an H100, burning for two seconds, producing a bit over 20 lb of thrust. It could be used to lift a rocket weighing up to 5-8 lb.

If the same motor was an endburner with propellant burning at about 3/4" per second, it would burn for about 10 seconds. That would make it an H-20, a bit over 4 lb of thrust. Chancy, even in a small one-pound rocket.

Another point: composite propellant burns much hotter than BP. In an endburner, the case is exposed to hot gases as the propellant burns. The H-20 example given above would have the aft end of the case (near the nozzle) exposed to hot gases for almost the entire burn. A heavy insulating liner would be needed unless the burn time were very short (in which case, why use an endburner?)

Taking that last point into consideration, it turns out that an endburner doesn't have a better volumetric loading than a coreburner – if the insulation requirements are taken into account. Consider a 1" diameter solid grain, as compared to a 1" grain with a (typical) ⅜" diameter core through the middle. The *volumetric loading* of the endburning grain is 1.00, and that of the coreburner is 0.86. But the endburner solid grain will need a bit of insulation. So it will has to be *smaller* than 1" diameter to fit in the same case, possibly 0.95" od, maybe even smaller. Comparing a solid 0.95" diameter grain to a 1" grain with ⅜" core shows that the solid endburning grain has less propellant than the coreburner, due to the extra needed insulation.

This doesn't mean "don't make endburners". It means that an endburner is the right motor for the right application. The right application is generally a long burn, low thrust, high-altitude attempt in a lightweight rocket. For general sport flying of larger rockets, the endburner is less useful than one of the coreburning variants.

TO POUR OR NOT TO POUR?

A propellant mixture is easiest to process when it is either (a) thin enough to pour, or (b) so thick that it's no longer extremely sticky; sort of like soft clay. Propellant mix that is the consistency of peanut butter is difficult to work with; it's too thick to pour, too thin to stay in place when tamped, tends to stick to the tamping stick.

The term "pourable" propellant deserves some discussion. In this context, "pourable" simply means that the propellant will *flow* if the cup is tilted. It *doesn't* necessarily mean "flows easily". Pourable propellant may have a consistency like that of ketchup, salad dressing, a "thick shake", drywall joint compound, or mortar for bricklaying, depending on its composition and the temperature.

Pourability depends in part on the size of the grain being cast. Propellant that is the consistency of drywall joint compound may come out of the cup as a large "lump", and can only be poured into large casting tubes. If you want to pour propellant into 18mm tubing, you'll need a thin propellant, more like ketchup

Here are some avenues for making propellant thinner or less viscous:

1. The mixture may be warmed. With PBAN, or with HTPB using slow-acting isocyanates, this is the simplest option. In fact, larger batches of the simple starter propellant described in this book may be pourable when warmed to the normal working temperature of 140°F.

   Isocyanate mixtures that include MDI or TDI may cure HTPB so fast that potlife may be reduced to a few minutes. For slow-acting isocyanates, it may be desirable to reduce slightly the amount of cure rate catalyst used, or even to reduce slightly the amount of isocyanate used. It will take some experimentation to obtain adequate potlife and a reasonable cure time.

   Above about 140°F, viscosity of HTPB or PBAN does not decrease a great deal; however, *sensitivity to ignition* continues to increase rapidly with increasing temperature. It is possible for a very high-burn-rate formulation to ignite from friction at elevated temperatures, so exercise caution.

2. The solids loading may be decreased. All other things being equal, a propellant with lower solids loading will flow more easily than one with higher solids loading. But a lower solids propellant has lower I_{sp} and lower burn rate (and may show a higher burn rate exponent) than otherwise. Of course, metals may be substituted to increase specific impulse, and burn rate catalyst added to increase burn rate. But these steps may introduce other undesirable properties in the propellant. For example, if a nearly-smoke-free propellant is desired, metal content must be kept to a minimum.

   Another potential problem here: a low solids propellant will settle more than a higher solids one. The propellant may have a layer of "rubber" (cured binder without much oxidizer) on top. Settling means that there will be more solids in the bottom of the grain, and grains from the top of a "stick" may exhibit properties different from those near the bottom. As a rule of thumb, solids content should not be reduced below about 70% unless there is a compelling need (very low AP content can make the propellant difficult to ignite or make it chuff more easily).

3. The formulation may be changed to use coarser oxidizer. Large particles have less surface area for their weight. Less surface area means the solids interact less with the liquids, and the propellant mixture becomes thinner and more flow-able. For example, a mixture that is 25% 200 micron AP and 50% 90 micron might be changed to 25% 400 micron and 50% 200 micron. This will decrease the burn rate, but again, a burn rate catalyst may be added to compensate.

   A problem: some workers have suggested that propellant containing a large amount of coarse AP will be less efficient than one with finer AP. The reasoning is that some of the coarse particles come loose from the binder and are ejected before they burn completely. Bonding agent is desirable in such propellants.

4. The formulation may be changed to use a *variety* of particle sizes of solids. Mixtures with a single particle size tend to be *dilatant*. This means that they will flow under very low shear, but when shear is applied quickly, a "logjam" tends to occur and the mix will not flow. Dilatant propellants are of course difficult to mix. Slurry theory says that a properly-distributed *mixture* of particle sizes with an average given size will be *less* viscous than a single particle size of that same given size. That is, a mix with 80% 200 micron AP would be thicker than a mix that contains, say, 10% 90 micron, 55% 200 micron, and 15% 400 micron, though both have about the same average particle size. According to Conley[88]:

   > "Mathematically it can be shown that the size-volume relationship maximizes when the particle size distribution fits a Gaussian distribution with a breadth at 1 sigma such that it falls on a 45° line on log-size, probability function weight graph. Such particle size distributions are log normal in distribution and tend towards Newtonian behavior."

   This requirement is met when the ratio of 400:200:90 micron AP is about 5:15:3. For this ratio, if X is the percentage of AP in the propellant:

   $0.2174 \times X =$ percentage of 400 micron AP
   $0.6522 \times X =$ percentage of 200 micron AP
   $0.1304 \times X =$ percentage of 90 micron AP

   Of course, addition of fine aluminum or other material may change this ratio.

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[88] Robert F. Conley, "Practical Dispersion: A Guide to Understanding and Formulating Slurries", Wiley VCH, New York 1996, page 56. ISBN 0-471-18640-6

5. The amount or proportion of plasticizer may be increased. Plasticizer is thinner than most binders. However, plasticizer may weaken the propellant, which places limitations on the plasticizer content. Generally, PBAN propellant should have at least four times as much PBAN+epoxy as it does plasticizer. HTPB propellant should have at least twice as much HTPB+isocyanate as it does plasticizer (some workers use more than this; experimentation will dictate).

   In this context, caution is advised in formulating a very high-solids propellant. In high-solids propellant the amount of binder is rather low, so the proportion of plasticizer must be reduced (or plasticizer eliminated) to maintain sufficient strength. For example, a propellant that is 75% solids might contain 14% HTPB, 7% plasticizer, 3% curative, and 1% miscellaneous liquids. If the solids are to be increased to 84%, the binder mixture might be 11% HTPB, 2.5% curative, 0.5% misc, and 2% plasticizer. Note that the *proportion* of plasticizer is lower in the second comp than in the first one.

6. A thinner plasticizer may be substituted for a thicker one. Some workers use 2-ethylhexyl acrylate, which is almost as thin as water. Unfortunately, the reason it's thin is that it has a low molecular weight and high vapor pressure. That is, it evaporates more easily than other plasticizers. For propellant that is to be cured at elevated temperatures 2-EHA is not recommended. And in any event, propellant made with 2-EHA should be kept in sealed containers and used within a few months of preparation.

   Isodecyl nonanoate (isodecyl pelargonate) is another thin plasticizer reported in the literature. It doesn't evaporate as easily as 2-EHA and is a good choice for high-solids propellants. However, it is expensive and not readily available to the experimenter. The author has not attempted to use this plasticizer and cannot comment on its actual utility.

7. A solvent may be added. This makes the propellant easier to mix, of course, but the solvent *must* be removed before cure. Usually, vacuum (with a proper trap) is required. In the author's experience about 2% toluene added to PBAN propellant took over 30 minutes at 29" Hg and 145°F to remove (unlike many pyrotechnic mixtures which may dry more easily, composite propellant is largely nonporous). If any solvent remains in the propellant after casting, it will evaporate slowly and the propellant will shrink and may crack In general, solvents in composite propellants are best avoided.

   EXTREME CAUTION! *NEVER* use chlorinated solvents (methylene chloride, carbon tetrachloride) in propellant! Some chlorinated solvents react violently with finely powdered metals. There are easier ways to commit suicide.

8. A denser material (aluminum or other thermic agent) may be substituted for some of the AP. A propellant that is 70% AP and 10% Al usually will flow more easily than a propellant that is 80% AP, because the denser material occupies less volume in the mixture. Consequences: the propellant with metal will have a higher density

than without. The exhaust will have a higher temperature and will erode nozzles much more readily. The exhaust will be "smoky" with aluminum oxide.

Notice that the phrase "...usually will flow more easily..." was used. Viscosity is a complex phenomenon, and when a mixture is changed the results aren't always predictable. For example, the simple propellant with copper oxide catalyst (1%) appears to be a good bit thicker than when lampblack (0.2%) is used, even though copper oxide is denser than lampblack or AP. Apparently there is some surface interaction of copper oxide with PBAN, which makes the mixture flow more poorly.

9. Bonding agent may be omitted. Tepanol seems to make the mixture more difficult to hand-mix. However, some professionals have indicated that Tepanol actually improves mixability and flow; this may be due to machine mixing of professional propellants, or some other factor unknown to the author.

10. A flow agent (surfactant) may be added. A surfactant is a "soap" that reduces surface tension so the mixture flows more easily. Triton X100 and lecithin have been used by the rocketry community; both are readily available and appear to be compatible with both PBAN and HTPB compositions. A typical amount of surfactant is about 0.1%, though the actual amount used depends on the particular formulation and is found (in industry) partly by trial and error. Too much is *worse*, not better.

    Two problems with surfactants: for a surfactant to be effective it must coat virtually all the solid particles. This may required extended mixing time (hours). Also, a flow agent may make the propellant "foam" more during vacuum processing. So more care must be taken during this step.

11. Propellant that will not flow well under ordinary conditions will often flow more easily when vibrated. Some workers use a massager device that attaches to the back of the hand. This hand is used to hold the bowl when pouring the propellant. Others use an orbital sander mounted upside down.

    Vibration of the propellant tubes tends to settle the propellant more rapidly. A vibration table is worth constructing if a lot of propellant is to be made.

Pourable propellant doesn't necessarily increase the consistency of propellant work, it just speeds it up a bit. If propellant is to be made on a daily basis and only a few formulations are contemplated, pourable propellant is something that may be worth investigation. Otherwise it may be easier to pack the stuff.

HOW TO POUR

Some workers have suggested that the propellant be poured down the side of the casting tube. The idea is that this minimizes bubbles in the propellant. The author's experience has been that propellant tends to build up and clogs the tube with this technique.

A technique used by some workers is to transfer the propellant to a paper cup or plastic container. A spout is "pinched", the casting tube held vertically, and the propellant mixture is slowly poured directly down the center of the casting tube, so that it does not touch the walls of the tube. The pour is stopped several times and the tube tapped a few dozen times on the bench, to settle the propellant and work out bubbles. Don't tap too hard! A torn casting tube makes for an awful mess.

"BOY THOSE E**** ENGINES ARE EXPENSIVE..."

We all hear it so often on rec.models.rockets. "Those rotten engines are so expensive. They've only got a few cents worth of materials in them. How can I make my own?"

Let's talk about the cost of these rocket motors, okay? Every adult knows that the cost of materials is not the cost to make an item; in fact the two aren't even close most of the time (kids are harder to convince of this, though that doesn't make it less true). The piston in an automobile engine has about twenty cents' worth of aluminum in it. But it must be cast (in a *very* expensive foundry, with lots of guys and gals working there, all of whom get unhappy if they aren't paid well for their work). And it must be machined to incredibly close tolerances (two choices here; pay a fortune up front for CNC equipment to machine it automatically, or pay a machinist a fortune over the long haul to do the work manually). Then there's three or four middlemen (and they DO perform a service that is worth their fee). That's why the cost goes up to about forty dollars.

A cake from the deli has about thirty cents' worth of flour, sugar, shortening. But a cake won't make itself. So it also has the labor of the people that mix it, decorate it, package it, etc. And the cost of the machinery to make it. That's why the cake sells for fifteen dollars.

This book has about eleven dollars worth of paper and copy cost in it. But if you tried to obtain the information in this book by yourself, it would cost about twenty times as much as you actually paid for it, and would take a year or more of intensive work. It took me five years of hard work and several thousand dollars of materials, etc. to obtain the knowledge, plus almost two years to put it on paper. Yeah, I had to get in that plug...

And of course, each of these items must have a decent profit included at each stage, else who would bother to make them?

So: a blackpowder C-motor has about six cents worth of raw materials in it. The company that makes them has to buy or build an expensive machine to make them. And hire people to run the machine. And fix it when it breaks down. And keep enough engines on inventory to cover the inevitable breakdowns and slowdowns. Of course, they often test 2-3% of the material for quality. Cost of those lost materials is trivial, but someone has to run the thrust stand and collate the data. Plus advertisement, handling irate customers, wholesale to stores, etc. Not to mention benefits for all the people involved, plus taxes of all sorts, plus insurance (THAT'S a biggie!), plus a place to make the motors (can't just do it in the backyard...). And let's not forget the cost of federal, state, and local explosives/hazards/business licenses, compliance with storage, OSHA regulations, hazardous material shipping costs, etc, etc., etc....

There are some goods sold today where the materials cost plus profit is a good approximation of the consumer cost. Rocket engines ain't one of them.

MAKING ROCKET ENGINES TO SAVE MONEY

Don't even think it.

Oh yeah, I know all about it. I've read the books that tell about how much money you can save by making rocket engines instead of buying them. I've seen the ads from other companies. It's all crap, folks.

I know several dozens of people who make their own rocket motors. I know personally of one person who does so AND saves money doing so. There may be another somewhere out there...

One of three things is likely to happen when you start making rocket motors. One possibility is that you'll make only those motors that you would have bought anyway – and no more. If you do this, you might actually save money. As noted earlier, I know one person who fits this category.

Second possibility: you'll get bored or scared soon (or those living with you will get scared...) and you'll quit. In that case, you have a bunch of chemicals and equipment sitting unused. You might be able to sell them, but odds are that you'll have spent much more than you would have to buy the few motors (since a few of the motors will have turned into bits & pieces).

Third possibility: you'll become so excited and enamored with the prospect of making rocket motors that it will consume you. You'll buy more equipment and materials than you could possibly use. Mixer, vacuum pump, lathe, bulk purchases of aluminum tubing and aluminum stock, graphite, drill press, tooling.... I know several hobbyists who have sunk $2000-5000 into their motor-making hobby. Yes, they are spending less than they would to buy the motors. But they're also testing and flying many *more* motors. And spending much more than if they weren't making motors.

Ahem....
This is not "saving money". Except maybe by male definition...

So why do people make motors, if not to save money? Although many start in the activity to save money, most of them seem to continue it for the excitement and the challenge. It makes them happy.

A hobby, be it stamp collecting, observation of bikinis and their concealed contents, or rocket motor design and construction, is a way to waste time and money; the intended consequence is *happiness*. Depending on your temperament, you may waste a lot of time and money making rocket motors. Or maybe you'll waste just a little. It is very unlikely that you'll *save* money in any real sense of the word. If saving money is your goal, it would be well to prepare for disappointment.

MOTOR CASINGS OF ALL SORTS

Motor casings are a continual expense for the experimenter. Consequently, all sorts of materials have been used -- well, tried -- for motor casings. Usually, cheap materials are sought. Of course. So let's explore some casing materials:

The standards for experimental use are aluminum and phenolic. Aluminum alloy 6061-T6 is easy to find and very strong indeed; a 29mm motor made with 17 gauge wall (0.058" thick wall) will handle pressures over 1000 psi. Phenolic comes in several grades. XX grade is "paper phenolic"; paper is soaked in phenolic resin, then the paper is wound around a mandrel and heated to cure the tube. CE grade phenolic is made with cotton cloth instead of paper, and LE uses linen cloth; both are stronger than paper phenolic and priced accordingly.

Incidentally, the word "phenolic" is often applied to materials that do not contain phenolic resin, including the so-called "G-10" material (which often uses epoxy resin rather than phenolic resin). Phenolic resin has the very desirable property of not melting; instead, it chars, and the char is fairly strong. Epoxy resins *can* melt, so epoxy-bonded tubing must be insulated from naked flame. Just be aware of what you are purchasing.

Other materials that have been tried, not necessarily by me:

Steel EMT (metal electrical conduit) -- this material is readily available in any hardware store. It has been formed from sheet steel and has a welded seam. I've heard reports of EMT being used successfully in "micrograin" motors (no, I'm not gonna tell you what that is; either you know already or you don't need to know...). Presumably, micrograin burns so doggone fast that the material doesn't have time to stress enough to blow itself apart. And I've also heard of it being used for other types of motors. However, I don't recommend it.

Welded seams aren't bad if the weld has been made properly to stand the pressure. But EMT isn't intended as pressure tubing and the weld may give.

Another point on EMT. Steel can fragment when it blows. EMT may split along the seam or it may fragment; it depends. Steel shards can go farther than you'd believe. Some sort-of good news: steel fragments *will* show up on x-rays, so the doctor should be able to remove them.

Water pipe (galvanized or "black" pipe) -- also steel tubing, thicker-walled than EMT, also formed from sheet and with a welded seam. For the reasons outlined above, it isn't recommended either. Bigger fragments...

Automobile exhaust pipe -- I've actually seen this suggested in an old publication. To be fair, the motor described was a micrograin motor, so this pipe was satisfactory for the tenth-of-a-second burn. But exhaust pipe, like EMT and water pipe, is welded. Nope.

PVC water pipe -- "Schedule 40" thick-walled PVC has been used by a fair number of experimenters, and is even recommended by some authorities. It has the same dimensions as steel water pipe. Strength is fairly decent; in small diameters it is rated at several hundred psi. It is quite cheap, and quite easy to work with.

However: I don't use it as casing material (I did try it once). And I cannot recommend it. First, it *is* low-melting plastic and doesn't stand heat well at all. So the casing *must* be carefully insulated from the burning propellant and from the heat of the nozzle. Thick paper or thin rubber are often used for this insulation. Still, I have seen PVC casings that bulged a bit during the burn and stretched like taffy afterward.

Another point: this material (and water pipe) have dimensions that are a bit off from standard motor sizes. So one must either build one's rocket to fit these motors (and use adapters to fit standard motors) or adapt smaller motors than the rocket would ordinarily hold.

Example: you want to use a PVC-cased motor in your 29mm motor mount. The largest PVC size that fits is called "¾ inch", which is approximately the inside diameter. Add a liner for insulation and the propellant diameter decreases to ⅝". In this size, a six-grain Bates motor with ¼" core, 1" long grains is likely to be an F-motor... And a slow propellant is needed for such a long motor. Which makes the insulation requirements more rigorous. And increases erosive burning. Which further decreases delivered specific impulse.

As the diameter goes up, the max pressure that the pipe can handle goes down.

Last but not least: like steel, PVC fragments when the motor CATOs. And *THOSE* shards *don't* show up on an x-ray...

Aluminum pipe -- Water-pipe-sizes are available in aluminum, same nominal dimensions as Schedule 40 PVC and galvanized pipe. This stuff may work, but it isn't a whole lot cheaper than proper seamless aluminum. Note that much of the "size" argument against PVC applies to aluminum pipe of this type as well.

Aluminum pipe can be had at the scrapyard at much lower cost than virgin pipe. But without a pedigree...you don't know what you're getting. Some of the 3000 series alloys have about a quarter of the tensile strength of 6061 alloy, and may blow on the first try.

Seamless steel tubing -- as noted earlier, steel fragments. With that in mind, a properly designed steel-cased motor has certain advantages over aluminum: a higher strength-to-weight ratio, and better strength at elevated temperatures. To take advantage of the strength-to-weight ratio requires a *large* motor. Example: a chrome-moly steel casing for a 3" o.d. motor at 800 psi may be a mere 1/16" thick. With liner and casting tube, the od of the propellant might be about 2.65". A 32" long BATES motor made with this casing, using 1" cores in the grains, would hold about 3700 grams of simple propellant and provide approximately 7600 N-s total impulse. Switching to aluminum, one might use a ⅛" thick case and the same liner and casting tube thickness. The propellant od would be 2.525". The 32" long motor would hold about 3300 grams of propellant and produce 6800 N-s. Yes, a significant increase. No, not an enormous one.

Generally a significant advantage will not be seen for steel in sizes under (roughly) 3" diameter. If you're planning an experimental space shot (don't laugh; some are doing just that), steel may be the proper material for the casing.

Notice that the word "seamless" was used. Welded tubing may come apart at the weld. Or it may fragment...

For Tripoli experimental launches, steel casings are verboten.

Paper tubing -- spiral-wound paper tubing simply isn't strong enough in most cases (pun intended). Convolute-wound tubing (rolled up like paper towels) may be strong enough. That will require experimentation. I did try a 1" id, 1 5/8" od convolute tube in a 4-grain motor that was to deliver pressure of about 500 psi. The case split wide open (forward closure and nozzle remained in place). You may have better luck.

The argument about non-standard diameters of pipe also applies to paper tubing. One can purchase 29mm o.d. paper tubing; it is 3/4" i.d.

Fiberglass composite tubing -- usually made from fiberglass wrapped around a mandrel and wetted through with epoxy resin. Expensive but can be as strong as steel. The epoxy resin doesn't stand up to high temperatures, so an insulating liner ordinarily is required. This is the material often referred to as "G-10". The best fiberglass casings are *filament wound.* Look it up.

The determined experimenter can make fiberglass casings in much the same manner as airframe tubing is "glassed". It's a good bit of work. A liner tube can be used as the "inside" of a casing, and fiberglass cloth and epoxy resin applied directly to it. Sufficient strength is needed to withstand chamber pressure, so a wall thickness of about 1/16" in small motors is often used. That's a lot of fiberglass. For routine motors this is a royal pain. For a special large motor it may be worth while.

The average experimenter looks at anything that's remotely tubular and seems to be strong as a potential rocket motor casing. Don't fall into that trap. That same average experimenter will save money and time in the long run by using proven materials.

CAN I SUBSTITUTE...?

No. You may not.

Consider the individual who has never before cooked, knows nothing whatever about it. He wants to make a cake. He can't find cake flour on the shelf. So he substitutes Portland cement; it looks almost the same and it gives much the same consistency while mixing. Those who use the end product will find it unsatisfactory... (I know, it's farfetched...)

Now consider the semi-cook who can't find cake flour. So he substitutes rye flour. Again, the final product will be unsatisfactory. Not so farfetched.

Now consider the reasonably-knowledgeable cook. The cookbook says that a cup of cake flour can be substituted by a cup minus two tablespoons of all purpose flour. He does this. The cake comes out...but it's not *quite* right. It's a little heavy, a little greasy.

Those of you who cook regularly know how much of a difference can be made by substitutions, even when the substitutions appear to be trivial. Soybean oil used in place of olive oil in salad dressing will lack in flavor and aroma. "Baker's ammonia" used in cookies gives a light, crisp cookie not obtainable with baking soda. Margarine instead of butter in pound cake gives a result that, to my taste, is an insult to the name "pound cake".

And so it is with propellant. Substitutions cause changes. The gross nature of the change may be obvious (or not); the subtle differences may be unpredictable.

I will not advocate substitutions because there's rarely a simple way to predict the result of the substitution. The individual who substitutes without specific foreknowledge and experience does so at an unknown risk. The cook who uses margarine instead of butter risks only the ire of those who eat the cake. The propellant "technician" who substitutes potassium chlorate for AP in the propellant may become aware of the problems when it ignites in his face.

The professional does not substitute. He *formulates*. He begins by postulating the desired propellant properties, then compounds a propellant that should fit the bill. As a scientist, he can *predict* to some degree what the result will be before it is done. But the propellant is tested rather thoroughly anyway...

Remember: you're not doing this to save money. You're doing this for the love of the work. Don't try to cheat by substituting ingredients. You will make you very unhappy.

SAFETY RANT

Making propellant and rocket motors are dangerous actions. Driving a car is dangerous. Building a house is dangerous. Rock climbing, volleyball, skydiving, basketball, scuba diving, hunting, football, soccer, archery, skeet shooting, canoeing, motorcycling, bicycling. Cooking (burns!), walking (how many have stumbled and sprained an ankle or broken a bone while walking? I have...), making love (STD's?), eating dinner (why is there a Heimlich maneuver?). All are dangerous.

Perfect safety doesn't exist. If you choose to drive a car, play soccer, pick up a strange female at a bar, or make rocket propellant and rocket motors, you accept the attendant risks.

What are those risks in propellant making? I don't know all of them.

In the safety guidelines, and elsewhere in this book there are ways described to minimize certain risks of which I *am* aware. But I don't know all the risks. I have never worked for a propellant company. I have not been professionally trained in propellant work (those who have, often aren't permitted to share that information). I have learned by reading the literature, by conversation with others, and by a bit of deductive reasoning.

Exactly *how* risky is home propellant making and motor construction? I don't know that either. In making propellant as an experimenter you are carrying out operations that ordinarily are carried out on a large industrial scale. Operations that ordinarily are performed in very remote locations. Operations that ordinarily are performed by people who have been trained specifically for the work. When you choose to do it home-brew, you accept risk. Risk that I cannot quantify.

As I write this I've received e-mail from a friend who was burned in a propellant accident. By his own statement, he did not use certain safety equipment that would have minimized the results of the accident. This is not to lay blame, but just to make an observation. He accepted risks, and there were undesirable consequences.

To repeat: if you elect to make composite propellant and motors, ***YOU ACCEPT*** the attendant risks. Next week you may lie burned and screaming on a hospital bed. Alternatively, you may make propellant for the next ten years until you lose interest, and never have an accident. Either is possible. I don't know which is more likely. I don't have the data.

I'm not omniscient. I just don't know. So don't ever be stupid; always be careful out there.