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Capt. BERTRAND R. BRINLEY
Project Officer, First U. S. Army Amateur Rocket Program

ROCKET MANUAL FOR AMATEURS

THE COMPLETE, AUTHORITATIVE HANDBOOK FOR SAFE PROCEDURES IN

* DESIGN
* TESTING
* PREPARATION OF FUELS
* FIRING

OF ROCKETS WHICH YOU CAN MAKE YOURSELF

Foreword by WILLY LEY

BALLANTINE BOOKS

IN LITTLE MORE than two decades, rocketry has advanced from an experimental science fostered by amateurs to vast governmental programs that have already succeeded in putting satellites into orbit around the Earth, sent rockets out beyond the Moon, and will soon probe further into space.

Yet astonishing as this progress has been, it represents only the first step in the exploration of a new scientific frontier. To support and maintain the rocket programs of the United States will require the best thinking of thousands of young scientists and technicians.

In private industry and in government, the search for such creative minds is pursued as a matter of urgent necessity. Captain Brinley, as Director of the 1st Army Amateur Rocket Liaison Program, has helped thousands of young people to prepare themselves for careers in the new science of rocketry.

In this book he tells you how to organize your own group for rocket experimentation. He shows you how, for a few dollars, you can design and build rockets that will surpass the best performance of rockets built by pioneer scientists. In step-by-step directions he outlines safe procedures for rocket testing and firing. And in the final chapter he tells how to evaluate accurately the performance of your rocket so that you gain the maximum of information.

This is an original publication—not a reprint.

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ROCKET MANUAL
For Amateurs

by Capt. Bertrand R. Brinley

Foreword by Willy Ley

Illustrated by Barbara Remington

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FOREWORD

I know in advance of publication that this book will be subjected to strong criticism by some people—and will be hailed by others—with a good chance of being labeled "controversial."

Rocket experimentation by amateurs just happens to be one of the areas where people fail to see eye to eye. Nor is this controversy of whether people should be permitted to do as they please (within reason, of course) or whether Something Should Be Done as new as it looks. Even before the space age was headlined by the beeps from Sputnik No. 1 there were dedicated groups of amateur rocket experimenters who could not only point to successful flights but to an unblemished safety record. They could also tell stories of harassment of various kinds.

But it is true that the problem has assumed major proportions since Sputnik No. 1. For a year or so virtually every youngster wanted to build rockets. And there have been accidents, even fatal ones. The reaction to these accidents took different forms. On the one hand several companies which are in the rocket business issued safety manuals free of charge. So did the Army. Somewhat later the Armed Forces began to assist amateurs actively, as is told in the body of the book by the man who did much of the assisting. On the other hand the large and respected American Rocket Society came out repeatedly against any and all amateur experimentation. And I have had discussions with legislators of various states who favored starting a drive, as if amateur rockets were narcotics, all in the name of safety, of course.

The two arguments most often advanced are (A) it is not safe and (B) the amateurs will not be able to discover something that the professionals have not already done. As for argument (A), the simple fact of life is that it can be highly unsafe but that accidents are always due either to carelessness or simple lack of knowledge. Both of these can be remedied. As regards argument (B), my favorite story is that at one university I saw a medical student dissect a human hand. I could have told him that he would not learn anything that could not be found in medical texts, with fine colored illustrations, and that he had absolutely no chance of making a discovery. My statements would have been perfectly correct, yet have missed the mark by several miles. That student did not lift out the various blood vessels and muscles to find something new for others, he did it for himself, in order to learn and to gain practice.

I might also ask where the professionals came from originally. The young Russian student of engineering, Blagonravov, certainly was not a professional back in 1932 when he built his first rocket. And then there was a group of people on the outskirts of Berlin building rockets. Their names were, in approximate order of age: a high-school teacher called Strache; a man with a degree in engineering but no engineering practice (because of the first World War and the subsequent inflation) called Nebel; a man who had studied mainly zoology and who had thought he would become a geologist, myself; a young man who had begun to study engineering (interrupted by the inflation, too) and who happened to be the only one with machine-shop experience, Klaus Riedel; a high-school graduate who was beginning to study engineering, Wernher von Braun; and finally, a high-school boy who intended to study engineering later on, Helmuth Zoike. This group of rank amateurs built the first German liquid fuel rockets.

Some years earlier, in New England, a physics professor by the name of Robert H. Goddard had also begun to putter around with rockets, to the amazement (and amusement) of quite a number of people who now recall with some regrets that they saw no future in the professor's puttering.

Well, if the first generation of experts had to begin as amateurs, what does anyone expect the next generation to do? Learn how to draw parts with great accuracy without any knowledge of what these parts do, where they fit in and why they exist in the first place?

Just because I was in one of the first groups, a group which had explosions but never an accident to a person, I am more aware of the need for safety than many others who use the word frequently. Yes, safety has to come first and last and every quarter inch in between. But those who want to learn should be permitted to learn—in safety.

WILLY LEY

Chapter I

ORGANIZATION, SAFETY, AND THE SCIENTIFIC METHOD

Before any young man, or group of young men, embarks upon a project as potentially dangerous as rocket experimentation it is advisable, first, to get honest and straightforward answers to some very serious questions. The first question is: WHY DO YOU WANT TO EXPERIMENT WITH ROCKETS? The second question is: WHAT DO YOU HOPE TO ACHIEVE BY IT? And the third question is: ARE YOU WILLING TO MAKE THE SACRIFICES AND TAKE THE ELABORATE PRECAUTIONS NECESSARY TO ENSURE THE SAFETY OF YOURSELF AND OTHERS, AND ARE YOU WILLING TO ABIDE BY THE LAW?

If your answer to the first question is that you are thrilled and fascinated by things that burn and explode, and you love to watch fireworks displays, or you simply want to send a rocket higher than the boy next door, then this book is not written for you, and you had better find something less dangerous to amuse you. You are looking for a *hobby*. And amateur rocket experimentation is not a hobby; it is a serious business.

If you do not understand what is meant by the second question, or you can think of no answer to it other than the fact that it gives you some personal satisfaction to watch a highspeed projectile go zooming off into the air, then this book also is not written for you, and you had better find something more productive to do with your time. Amateur rocket experimentation can be justified only on the basis of its educational value to those participating in it. It is a means of learning more about the sciences and the special technologies of the missile era. And the rocket itself is merely a tool for teaching, perhaps the most useful one man has ever devised.

If your answer to the third question is "No!", or if you do not feel all the precautions recommended in this book are necessary, then you had better devote your time to something that does not have the potential of injuring, or possibly killing, other people. For in amateur rocketry, constant attention to the safety of participants is essential and important above all else.

These three questions must be kept uppermost in the mind of the amateur experimenter if he is to achieve anything in his work, and if he is to live to profit from it. They must guide his every action, and against them he must measure his results.

In this chapter we will consider the methods by which the amateur can achieve the most effective results before getting into the area of actual rocket design and construction. There are three major aspects of amateur rocket activity which deserve careful attention. They are:

ORGANIZATION
SAFETY
SCIENTIFIC METHOD

The amateur experimenter must give careful thought to each of these aspects of his work if he is to achieve anything worthwhile, and if he is to gain community support and assistance. Amateur rocketry is not something that can be engaged in haphazardly, on the spur of the moment, and with no planned program of activity. Neither is it an activity that can be conducted clandestinely—behind the barn or in the cellar—without the knowledge and support of parents and community officials. *Organization* (of both the group and its projects), *safety* and *scientific method* all have as their objective the establishment of a safe and productive working atmosphere. Such an atmosphere is important to any group effort. It is doubly important in the case of an activity as fraught with dangers and physical hazards as amateur rocketry is. Let us first consider the matter of organization.

I ORGANIZING A ROCKET SOCIETY AND A PROGRAM OF EXPERIMENTATION

Amateur rocket experimentation must necessarily be a group effort. Although there are a few examples of outstandingly gifted young people who have worked by themselves and produced very advanced rocket hardware, they are so few that they must be considered unusual. Generally, these individuals are fortunate enough to have more facilities and money at their disposal than the average young person has. But they do not have the facilities to conduct a really far-reaching program of flight testing, and almost without exception they fall short of the achievements of well-organized small groups of experimenters. The most successful amateur rocket groups in the country are almost invariably small organizations of five to ten individuals who share a common interest in advancing their scientific knowledge, and each of whom finds in the study of rocket science a chance to exercise his talents in his own particular specialty, be it chemistry, metallurgy, electronics, mechanical engineering, or even medicine. (This appraisal, of course, excludes those few rather large amateur rocket societies which have been organized for periods of ten to fifteen years, mostly in the Southwest and on the Pacific Coast; but which consist primarily of adults who grew up with rocketry and have continued to pursue it as an avocation.)

The reasons why amateur rocket experimentation seems to flourish best among rather small, but well-organized groups are many. Among them is the fact that rocket experimentation, even on a small scale, costs a certain amount of money. Not a great deal of money, except in the case of very ambitious projects, but enough to be beyond the ability of one or two young men to finance it out of weekly allowances or part-time earnings. Another reason is the fact that rocket design and construction can be a rather complex matter, and the variety of skills required and the depth of knowledge one must acquire in a wide range of subjects almost precludes the possibility of one individual mastering it all by himself. On the other hand, successful amateur rocket groups seem to have discovered that "too many cooks can spoil the broth," and that amateur rocketry can attract a lot of people who are fascinated by the subject, but who do not seem to do any work or make any constructive contribution to the group effort. Frequently, these individuals are people who just love to be members of some organization, but who spend most of their time arguing at great length over obscure and relatively unimportant provisions of the group constitution or by-laws, and who always seem to disagree with the way things are being done. Others among them are simply "dead wood" who are good listeners and enthusiastic supporters of the group, but who never make any concrete contribution in terms of physical work. These persons invariably create friction and jealousies within the group and make it virtually impossible to adopt a unified program of activity and establish clear-cut objectives for research and development work. They are frequently long on ideas (particularly elaborate ones) and talk, but very short on performance. Successful amateur rocket groups have learned to eliminate them from membership at an early stage.

If I were asked to define the *average* or *typical* amateur rocket group in America that is successful in its work and has an intelligently planned program of study and developmental projects under way, I would say that it consists of *seven* bright young men between the ages of 13 and 17, *one* sympathetic and understanding parent or high school teacher who acts as an adult adviser for the group, and *one* engineer or chemist who acts as a technical adviser. This composition of membership does not give the group everything that it needs in order to carry on a full-fledged program of experimentation; but it does represent the organizational nucleus which can obtain for the group the support and assistance it needs from other sources. The fact that this pattern of organization is repeated so frequently throughout the country, and produces results, is evidence enough of its validity.

This does not mean that every group must consist of seven members. Three or four may be the optimum number in many cases. In other cases a group as large as twenty may be able to work effectively together, but this is rather doubtful. In all the thousands of amateur rocket groups I have had a chance to observe and to correspond with, I do not know of one with a membership of more than twenty that has done anything worthwhile.

Composition: The membership of a rocket society should represent as wide a variety of skills and interests as are compatible with the basic purpose of the group. A wide range of knowledge in the basic sciences is needed in order to understand how a rocket functions and to make proper use of it as an experimental vehicle. For this reason successful rocket groups have generally been made up of members whose particular interests are quite different, but whose general interest in the advancement of scientific knowledge about the universe is mutually shared by all other members of the group. Oddly enough, a great many very productive groups are made up of young people of such varied interests that none of them can be said to be interested in *rockets themselves*. Rather, they are interested in only one part of the rocket, or in only one of the many things that rockets can do or be used for. None can properly be described as a *rocket enthusiast*. A typical group may consist of one young man who wants to be a mechanical engineer, one or two others who want to be chemists, another who wants to be a doctor, another who is a radio ham and wants to be an electronics engineer, or just a radio repairman, and another who is only interested in photography. The boy who wants to be an electronics engineer finds in the rocket a chance to further his knowledge of electronic circuitry and telemetering systems and to test his ability to devise practical methods of communicating with the rocket in flight or controlling certain of its actions remotely. The photographer finds an opportunity to test his ability to get good pictures of rocket launchings, or pictures of the earth taken from the rocket in flight, and to test his ingenuity in devising the means of taking such pictures.

Each member of the group similarly finds a challenge in his own particular field represented in the over-all project of getting an efficient rocket into the air and making some use of it while it is there. He contributes from his own special knowledge to the total effort of the group, usually is put in charge of the particular phase of the project in which he happens to be most expert, and assists in other phases of the work as he is able. Thereby each member is able to exercise his own talents in a rewarding fashion, and is able at the same time to gain a considerable knowledge of rocket technology through association with his fellow members. This pattern of functional division of work, according to the individual abilities and interests of the separate members, is followed by nearly every successful amateur rocket society.

The Adult Adviser: Ever since amateur rocket activity became a matter of public concern some two years ago the question has been asked, "Who is competent to advise an amateur group interested in rocket experimentation?" The answer is that there are probably only a hundred or so persons in the entire country who could be considered fully qualified to advise an amateur rocket club in every phase of its activities. Obviously this small number of *fully quali-*

fied experts cannot advise every amateur group, and as a practical matter they are not available to advise even one group, because they are certainly among the busiest people in the country today.

Common sense dictates, however, that the adviser to an amateur rocket society need not be an expert in anything. He need only possess mature judgment, "horse sense" and some knowledge of the sources from which he can obtain information and expert advice for the group. It is unrealistic to assume that any one person can give a group all of the technical advice that it needs, or even to assume that the group can get it all from one source. It therefore makes no difference whether the adult adviser has any technical qualifications at all; and it may be better if he has *none,* because he will then be less inclined to assume that he knows something which, in fact, he does not. The president of a large corporation, such as General Motors, is not usually a person who is proficient in any field except management, and it is not necessary that he even know on which side of a car the gas cap is located. His job is to see that the firm has the best technical and production resources and that its operations are productive and profitable. If there is a need for more and better engineers, he directs that they be hired. It is the same with the adult adviser for a rocket group. He can be an interested parent, a high school teacher, a boy scout leader, or anyone competent to lead and supervise the activities of young people. It is only necessary that he have an understanding of the psychology of young people, and sufficient maturity to distinguish between what is foolhardy, and what is not.

The Technical Adviser: A group may or may not have a particular person available to it as a technical adviser. As pointed out earlier, a rocket group must expect to get its technical guidance from a variety of sources, and no one person can be expected to have all the knowledge necessary to give competent advice in the wide variety of technical fields that rocket science encompasses. However, any person trained in one technical field generally has some familiarity with several others and a good grounding in the basic sciences. Most importantly, he is likely to be able to recognize hazards when he sees them, or to know when the group is venturing into an area that is apt to prove dangerous; and he should be reasonably familiar with the sources from which technical information can be obtained. Many groups have enlisted the help of engineers, chemists, or technicians from industry or universities located near them. Such a person is frequently able to give the bulk of the technical advice the group needs, and knows where to get the rest. Even an expert machinist can be of considerable help.

Constitution and Safety Code: Once a group has decided upon the persons who will constitute the original membership of the society, and has found a willing person in whom it has confidence as an adult adviser, the next step that should be taken is to hold an organizational meeting to decide upon the rules under which the group will operate. Most groups draw up some sort of constitution which defines the conditions of membership, provides for the election of officers and the raising of funds, establishes the time and place of meetings, and in general outlines the objectives and the manner in which the club shall operate.

In addition, a safety code is usually written up by a group appointed for the purpose, discussed and voted upon by the membership at large, and adopted as part of the by-laws of the group. Failure to abide by the provisions of the safety code is considered a basis for revocation of membership in most groups.

The safety code is not intended to be a complete listing of safety rules, for such a list would be virtually endless and contain far too much detail to be an effective instrument for enforcing safety discipline and encouraging safety consciousness among the members. The safety code is really more of a code of conduct, outlining the standards of personal conduct which the group feels are important to the safety of the group as a whole, and includes a few of the more important safety rules pertaining to the handling of propellants and the conduct of operations at the launching site.

A sample constitution adopted by a rocket society is reprinted for you here as a model on which you can pattern your own; and a sample safety code follows.

Model Constitution: The framework of the constitution presented here is based upon constitutions adopted by the

White Plains Rocket Society of White Plains, N. Y., the Richland Rocket Society of Richland, Washington, and the Astronautical Research Society of America of Bronx, N. Y. It is intended only as a model on which you may pattern a constitution of your own. Additions or deletions may be necessary in order to adapt it to the particular purposes and composition of your group.

CONSTITUTION

ARTICLE I

Name

This organization shall be known as the.............. of ....

ARTICLE II

Purposes

The basic purposes of this society shall be:

a. To conduct experiments, research projects and other educational activities designed to increase the knowledge of its membership in the science of modern rocketry and in the special technologies related to it.

b. To promote and foster the exchange of information with other societies engaged in similar activities.

c. To develop and encourage the establishment of safety procedures among its own membership and to recommend such procedures to all groups and individuals interested in the study of rocket science.

ARTICLE III

Membership

The conditions determining eligibility for membership in the society shall be as follows:

a. Membership shall be open to anyone over the age of .... who exhibits a sincere interest in the purposes and objectives of the organization, and who presents some substantial evidence of accomplishment in the fields of scientific research which the society pursues.

b. A prospective member must submit in writing an application for membership, together with the permission of his parents or a legal guardian.

c. Members must be confirmed by a .... vote of the existing membership of the society.

d. The number of members may not exceed .... unless this number is subsequently changed by amendment of the constitution in the manner herein provided.

e. Any member may have his membership revoked for cause by a .... vote of the full membership in regular meeting for violation of any of the conditions of membership established in the By-Laws, or for an infraction of the Safety Code of the society.

ARTICLE IV

Officers

a. The officers of the society shall consist of:
   President
   Vice-President
   Secretary-Treasurer
   Range Safety Officer

b. In addition the society shall select by decision of a majority of the members, an:
   Adult Adviser
   Adult Technical Adviser

ARTICLE V

Meetings

Meetings of the society shall be held weekly or at the call of the President at a place designated by majority vote of the membership at large.

ARTICLE VI

Operations

The society shall conduct such operations as are consonant with its aims and objectives, the abilities of its members and the limitations of its funds and physical facilities, to include:

Research projects
Lecture and film programs
Static firing tests
Launchings
Special study programs

In addition, the society shall adopt and enforce the observance of a strict code of safety which shall govern the activities of all of its members.

ARTICLE VII

Funds

The society shall derive its funds from the assessment of regular dues, special assessments as voted by a .... majority of the membership, and from donations it may solicit from business organizations or other agencies at the discretion of the duly elected officers functioning as an Executive Committee.

ARTICLE VIII

Amendments

The constitution of the society may be amended by a .... vote of the full membership, to be taken not earlier than the second regular meeting to follow the submission of proposed amendments.

BY-LAWS

(The by-laws to the constitution should cover in detail such subjects as: the duties of officers; the conduct of elections and voting procedures; the amount and method of assessment of dues; the conditions for impeachment of officers or members; and provision for their amendment.)

Model Safety Code: The safety code presented here is representative of the type of code established by many rocket societies throughout the country, as a guide for the conduct of their operations and as a means of controlling the activities of their members. As explained in the text, the safety code is not intended to be a complete listing of the safety precautions that should be taken in every phase of rocket experimentation. Such a list would be far too detailed to represent an effective code. Rather, it is intended to set standards of safe conduct for the group and to cover only the major precautions which should be observed.

Failure to abide by the provisions of the safety code is considered a basis for revocation of membership in most groups.

SAFETY CODE

I All members of the .... agree to conduct themselves in a manner which will best insure the safety of themselves and others, and to observe the specific safety precautions recommended by the Safety Officer and adopted by the group.

II All devices must be fired or tested only in the presence of a qualified expert, and all devices and procedures must be tested for safety by an expert and approved by the Safety Officer before they are adopted for use.

III Permission of parents must be obtained by all persons attending a launching or static firing.

IV The testing or firing of any device will only be done with the knowledge and consent of the local governing authorities, and after the officers of the society have determined that the conditions of the test satisfy the requirements of state and federal agencies exercising jurisdiction over the transportation and handling of explosives and the use of air space.

V No device will be fired, either statically or in flight test, except by means of a foolproof electrical device which can be operated from a safe distance.

VI At static firings and launchings all persons must be adequately protected by protective wearing apparel recommended by the Safety Officer, and must stay within the bunkers and revetted areas designated by the Range Officer. Adequate fire-fighting facilities must be available, and emergency first-aid equipment must be on hand with a person who possesses a Red Cross certificate in first aid.

VII No member will be permitted to experiment with propellant combinations independently of projects assigned and supervised by the society Technical Adviser, nor will he be allowed to keep fuel or oxidants at his home. Violations of this provision of the code will result in immediate dismissal from the society.

VIII Rockets will be flight tested only at the approved launching site of the society, and only on dates designated by the Range Officer after proper clearances hand with a person who possesses a Red Cross certifi-

IX No visitors will be permitted at the launching site except by the invitation of the society, and upon the understanding that they will abide by the regulations of the society governing launching operations.

Seeking Sponsorship: Sponsorship by other agencies and organizations can be extremely important to an amateur rocket society, whether it takes the form of outright financial assistance, donations of materials, or just plain moral support. To the embryo rocket society which demonstrates a seriousness of purpose, a due regard for the safety of its members and the general public, and an ability to produce well-designed hardware, such support and assistance is not difficult to come by. For one thing, rockets make news and young people interested in science attract public attention these days. Most any organization likes to be associated with things which attract attention and get space in the newspapers. Time and time again it has been demonstrated that once an ambitious young rocket group has a few initial successes and gets itself talked about in the newspapers, offers of help and assistance come pouring in from all sides. Also, nearly every person is impressed by young people who demonstrate the initiative and the enterprise to do something that is not expected of them in the normal course of events. Professional people, particularly, seem to have an irresistible urge to help, guide, and advise young men and women who exhibit talent.

There are a great many organizations and business enterprises in any community who have resources and facilities that can be of immense help to a group of struggling young scientists—the problem is to convince them that such an investment is worthwhile, and that the group concerned deserves help. As an example, I know of one rocket society in a small community that had a very difficult time getting any sort of assistance until, by dint of hard labor and persistence, it managed to put together a five-foot rocket which was successfully fired to a height of one mile on an Army range. The resultant newspaper publicity so thrilled the town that within two weeks the group was deluged with offers of material and assistance. The local telephone company made them a present of two miles of communication wire and twenty telephones. The Chamber of Commerce offered to sponsor the group's activities. The town council invited them to present a proposal for the establishment of a launching site on the outskirts of town. A local machine shop offered to machine their nozzles and nose cones free of charge, and to train members of the group in the operation of a metal lathe. The school board made the facilities of the school shop available to the group and offered the school as a meeting place. Several near-by industries offered free materials, parts and technical advice. In no time at all, the group had a dozen technical consultants available to it.

All of this stemmed from just one thing—solid evidence of achievement and a little publicity about it in the newspapers. This pattern has been repeated in the cases of hundreds of other small amateur groups throughout the country. One secret of success in getting community recognition seems to be to get the ear of a sympathetic newspaper man. Reporters readily sense the human interest value in the familiar story of budding young scientists struggling to obtain the assistance that they need, and trying to convince the world of the merit of their work. In innumerable cases a local reporter proves to be the key man in getting community organizations and business establishments interested in helping amateur rocket groups, simply because it means rich story material for him and his newspaper.

Another technique that has proved effective in enlisting community support is to arrange for presentations or demonstrations by the most articulate members of the group before luncheon meetings of such community service organizations as Kiwanis, Rotary, Elks, Lions or the Junior Chamber of Commerce, or a local American Legion Post. Have your adult adviser or your group president get in touch with the Program Chairman for any such organization and offer to present a half-hour talk and demonstration explaining the group's work at one of the regular weekly luncheon meetings. Such opportunities are easy to arrange because the average Program Chairman is continually scratching his head for new ideas, and forty-eight weeks of the year he finds himself buttonholing some speaker at the last minute to fill in the ever-present vacancy in his schedule. You will be surprised at how impressed and responsive such an audience of business men can be when they listen to a group of young men explain the intricacies of a scientific project that is completely over the head of the average listener.

Once you have made an initial impression with such a presentation, however, follow it up immediately. Don't let the idea cool off. Contact the key members of that organization the very next day (or the members who seemed to be most impressed with your presentation), and suggest to them that they appoint a committee to meet with officers of your club to discuss the details of a program of support for the club's projects. The members of such organizations as Kiwanis, Rotary, etc., are usually very influential men in the business and political community. Many of them know the Mayor, the Chief of Police and the Fire Chief by their first names and have been friends with them for years. Their voices carry a lot of weight and city officials generally have confidence in their judgment. A proposal to city officials coming from them will get a much more sympathetic hearing than if it were to come directly from the spokesmen of your own club. Such men also are well-acquainted with the industrial and business firms in the area; they know what each of them makes or sells, and they know what facilities they have. Moreover, their own organization usually includes the prominent officials of such firms in its membership. Most service organizations are created to foster and promote within the community projects and activities very similar to yours. Take advantage of them.

The same sort of an approach can be used in the case of large industrial firms in your area that happen to have a sizeable staff of engineers and technicians, or which manufacture equipment or material that is useful to your group. With a little imagination and some aggressiveness on your part, you can get the help you need, providing you impress the people you approach with the seriousness of your group and the fact that your work has a scientific and educational purpose. Nobody can be expected to be interested in helping a group of young men to set off fireworks. But they *will* be interested if you can point to some achievement your group has been responsible for (such as a well-designed and constructed piece of hardware, or a testing device that has an obvious scientific purpose) and they feel that you intend to continue with your projects and have not just been smitten with a fad.

Seeking Technical Help and Advice: Technical help and advice is available to the average group from a great many more sources than you may realize. One of the best is a university, particularly a technical one. In this day and age there is scarcely a town or village in the country that is not within driving distance of a seat of higher learning. Have your adult adviser contact the head of the physics department, the chemistry department or the mechanical engineering department at any such institution. You may be surprised at the willingness of professional educators to devote time and effort to the education of the young for no reasons other than the joy of doing it and the deep sense of dedication that most teachers have. Bear in mind, always, that such people are busy and have their own schedules and obligations to abide by. If the members of your group are polite, studious, unobtrusive, and willing to listen, you will get much farther with educators than if you badger them with inconsequential questions at inconvenient times. Do not call such a person on the phone, or go to see him, the moment that some idea or knotty problem occurs to you. And do not permit the members of your group to do it. Arrange for regular meetings with anyone from whom you seek technical advice (at *their* convenience, not yours) and save all your questions and problems for that time. You will be amazed at how often a really hot idea looks like a crazy pipe dream after you have thought it over for a week, and how often a complicated problem is not a problem at all when you have devoted sufficient thought of your own to it. It is a good rule in life never to open your mouth the first time that an idea occurs to you. Think it over for awhile and consider it from every angle. After you have thought about it for a few hours, or a few days, and it still seems to be a good idea, then it is time enough to talk it over with someone else. You can save yourself and your group a lot of embarrassment this way; and you will earn a reputation as a sober thinker, rather than a blabbermouth.

In addition to colleges and universities there is a host of other sources for technical help. We have already mentioned industries as one prime source, and it is not necessary that they be right next door. You can always get a certain amount of help by corresponding with any firm. You can also arrange to travel once a month, or once a week, to some near-by city where a large industry happens to be located, if you really want the help and advice you are seeking. You can also find out where the nearest chapter of the American Society of Mechanical Engineers, or the American Rocket Society is located and arrange to have your group occasionally attend monthly meetings as guests.

You can also take a long, hard look around you within your own community. Maybe a retired engineer or physicist lives right next door to you. (I know of an eighty-five-year-old Polish physicist who is the principal adviser to an amateur group in the Hudson River Valley, and he is tickled to death to be able to keep his hand in the profession to which he devoted his life.) There is no village in the country that cannot reach a TV repairman on the telephone. Yours can tell you a great deal about electronic circuitry. If you have hot air heating in your house, the man who installed it can show you how to work with sheet metal, and will probably let you use his bending brakes and dies to form the flanges on your fins. The next time your mother calls the plumber, strike up a conversation with him. He knows a lot about working with metal tubing, tapping holes, and threading pipe ends. Your local telephone company has a lot of engineers and technicians on its staff. So does the city water department, the department of power and light and the gas company. Any large garage has drills, metal saws, tapping and grinding equipment, and the people who know how to use them; and every town of 15,000 to 20,000 people has at least one machine shop.

And finally, of course, there are the many installations of the armed forces scattered throughout the country. Each of the uniformed services has been authorized by the Department of Defense to lend technical assistance and to furnish other types of support to deserving groups of amateur scientists. The Army's policy in this respect is by far the most liberal and the most far-reaching. If you happen to live somewhere near an Army technical installation, or a large post that has tremendous open land areas and no air-traffic problem, you probably will be able to get a great deal of technical supervision and maybe even a chance to static test or launch your rockets. Bear this in mind about military installations, however. They are not all the same. All of them do not have the same facilities, the same categories of personnel, nor are they engaged in the same type of activity. Some are merely large troop training centers, some are technical arsenals or research centers, some are personnel processing centers, some are record centers, etc., etc. If you happen to live within a few miles of Fort Sill, Oklahoma, you are lucky. The Army Ordnance Missile School is located there and your group can get what amounts to a complete course in rocket science over a period of time, and a chance to fire its rockets. But if you happen to live next door to the Army Personnel Records Center in St. Louis or the Army Finance and Accounting Center in Indianapolis, you can get no help at all, unless you are interested in how the payroll is made up for a missile battery. Do not blame the commanders of military installations if they refuse to give you help. They are authorized to help you, but only *if* (and it is a big "if") they have the facilities and qualified technical personnel to do it, and only *if* such help does not interfere with the accomplishment of their basic mission. Naturally, the commander of Fort Mason, California cannot permit you to launch a rocket on his post, which is right in the middle of the city of San Francisco; but he would probably be willing to tell you how far it is from San Francisco to Tokyo, because it is his business to ship military personnel to the Far East.

II SAFETY

If your group wants to be on hand to greet the first man to return to earth from the moon, or to play some part in getting him there and back, the first requirement is to stay alive long enough to do it. And if you want to shake his hand or pat him on the back, you can do a much better job of it with five fingers than you can with a severed stump. Rocket experimentation can be a frightfully dangerous business, and there is no sense in risking your future happiness and well-being in an ill-conceived and badly-executed attempt to show your friends and neighbors how smart you are.

Throughout the entire course of your group's program of experimentation the idea of personal safety and the avoidance of injury must be uppermost in everyone's mind. The ends of safety must be served first: the advancement of science and of knowledge comes second.

In the field of rocket experimentation there are three important facts of life which all amateurs must know and recognize. If you cannot appreciate the importance of these three things, you have no right to be experimenting with rockets and endangering the lives and property of other people.

1. A ROCKET PROPELLANT IS ONLY A HAIR'S BREADTH AWAY FROM BEING AN EXPLOSIVE COMPOUND. UNDER THE PROPER CONDITIONS OF HEAT AND PRESSURE IT *IS* AN EXPLOSIVE COMPOUND.

2. THERE IS NO ESSENTIAL DIFFERENCE BETWEEN A ROCKET AND A BOMB, EXCEPT THAT THE ROCKET HAS A HOLE IN ONE END (AND THIS HOLE CAN BECOME BLOCKED).

3. A ROCKET IS A FREE-FLIGHT PROJECTILE. IT FLIES FAST ENOUGH TO KILL.

Safety is largely a matter of your mental approach to the operation you have in mind. Get in the habit of thinking of your rocket as a BOMB. Make up your mind that *it is going to explode,* and then you will find yourself taking certain precautions by instinct that you might not otherwise think of.

Also, *remember this*: most accidents happen when people are doing something that they have done a thousand times before, like stepping into the bathtub, holding a match to the gas jet of a stove, or backing a car out of a driveway. Familiarity breeds contempt; and it is just because we are so familiar with what we are doing that we become contemptuous of it and insensible to its hazards. When we are approaching a new and unfamiliar task, or doing something for the first time, we are naturally cautious.

This is why the Army establishes strict, "by-the-number" routines for every hazardous operation, particularly on firing ranges and in munitions dumps. Violation of the routine is a basis for severe disciplinary action, whether an accident results, or not. You must take the same attitude in all the work your group undertakes. The routine that is designed to prevent accidents must be followed faithfully, no matter how unnecessary it may seem, or how boring it is to follow it.

A third thing to keep always in mind about safety is the fact that even though you may not always be able to prevent an explosion, you can almost certainly prevent yourself from being injured by it. Proper protective clothing and equipment, shockproof shelters and barricades, and plenty of distance are the essential ingredients of personnel protection. After all, it is not the explosion that is so dangerous. It is being exposed to it that hurts. If you can cut down the time and degree of exposure, you can similarly reduce the likelihood of injury. In many lines of work explosions are a common thing. They occur frequently in propellant manufacture and research, in munitions plants, chemical plants and ordnance arsenals. In the case of blasting operations, and certain new metal forming techniques, they are deliberate. Seldom is anyone hurt in such explosions, because: they stay as far away as possible, they take cover behind barricades, they are wearing protective gear, and they are following the prescribed routine. If you can make certain that the members of your group observe the same sensible precautions, no one will be injured, no matter how many of your rockets explode.

Safety Rules: Throughout this book safety rules and warnings of hazards appear in virtually every chapter under the subject headings to which they apply. For the general guidance of your group, and because they apply to virtually any type of hazardous activity, a list of basic rules to follow is included here. You might want to copy this list and post it in the place where you hold your meetings.

PERSONAL AND GROUP SAFETY PRACTICES

1. *Safety rules are for you*

   NEVER take the attitude that safety rules are only for the other person. Safety rules are established by experts who invariably take the same precautions themselves. In the field of rocketry, safety rules are the result of painstaking research, trial and error, and costly mishaps.

2. *Research your project before you start building hardware*

   Remember that your work is *experimental* in nature. Before attempting any experiment, be sure to check and recheck reference data available to you from schools, libraries, industry, and government.

3. *Never work alone*

Two heads are always better than one. Your chances of serious injury are reduced proportionately by the number of capable assistants you have. There must always be someone available to help in event of a disabling, crippling, or blinding accident. Experienced sportsmen observe this basic rule of survival; as a junior rocketeer, you must obey it.

4. *Don't hide your activities*

Though you may think they'll cramp your style or hinder your activities, let your parents, teachers, and local authorities know what you are doing. They are wiser and more experienced than you, and will encourage you, provided you observe and implement all safety precautions.

5. *Get an adult supervisor*

Under no circumstances should you build a rocket, mix rocket fuel, load a rocket, or attempt to launch it without guidance and supervision by an adult. Look around . . . you'll find some adult who is interested in your project, whether he is a parent, teacher, official, brother, or neighbor. Your supervisor may not be an expert in anything but common sense, but don't work without him.

6. *Safety lies in orderliness and neatness*

Be neat. Keep your working area free from trash, dust, and scraps of metal and material. Don't work in your basement or attic unless it is clean, has good heating, good lighting, and good ventilation.

7. *Be prepared for emergencies*

Make sure adequate fire prevention measures are available. Face shields, gloves, and a first aid kit should be on hand, as well as a telephone in event of fire, explosion, or major physical injury. Check for open flames, exposed electrical heating, exposed wires, poor electrical fittings and switches. DO NOT SMOKE AT ANY TIME while building, fueling, testing, or launching.

8. *Listen to advice*

Don't be a martyr to science. Disregarding sound advice from others may cause you to lose your life. At least consider the merits of other plans, approaches, and ideas.

9. *Organize your work before starting*

When your research is completed and double-checked, decide on a plan of action. Organize your plan and develop a step-by-step checklist. Integrate all safety precautions into your checklist. Go over all phases of your plans at least twice before starting, to make sure you haven't overlooked anything. As an additional check, ask your supervisor to review your plans. Finally, make certain you follow your outline.

10. *Consider the safety of others*

Remember that you are responsible for the safety and welfare of those around you. This holds true whether you are in the laboratory, workshop, in transit, or at the launching site. Carelessness on your part may well result in death or injury to the innocent.

11. *Prepare for the worst*

It is characteristic of youthful optimism to think only of what will happen if everything goes right. Get in the habit of thinking about what will happen *if everything goes wrong*. You'd be surprised how many weaknesses and hazards you may discover in your plan by this simple switch in mental approach.

III SAFETY THROUGH SCIENTIFIC PROCEDURE

Adopt a scientific mental approach: There is much that you can do to ensure the safety of yourself and others by simply adopting an intelligent and scientific approach to your project. The suggestions which follow do not represent specific precautions to be taken against specific hazards; but rather constitute a summary outline of a procedure you can follow in order to eliminate as much guesswork as possible in the development of your rocket.

All scientists and development engineers follow similar patterns in their work. Even in the automobile industry, where there is over fifty years of accumulated know-how in the production of millions of vehicles, each new model is the result of this same careful, painstaking process—which may start as much as three years before the new model appears in dealers' showrooms.

Professionals work this way in order to avoid costly mistakes. They attempt to predict, calculate, or prove the performance characteristics of every mechanism or device under development before the item itself is produced. You can save yourself time, money and possible grief by learning to work in the same manner.

Plan your working procedure: You do not necessarily have to follow every step in this procedure. On the other hand, there may be steps you will want to add. The point is to establish for yourself an orderly working procedure which will ensure an end product from which most of the "bugs" have been eliminated in the design and testing process.

1. RESEARCH

Do all the research you can. Do it continuously during the development of your project. Research is often the first proving ground of the feasibility of an idea. You may discover someone has already done exactly what you propose to do and can give you valuable, time-saving data. Of more importance, someone may have already demonstrated that it is impossible to do it, and save you time.

2. EXPERIMENTAL DESIGN

This is the first phase of actual design work. Get your idea on paper as early as possible. By just making a drawing, you can uncover faults and weaknesses in a design, and bring to light design and construction problems which may require further research to solve.

Even at this early stage, professional designers frequently have scale models constructed of wood or other material, to help them determine basic shapes, proportions, aerodynamic characteristics, etc.

3. PRELIMINARY DESIGN

After you have decided upon the general characteristics of your rocket and computed its theoretical performance, etc., you are ready to make detail drawings of the complete rocket and component parts. These drawings should be complete; but remember that they are only "preliminary." You may change your mind about some details or develop better ideas in the very process of making the drawings. You will make further changes after you have built test models of various components and have a chance to correct errors.

4. BUILDING YOUR FULL-SCALE MOCK-UP

The next step is to build a full-scale mock-up of your rocket from your preliminary designs. This can be done from cardboard, wood, or any other easily workable material. Engineers use mock-ups to determine: (1) whether their design ideas have allowed sufficient clearance for all parts to fit in place (without "interference"), (2) whether the parts can be assembled in the sequence planned, and (3) whether special fabrication problems will be involved, etc.

5. TEST MODELS & WORKING SCALE MODELS

It is important, in most cases, to construct actual working models of some components to determine whether they will perform as expected when subjected to certain tests. These models can be either full-scale or smaller, as long as the materials used and the proportions conform to the actual design. With rockets, it is most important to construct a small-scale working model of the rocket engine, which can be tested safely, and to actually construct and test various working parts, such as parachute ejection mechanisms, receivers and transmitters, firing devices, etc. When your rocket is several hundred feet in the air, it is too late to try to determine whether all the parts will actually work. Once a working model has passed all its tests, it is a simple matter then to make it any size you want, as long as the dimensions remain proportionately the same. Remember that such things as temperature, humidity, acceleration, etc., can have an effect on the performance of working parts. Take these into consideration in your tests.

6. Final Design

By the time you have completed steps 4 and 5 you will have discovered many things about your design requiring improvement or change. You will discover further things that will change your design when you actually start final construction. These are called "production changes." But it is time now to make your final design drawings incorporating all of the lessons you have learned from your tests. These are the drawings from which you will build your final product. Make them good. Make them accurate.

7. Prototype Construction

The "prototype" is the first full-scale completely operational model of a product to be produced from the final engineering design. If you are intending to build more than one rocket from the same plans, then the first one you build is the prototype. Succeeding ones are production models.

Construct the prototype carefully and painstakingly. A good design can be ruined by faulty workmanship. Don't use a part, or a type of construction, that has not passed your tests.

Remember that the prototype is still an experimental vehicle. It is normal for many design changes to be made after its performance has been analyzed. Don't be stubborn about changing a pet idea after actual performance tests have demonstrated that it will not work.

If you follow the preceding steps, or a similar pattern, you can be confident that you have "developed" a rocket —not just built one. Its chances of successful performance will be much greater. And—the safety of yourself and others will be that much more certain.

IV AMATEUR ROCKETRY AND THE LAW

Before your group reaches the stage of actual propellant preparation, static testing, or the launching of rockets, there is one more important aspect of your activity which must be given very careful consideration and thoroughly checked out, and that is the *legality* of what you are doing.

We all must live with the law; and most of us try to abide by the laws of society and support them, because we recognize that it is the only way to maintain order and still have the freedom to do the things that we want to do. As an amateur scientist who hopes some day to work in the nation's space program, you cannot afford to run afoul of the law, and neither would you want to.

Appendix A on page 332 contains a summary of current state laws applicable to amateur rocketry as a guide for you. The actual texts of the laws can be obtained from your town clerk or by writing to the legislative assembly of your state. Bear in mind that by the time you read this book the list shown in Appendix A may no longer be complete or up-to-date. Its real purpose is to emphasize to you that such laws do exist, and to furnish you with the official designation of the laws with which you should be familiar.

Very few states have, so far, enacted legislation aimed specifically at amateur rocket activity. Those which have generally recognize the fact that there are educational values to be considered which must be given equal weight with considerations of public safety. In several instances, no public law has been passed, but some official or state commission has been given the authority to establish *regulations* governing amateur rocket experimentation. These regulations, of course, have the full effect of law as long as the courts uphold their legality. In the states of California and Connecticut it is the State Fire Marshal who has been given this authority. In the state of Washington it is the State Aeronautics Commission. In the state of Vermont the State Department of Education and the Bureau of Aeronautics jointly share the authority. The latter case is significant. Vermont is the only state in the country in which the educational value of amateur rocketry has been so formally recognized that the Department of Education has been granted partial authority over it. The state of Washington is equally cognizant of this. The state of Connecticut has probably taken the most restrictive and prohibitive attitude of all, and the state of South Carolina is not far behind.

Whatever the laws in your particular state may be, you must abide by them, and adapt your program to their provisions—unless you can arrange to do your work in some neighboring state which may have more liberal laws. And, in addition, you must abide by the ordinances of your own community, which in many cases may prohibit such activity altogether. As far as federal law is concerned, there are only two agencies which exercise jurisdiction in any area which amateur rocket activity might invade. One is the Civil Aeronautics Administration and the other is the Interstate Commerce Commission. The former is concerned with anything that is projected into airspace above an altitude of 500 feet, *anywhere in the country,* and any activity or building that takes place within five miles of an airport. Permission must be obtained from a Regional Administrator of this agency for *each* rocket launching. It is a good idea to contact the Regional Administrator in your area (he is usually located at some prominent airport) and have a frank talk with him about your plans. The Interstate Commerce Commission is concerned with regulating the transportation of explosives and inflammables on highways, bridges and tunnels, and establishes classification ratings for all types of chemical substances. If you intend to transport any kind of rocket propellant on any public highway, or across a state line, you had better let the ICC know about it, as well as state and local police all along the route you intend to follow.

For groups who do any type of radio telemetering, the approval of a third federal agency is required. This is the Federal Communications Commission. This agency is responsible for control of the airwaves and allots the frequencies and channels for all types of transmission for whatever purpose. Certain bands are assigned to amateurs and to commercial users of radio, such as taxi companies, police departments, etc. You must make certain that you are operating within the regulations of this agency if you intend to do any type of radio transmission.

The most important legal hurdle for any group, however, is to obtain the permission of its own local police and fire departments. These authorities come first in the line of authority, and their permission must be obtained regardless of what the provisions of state laws and federal regulations may be. You might be complying with every state and federal law on the books and still be fined $100 by a local judge for violating a city ordinance. The sensible thing to do is to have a conference with the Chief of Police and the Fire Chief in your town *before* you attempt any experimentation involving propellants. Show them what you want to do and the area in which you want to do it. If they say "No," suggest another area, and ask them what they want *you* to do in order to earn their approval. Most such officials are reasonable men, and they will try to make it possible for any citizen to do what he wants if a way can be found to do it within the law and if it will not infringe on the rights of others. Remember that if you have an accident or create a public nuisance of any sort, you will not only put the officials on the spot who cooperated with you, but will probably destroy your chances of continuing your experimentation.

Most existing state and local laws applying to rocket experimentation are those currently in effect to control the use of fireworks, and storage and handling of explosives and blasting operations. In nearly every instance, provision is made in the law for permits to be issued to qualified persons and agencies which will authorize them to conduct such operations under certain specific conditions. Find out what you need to do to get such a permit for your group, and have your adult adviser obtain it. Don't take a chance with the law.

Chapter 2

BASIC ROCKET DESIGN

Paradoxically, the most modern type of motive power—the rocket—is at the same time the simplest and the oldest motor known to man. It has been in use for seven centuries, perhaps even longer. Yet only during the past twenty years has man been able to put it to effective use and to develop it toward its full potential. Its basic elements are disarmingly simple. But to make these elements work together efficiently, and to develop propellants which will make the rocket a practical and useful vehicle has stretched the limits of man's technical resources and pushed the frontiers of his knowledge of the basic sciences outward.

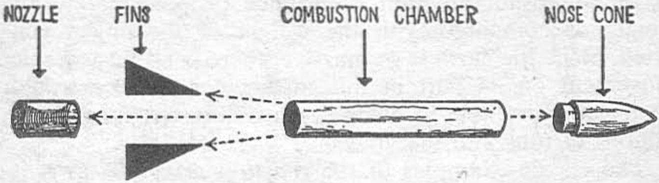
Development of the rocket to the gigantic dimensions of the missile we see today—capable of traveling distances of 5,000 to 6,000 miles over the earth's surface, and probing many times this distance into outer space—has been largely a matter of developing fuels, structural materials and thrust chamber designs which can make more efficient use of the rather simple principle of the rocket motor. No new scientific discoveries have been necessary in order to achieve this. Rather, it has been a question of waiting until the arts of metallurgy, chemistry and thermodynamics were better understood by man. This is typical of all technological development. Great scientific discoveries of one age are frequently not exploited for many generations—or even centuries—until mankind has acquired the companion knowledge and developed the tools which are required to make effective use of them. The steam engine—conceived in principle by Isaac Newton—lay dormant for two hundred years until a Welsh miner decided it was practical to lay steel rails on which a steam locomotive could run, and until engineers developed methods of manufacturing boilers, pistons, rods and valves that were sufficiently strong to withstand the pressures and stresses placed on them.

The principle of rocket propulsion is based on Newton's third law of motion which states that for every action there is an equal and opposite reaction produced—normally in an opposite direction. In simple terms this means that if you lift an object weighing fifty pounds a distance of one foot you are also exerting fifty-foot pounds of pressure on the earth. And, theoretically, the earth should move in the opposite direction a distance proportional to its weight as compared with the weight of the object you lifted. Since the earth is so massive, there is no measurable movement on its part in this instance; but there would be if you were able to catapult an object weighing many billions of tons into the air.

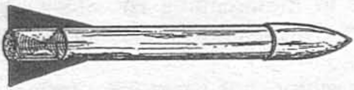
The classic examples of the *reaction principle,* as it is called, are the firing of a gun, and the escaping of air from a balloon. When a gun is fired it recoils, or kicks back, in a direction opposite to that which the bullet took. When air escapes from a balloon, the balloon flies off in a direction opposite to the escaping air. Since rocket motors work on the same principle they are often referred to as *reaction motors.*

In the rocket motor, hot gases are produced by means of rapidly burning some chemical substance (liquid or solid) which is called a propellant. A propellant generally consists of a fuel (or reducer) and an oxidizer (or oxidant). Neither will burn satisfactorily by itself, but in combination they create a chemical reaction which produces heat, and gas products which have mass and weight. The heat generated by this reaction creates a pressure within whatever vessel is being used. This pressure acts to drive the gas products out of the vessel, through any opening that is provided. In a pistol, the chamber in which the burning of the gun powder takes place is the cartridge casing. The opening provided for the escape of the gas products is the muzzle of the barrel. In a rocket it is very much the same. The main body of the rocket motor is called the *combustion chamber.* The escape port is generally called the *nozzle.*

A combustion chamber and a nozzle together constitute a complete rocket motor—in its simplest form. But even for simple rockets two other things are required in order to give the rocket direction and stability in flight. These are: a nose cone, and fins. In Illustration *1* these four basic elements of a simple rocket are shown. The only items which must be added to this assembly to make it fly are the propellant (fuel, plus oxidizer) and a means of igniting it. Illustration 2 shows all the essential parts, with dimensions, of a basic rocket which you can build as a beginning project.



EXPLODED VIEW of SIMPLE ROCKET



ROCKET ASSEMBLED

ILLUSTRATION NO. 1

Before you begin the construction of a rocket, however, it is advisable to consider some elementary principles of rocket operation, and some of the factors which can cause a rocket to become an extremely dangerous "weapon" capable of causing death or injury.

A rocket achieves its forward motion by expelling, or exhausting, hot gas particles from a nozzle. This *motion* of gases toward the rear causes the rocket body to move forward, as a *reaction*. The gases *do not push* against anything. It is simply their *velocity* as they move rearward, multiplied by their mass, that determines how much force, or *thrust,* is imparted to the rocket. Naturally, it is desirable to have as much gas as possible (mass) ejected from the nozzle as rapidly as possible (velocity) in order to get a high degree of thrust. To achieve this, it is necessary to burn a substance in the rocket chamber which will create a large volume of gas rapidly and produce enough pressure to drive the gases out of the chamber at a high rate of speed. The substance must not burn so rapidly that it amounts to an explosion, however; and neither must it

A BASIC ROCKET FOR BEGINNERS

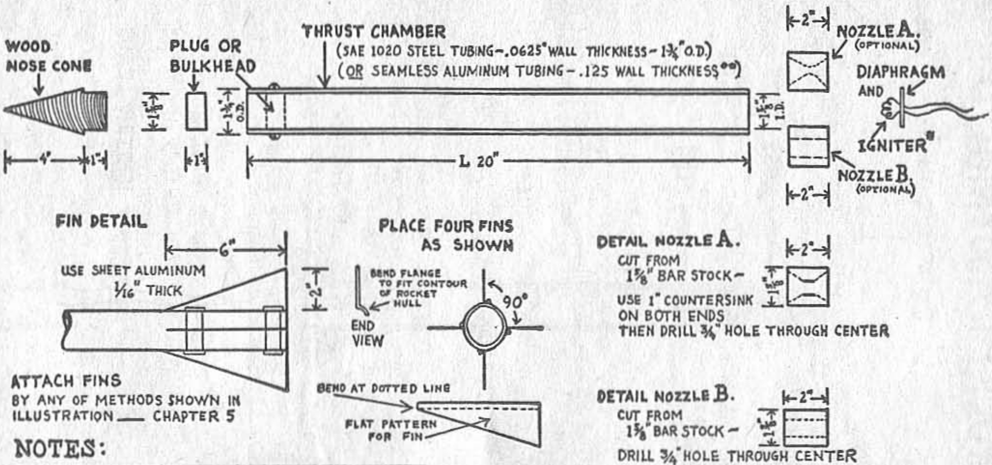


ILLUSTRATION No. 2

NOTES:

*1 FOR DETAIL OF DIAPHRAGM-IGNITER ASSEMBLY SEE ILLUSTRATION ___ CHAPTER 5.

**2 DO NOT USE ALUMINUM TUBING IF NOZZLE IS USED — USE STEEL ONLY.

3 ROCKET CAN BE FIRED WITHOUT NOZZLE IF DESIRED.

4 NOZZLES SHOWN ARE NOT DESIGNED FOR HIGH PERFORMANCE, BUT FOR EASE OF FABRICATION FOR BEGINNING GROUPS. FOR MORE EFFICIENT NOZZLE DESIGN SEE CHAPTER 4.

5 USE HEAVY METAL SCREWS 3/16" TO ¼" IN DIAMETER TO FASTEN FOREWARD BULKHEAD AND NOZZLE TO ROCKET BODY — 4 SCREWS EQUALLY SPACED. BRAZE ENTIRE PERIMETER TO PREVENT ESCAPE OF GAS PRESSURE.

BASIC ROCKET ASSEMBLED

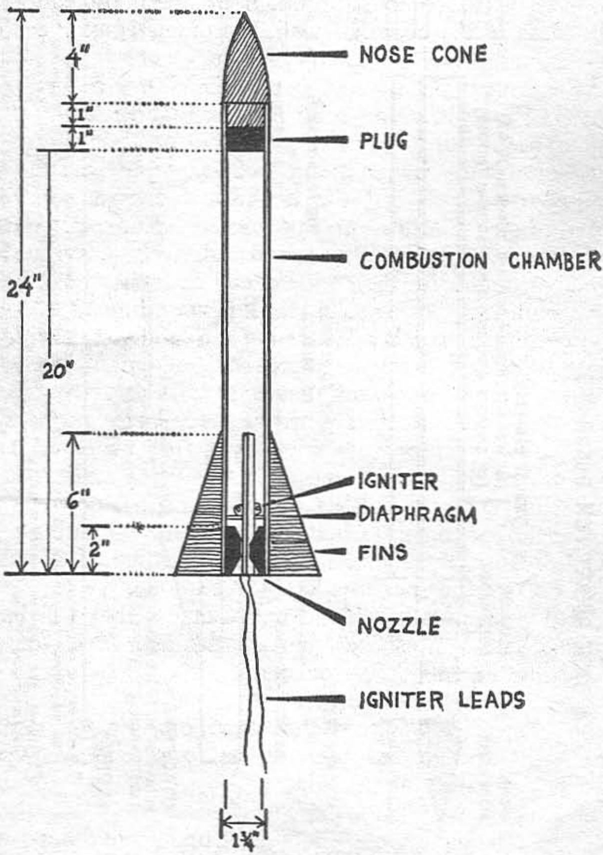


ILLUSTRATION No. 3

be allowed to create so high a pressure in the chamber that it will crack the chamber casing before the gases can be expelled. Preventing this from happening, of course, is a matter of engineering design; and this design must achieve a balance among a great variety of factors, any one of which can cause a failure of the system if it is not properly controlled. The most important of these factors are: the burning temperature of the propellant substance, the burning rate (i.e., how much of it is burned in one second), the size of the combustion chamber, the composition and thickness of the chamber wall, the diameter of the nozzle throat, and the length of the nozzle.

The propellant substance burned in the rocket motor chamber may be either solid or liquid; and if solid, it may either be in the form of a cast grain or a tightly packed powder. Nearly all amateur rockets employ a solid propellant, and 95% of these are in powder form (usually a mixture of a zinc dust and powdered sulfur). Powders, of course, are readily mixed and relatively easy to load, which accounts for their widespread use. They have serious disadvantages, however, in that it is very difficult to control the density to which they are packed, and virtually impossible to predict with any accuracy how rapidly they will burn. Generally speaking they tend to burn unevenly (frequently due to excess air being trapped among the particles) and this uneven burning may disturb the aerodynamic balance of the rocket, causing it to travel erratically and zoom off in unpredictable directions. Also, powders tend to burn *all at once,* rather than gradually, creating a very high pressure for a very short period of time. If this condition occurs, the rocket is likely to explode.

These eventualities (and many others that will be discussed later) must be guarded against. It is therefore advisable that amateur rockets:

a. Be *overbuilt* from the standpoint of the size and strength of materials used so as to provide as wide a margin of safety as possible.

b. Be launched, or tested, only under conditions which will ensure the absolute safety of all participants, and which allow for the fact that the rocket may:

explode while being loaded.

explode on the launching stand.
rise ten feet in the air and explode.
rise only a short distance and then fall to earth still spitting out chunks of burning propellant.
do a complete loop and plunge back to earth under full thrust.
rise normally a short distance, then keel over and fly horizontally in any direction of the compass.

These, and many other odd things can happen when you start to experiment in a field where even the professionals don't know all the answers. If you don't believe it, read this description of an amateur rocket launching from the records of a West Coast society that has been conducting rocket experiments for approximately fifteen years: "After having risen only 20 feet and then going back down to about 4 feet, it continued to fly for about half a mile, setting fire to the sage brush as it went, at a speed close to 350 miles an hour."

Amateurs must understand that the rockets they design and build are what the military calls "free flight" rockets. In other words, there is no means of guiding or controlling the flight of the rocket once it has left the launcher—except, perhaps, the wishful thinking of those who designed it and the prayers of the spectators. (Even if a very advanced amateur group were to build a guidance system into a rocket, it could not be considered reliable enough to permit the assumption that it would go where it was intended to go.) For this reason, amateur groups must never launch even small rockets except in areas where there is no human habitation of any description *in any direction* for a distance greater than the maximum range of the rockets being fired. And they must also have the permission of the local authorities who have fire and police jurisdiction in that area. How to calculate the size of the clear, or *safe,* area that you need is covered in Chapters 8 and 9, together with many other aspects of safe launching operations.

The basic rocket shown in Illustration *2* is, of course, elementary both in concept and design. It is intended as a beginning project for the individual rocketeer or newly-organized group. It is not designed for high performance, but rather with a view to reasonable safety and ease of fabrication. If desired, the rocket can be made and test-fired without a nozzle as long as a diaphragm or some other type of retainer is used to hold the propellant in place initially. For beginning groups it is probably better to follow this procedure initially, and then to construct similar rockets with nozzles in order to compare performance.

The Nozzle: The two nozzles shown in the illustration are likewise not high-performance designs. They are "rule-of-thumb" designs which are relatively easy to fabricate and which have a generous safety allowance in the ratio of combustion chamber diameter to nozzle throat diameter. The ratio used is close to 2 to 1. Generally, amateur rocket groups have found that nozzles function with fair efficiency, and explosions do not occur, if this ratio never exceeds 3 to 1. (I.e., a rocket with a chamber inside diameter of 1½ inches should have a nozzle with a throat *no smaller* than ½ inch in diameter.) This ratio is based purely on experience, after many hundreds of rocket launchings, and not on engineering principles. It cannot be substantiated by calculation that this is an optimum ratio. It seems to give satisfactory results, however, providing other design factors are not out of balance. In Chapter 4 you will learn more about the factors that determine correct nozzle design and you will find there a thorough exposition of the calculations necessary to determine the proper nozzle dimensions.

Each of the nozzles shown in Illustration 2 can be made with a minimum of machining, a drill press being the only machine tool necessary for the drilling and countersinking. The finished nozzle should be as smooth as it is possible to make it, however, and it should be a tight press fit in the end of the rocket chamber. The sharp edges at either end of the throat section should be filed smooth and slightly rounded to prevent unburned propellant from accumulating at this point and possibly causing the nozzle to clog. A clogged nozzle means that an explosion will result unless the chamber walls are unusually strong.

The nozzle is attached to the body of the rocket with four machine screws of at least $\frac{3}{16}$ of an inch diameter placed equi-distant from each other around the circumference of the tubing. Get an engineer or a machinist to check the shear strength of the screws you are using. A machinist's or engineer's handbook will tell you. Make sure that the combined shear strength of the four screws is far in excess of the expected chamber pressure. Otherwise the nozzle may be blown out of the end of the rocket. Assume that the maximum chamber pressure developed by this rocket will be in the neighborhood of 600 to 700 pounds per square inch, and that the nozzle cross-sectional area exposed to this pressure is approximately 1.6 square inches. Make sure that you do not drill completely through the nozzle nor into the rocket chamber at any point when using screws for attachment.

An alternate method of attaching the nozzle, if you can get the work done, is to thread the entire length of the nozzle and an equal distance inside the rocket tube. Naturally, this is a more convenient method of attachment and it simplifies loading and insertion of the diaphragm. But if you use this method you must be extremely careful that propellant particles do not become stuck in the threads. Even a small amount can cause an explosion when the threads are tightened.

Care must be exercised to insure that the nozzle throat aperture is correctly aligned with the center line of the rocket body. When drilling and counter-sinking make certain that the drill is precisely centered and the angle of attack is exactly parallel to the outer surface of the nozzle. Even the slightest deviation from true center will cause the rocket to veer off sideways in flight.

The metal used for the nozzle should be the hardest, most heat-resistant type obtainable, consistent with machining requirements. SAE 1020, low carbon steel is satisfactory for low-performance rockets, but a chrome-molybdenum alloy is better. Get an engineer or metallurgist to advise you on this, if possible.

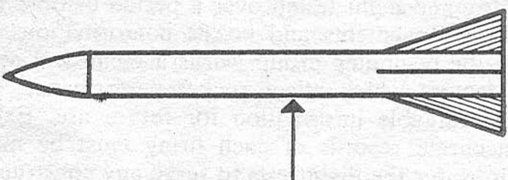
The Rocket Body: The rocket body should be of *seamless* steel tubing (SAE 1020) preferably, although aluminum is permissible for smaller rockets where a high-performance nozzle is not used. If you use steel, the wall thickness should be approximately 0.625 inches for a rocket of 1¾ inches outside diameter. A wall thickness of .125 is recommended for aluminum tubing, although $\frac{3}{32}$'s of an inch may be satisfactory. Care should be exercised in drilling holes to ensure that they are perpendicular to the surface and not canted.

The forward bulkhead, or plug, is cut from bar stock of 1⅝ inches diameter, and like the nozzle, should be a tight press fit in the rocket body. Attach the bulkhead with four of the same size machine screws used on the nozzle. To prevent leakage of pressure around the perimeter of the bulkhead, it may be brazed. But if you prefer to accomplish the loading of the propellant through this end of the rocket, so that the nozzle may be brazed in place, you can fit a tight rubber seal into the rocket body between the bulkhead and the nose cone. In this case, it is desirable to fasten the nose cone in place with screws, also, in order to hold the rubber seal tightly against the bulkhead.

The Nose Cone: The nose cone is made of wood and may either be turned on a lathe or whittled to shape. It, too, should be a tight press fit in the rocket body, but this is not important if the bulkhead is brazed in place. The nose cone can perform a useful function in balancing the rocket properly. It is desirable that the rocket be in balance when suspended at a point somewhere around its midpoint. Definitely, the center of gravity must be forward of the center of the fins.

ILLUSTRATION NO. 4

Aerodynamic Balance



Balance your rocket, loaded with sand or some substance of the same approximate weight as the propellant. If it is nose-heavy, you can compensate by hollowing out the nose cone. If it is tail-heavy, you can insert lead weights in the nose cone to adjust the balance forward.

The Fins: The fins of the rocket should be made of $\frac{1}{16}$th inch thick sheet aluminum. They may be attached to the rocket hull with band-type clamps, spot welding, or brazing. At the nozzle end, advantage may be taken of the screws which attach the nozzle to the hull, to also hold the fins in place. Do not attempt to place screws elsewhere on the rocket hull, however. For details of methods of fin attachment consult Illustration 24 in Chapter 5. To bend the flanges to the proper contour, take your parts to any tinsmith or a firm that installs hot air heating systems. They have the bending brakes to do a neat job for you.

The fins for this rocket have been designed according to a formula used by some amateur groups which is discussed in detail in Chapter 5. As you will see, after reading that chapter, there is no established method of calculating fin size and shape, even for professional rockets, without recourse to automatic computers—a procedure obviously beyond the capabilities of any amateur group. In the final analysis, fins must be flight tested by the trial and error method before a satisfactory configuration for any given rocket can be determined. Generally speaking, amateur groups tend to equip their rockets with much larger fins than are necessary. Many small rockets are successfully flown with no fins at all.

For a beginning project it is recommended that the small rocket shown here (or one similar to it) be fabricated in some quantity and flight tested over a period of time with different fin arrangements and nozzle conformations. By this means, the beginning group learns a great deal about the many factors which affect rocket performance, and accumulates valuable information for future use. Extensive and accurate records of each firing must be maintained in order for the flight tests to serve any constructive purpose. In Chapter 10 you will find a sample flight test data sheet and further guidance on this subject.

Diaphragm and Igniter: The diaphragm and igniter assembly shown in Illustration 2 is shown in detail in Chapter 5, Illustration 28. The diaphragm itself should fit snugly into the rocket body in order to perform its function and should be made of some easily workable and brittle material such as plastic or brass. The function of the diaphragm is to prevent the escape of gas from the burning propellant until enough pressure has built up to ensure thorough burning of the propellant and sufficient thrust to lift the rocket off the launcher. A rocket without a diaphragm may simply burn slowly on the launcher until all the propellant is consumed without having developed sufficient pressure for lift-off.

The diaphragm is designed to burst at high pressure and be ejected from the nozzle in small particles. For this reason they are sometimes called *burst diaphragms*. Naturally, the type and thickness of material used is of considerable importance. Here again, experimentation is necessary in order to determine just the right material and thickness required for a particular rocket. If the diaphragm is too strong, or melts into a tight ball which clogs the nozzle, a rupture of the rocket casing may result. Although copper has been used for this purpose, it is not recommended because of its tendency to melt rather than burst. Brittle plastics and brass are most widely used.

The igniter most generally used is a simple nichrome wire from any heating element and it is connected to a power source by wire leads. *All rockets must be fired remotely* from a safe distance. You will find directions in Chapter 8 for a safe firing set-up and the construction of a reliable firing circuit.

Propellant: This rocket is designed to burn a mixture of zinc dust and powdered sulfur mixed in the proportion of *3* parts zinc to *1* part sulfur by weight. This is a very commonly used amateur propellant and has been used successfully in a variety of proportions. You will find a thorough discussion of it in Chapter 3 with directions for mixing it in a theoretically optimum proportion; but since so many groups have used the 3 to 1 ratio with satisfactory results it is recommended that you conduct your early experiments with this simple mixture. Follow the safety directions in Chapter 3 for mixing, loading and compacting.

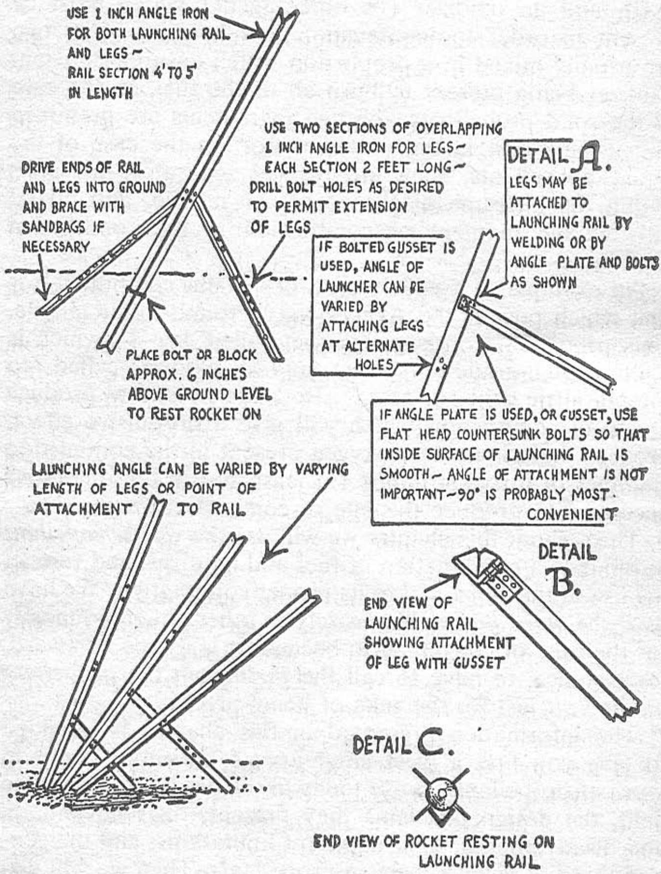
Launching the Rocket: Naturally, you should not attempt to launch even this small rocket without the permission of authorities in your community, and without having read all of the chapters in this book dealing with organization and safety, layout of a launching site and safe firing procedures. It is also a good idea to establish a program for static testing your rockets (as explained in Chapter 7) before any actual launchings are attempted. Usually, if your rocket has been correctly designed and built, it can be re-used for a flight test after a successful static firing. If the rocket fails in a static firing you would not want to have risked it in a free flight test anyway, so nothing has been wasted.

Any one of a number of different launching rack designs is suitable for launching this type of rocket. And as your group progresses you will undoubtedly want to design one to your own particular requirements. Further information on launching mechanisms is given in Chapter 8, but for the present the simple launching rail shown in Illustration *5* will prove satisfactory.

The performance of a given rocket design will vary widely according to the type of propellant mixture used, the density to which the propellant is packed, the type-burst diaphragm used, the accuracy of nozzle construction, and even temperature and humidity conditions at the time of firing. In addition, there is a host of other factors too involved to discuss here which can cause performance variations in apparently identical rockets fired under identical conditions. It is by direct comparison of test results, careful observation, and close examination of recovered rocket hulls that the average amateur group learns most about the mysterious factors it is trying to control. Rockets of the size and type detailed in Illustration *2* are capable of reaching altitudes between 1,000 and 1,500 feet using the zinc and sulfur propellant. A more refined nozzle design may double or triple this altitude. But do not be disappointed if the rocket you build does not approach these figures. The challenge is not met by achieving a record altitude. It is met *by learning how* to achieve that altitude. It is virtually axiomatic of rocket experimentation that much more is learned from failure than success. No one on earth can positively say what caused a rocket to perform perfectly—except that "nothing seemed to go wrong." But the causes of failures can frequently be pin-pointed—and when one has been explained, something has been learned.

ILLUSTRATION NO. 5

Tripod Type Launcher for Basic Rocket Described in Illustration No. 2



Chapter 3

ROCKET PROPELLANTS

What the amateur usually refers to as the *fuel* for his rocket is more properly described as the *propellant*. Professionals make a clear distinction between the two terms which is generally ignored in popular usage. Propellants consist of two things: a fuel (or reducer) which will not burn by itself; and an oxidizer (or other agent) which must be present in order for combustion to take place. The two are usually mixed in a proportion which ensures sufficient oxidizer being present to burn all of the fuel. In the case of the solid propellants, the two ingredients are premixed and usually cast in the rocket motor. In the case of the liquid propellants, they are carried separately in tanks within the airframe of the rocket or missile, and mixed only at the moment of combustion in the combustion chamber.

An example of a widely-used propellant combination is that which powers the Army's NIKE ground-to-air missile. This propellant consists of a fuel called JPL-4 (which is really a high-grade kerosene), and an oxidizer called red fuming nitric acid (or RFNA). Both are needed to produce a rate of combustion which will give a propulsive effect, because there is no free oxygen present in the combustion chamber of a rocket motor (at least, not in the quantities necessary to produce the rate of combustion required).

Throughout this chapter we will use the word *propellant* to indicate a combination of fuel and oxidizer, and restrict the use of the word *fuel* to its proper connotation. We have used the word *fuel* rather loosely in other chapters, mostly for the sake of convenience; because it is a little awkward, for instance, to have to call the *fueling pit* the *propellant loading pit* just for the sake of being precise.

The information presented in this chapter is intended to give you first a brief summary of the more common types of propellants in use today in the professional missile field, the design problems they present, their advantages and disadvantages, their apparent limitations, and the general trend of development in propellants. Then we will discuss the relatively few propellants that are used by amateur groups, and deal in specific detail only with the zinc and sulfur combination which is the most widely-used amateur propellant, and the one with which the most consistent results are obtained.

I TYPES OF PROPELLANTS

Although research is being undertaken toward the development of more advanced types of propellant systems, there are only two principal types of propellants in general use today. They fall into two broad classifications: those called liquid propellants, and those called solid propellants. As far as modern rocketry is concerned, the liquid propellants have been used more widely, experimented with for a greater period of time, and are capable of a higher level of performance. The solid propellants have only recently come into favor (after having been virtually forgotten), there are fewer of them, much less development work has been done on them, and to date they have not achieved the high-energy yields of the liquids. If you have been doing much reading on the subject you have probably become aware of a continuing controversy among missile scientists and development engineers as to whether the liquid propellants or the solid propellants possess the greater development potential, and on which of them research should be concentrated. This controversy is silly and pointless for several reasons; but most important among them are the fact that neither liquid nor solid propellants as we know them are likely to be the ultimate means of propulsion, and the fact that both liquids and solids have their proper place in a wide variety of uses. Neither one of them can be expected to usurp the field.

In the liquid propellant classification there are two major subdivisions: the *bipropellants* and the *monopropellants*. The bipropellants consist of a fuel and an oxidizer which are stored separately within the missile and are fed independently to the combustion chamber where they are mixed only at the instant of combustion (e.g., gasoline and liquid oxygen). This is necessary because certain combinations of fuel and oxidizer are self-igniting when mixed (e.g., aniline and nitric acid) and cannot be brought into contact with each other until the moment that combustion is desired. Other combinations, while they do not ignite spontaneously, nevertheless form highly unstable compounds when brought into contact with each other and are consequently very dangerous to handle and can explode without warning. As an example, the widely-used combination of alcohol and liquid oxygen, if not ignited upon contact, forms gelatinous globules which have *100 times* the explosive force of an equivalent weight of TNT. When this circumstance occurs in the laboratory, through a failure of ignition or for some other reason, all work must cease and the area must be cleared until the liquid oxygen has had a chance to evaporate. Evaporation of the oxygen takes from forty-five minutes to an hour.

Monopropellants are fluids which contain both a fuel and an oxidizing agent, either as a single chemical such as *nitromethane*, or as a mixture such as *ammonia* and *nitrous oxide*. These are stored and fed into the combustion chamber as a single fluid, thus eliminating the need for an additional tank, extra plumbing and extra storage and handling equipment, as well as mixing valves and complicated injectors. Another monopropellant which has been used is hydrogen peroxide (80% conc.) but it has a very low specific impulse compared with other liquid propellants.

Among the solid propellants you will also hear two types mentioned—*double-base* and *single-base*. But all solid propellants do not fall into one of these two categories, so that these are not comprehensive classifications. At present, many of the leading solid propellants in use are based on the nitric esters nitrocellulose and nitroglycerine. Those which contain only nitrocellulose are called *single-base;* those which contain both are called *double-base*. Obviously, there are many solid propellants which contain neither of these ingredients, so the terms do not apply to the entire field of solids.

Liquid Propellants

A table showing the composition of the more common types of liquid propellants is included in Illustration *8* at the end of this chapter. You will note that virtually all of them consist of some type of oxidizing agent and a fuel of the hydro-carbon family which is easily oxidized. The chart also shows the *specific impulse* rating for many combinations and the flame temperature produced during combustion. We will discuss the meaning of the term *specific* *impulse* and how it is calculated later in the chapter. For the present it is only necessary to know that it is a measurement of the ability of a propellant to produce thrust and it is expressed in seconds. The higher the value shown for specific impulse, the more powerful is the propellant. In the case of the liquid propellants the term *specific thrust* rather than *specific impulse* is sometimes used. This is because the measurement means something slightly different in reference to liquids, since it takes into account the rate of flow of the propellant into the combustion chamber. However, the two terms are equivalent in all respects except the method of calculation, and *specific impulse* has come to be more widely used regardless of the type of propellant being considered.

Although some amateur groups have experimented with liquid propellants, and some have actually constructed liquid-propelled rockets of acceptable design, the engineering problems involved and the hazards of working with liquid chemicals are such that serious experimentation in this field is beyond the capacity of all but a tiny percentage of the most advanced amateurs. It is not within the scope of this volume, nor is it considered advisable by the author, to present sufficient data on liquid propellants and liquid motor systems to enable the amateur scientist to undertake actual construction. It has been emphasized throughout this book that no experimentation involving the use of propellants should be attempted by the amateur without thoroughly qualified professional supervision. Particularly is this true of the liquid propellant field, where the dangers are the greatest. Unfortunately, a great many popular magazines and popular texts on rocketry carry disarmingly simple illustrations of liquid rocket motor systems which encourage the amateur in the mistaken belief that he can design and build one. These diagramatic representations of liquid motors and feed systems are intentionally oversimplified in order to enable the lay reader to grasp the fundamental principles involved. They are not intended to be design drawings and a successful motor could never be built with such drawings as the only guide, primarily because all design information relating to fuel flow control, method of ignition, methods of valve control, corrosion problems and a host of other engineering considerations has been eliminated from the diagram. Similar diagrams have been included in this book purely for the purpose of illustrating the basic elements of a liquid motor and the principles of its operation.

The liquid propellants possess certain very definite advantages, as opposed to the solids, but also pose certain design problems and storage and handling problems which render them less desirable from a standpoint of utility. Their chief advantages are:

Higher energy yield. (Considered as a group, liquids are approximately 50% more powerful than available solid propellants.)

They are readily available, and in most cases can be produced in large quantities.

Combustion temperatures are generally lower, as are combustion pressures, thus making possible lighter motor wall construction.

Fuel flow rate (and consequently combustion rate) can be controlled directly, making possible a wider range of performance for a given propellant.

They are relatively unaffected by changes in temperature, humidity and pressure and can be stored for indefinite periods of time if stored properly.

Their chief disadvantages are:

They require elaborate plumbing systems—which more than compensate for the weight saving realized by light motor wall construction—and which are of such intricacy that "temperamental" mechanical failures plague most liquid systems.

Many of the chemicals used are highly corrosive, requiring the use of expensive and hard-to-obtain materials for storage tanks, valves, fittings, seals, tubing and a host of other items.

Many are likewise extremely toxic, representing a hazard to personnel and requiring very costly storage and handling procedures.

Fueling time and the logistical problems involved in their transportation and storage render them almost useless for a great many applications.

Their low density creates a bulk displacement problem which is reflected not only in the size of storage and transportation facilities required, but in the size and weight of the airframe of the missiles in which they are used.

All things considered, it would appear that the single most important advantage of the liquid propellants is their higher energy yield (as evidenced by their specific impulse ratings). But considerable progress has been made toward reducing this advantage by development of increasingly more powerful solid propellants within the last few years. It must also be considered that the advantage of the liquids in terms of specific impulse is not a true measure of comparative performance of the two types of propellants in their ultimate employment within the airframe of a missile. Specific impulse is a measure of performance in terms of *pounds* of propellant consumed. In view of the lower density, and consequently greater bulk of the liquids, one must take into account the greater size and weight of the airframe required to accommodate them. This factor appreciably reduces the advantage of superior thrust since a given number of pounds of a liquid propellant must lift a greater weight of airframe than would an equivalent number of pounds of a solid propellant. This means that even if solid propellants never achieve the high energy output of the liquids, they may very soon reach the point where they *outperform* them in terms of payload delivered.

As examples, it can be cited that the satellite launching vehicles currently in use in this country have already abandoned liquid motors except for the first, or *booster*, stage of the missile. And the Army medium-and long-range artillery missiles CORPORAL and REDSTONE (both liquid propelled) are being replaced by the smaller, lighter solid rockets SERGEANT and PERSHING. In both cases the new solid types, roughly two-thirds the size and weight of their predecessors, will deliver the same size warhead the same distance with a lower impulse propellant, simply because of the weight saving in the carrier airframe. Naturally, they have other advantages also, which are important to the military; but are seldom taken into account by persons interested in arguing over the relative merits of propellants. These are: immensely simplified handling and firing procedures, zero fueling time, reduction in the amount and complexity of supporting apparatus, and a significant reduction in the size (and training) of the crew required to service and fire the weapon.

Combustion Performance of Liquid Propellants: Liquid propellants of the bipropellant type are fed into the combustion chamber of a rocket motor under pressure from tanks in which the fuel and oxidizer are stored separately. Usually some type of inert gas (such as nitrogen) is used as the pressurizer to force the fluids from their storage tanks to the injector which sprays them into the combustion chamber. In other cases, turbo-pumps are used to pump the fluids and these pumps are actuated by some type of gas generating substance such as hydrogen peroxide or a slow-burning cordite charge. You will learn more about these systems in the chapter on Motor Systems. In the case of the monopropellants, of course, the feed system is simpler because only one fluid is involved, but the methods used are the same.

Generally the fluid is sprayed around the walls of the combustion chamber in a helical pattern: this serves to cool the walls of the chamber, and also increases the chances of complete combustion by creating a fine, misty spray of fuel and oxidizer. As previously mentioned, ignition must be almost instantaneous or very dangerous, highly explosive, compounds may form. What happens from this point until the moment that hot exhaust gases are ejected from the nozzle exit is not completely understood and is still the subject of much research and development work; for many compounds may be formed, broken up and re-formed before the eventual exhaust product is produced, and several types of shock waves develop which contribute to what is called *combustion instability* and which inhibit the smooth flow of exhaust gases to the exit. Stated simply, however, the burning propellant produces hot gases which press against the walls of the chamber and seek to escape through the one exit provided by the nozzle. When sufficient temperature and pressure are produced to create a high enough velocity of exhaust gases escaping through the nozzle, *thrust* is developed and the rocket is propelled forward.

How much thrust is developed is dependent upon the inter-relationship of a combination of factors involving the design of the injection system, the design of the combustion chamber, the properties of the particular propellant combination, and the design of the nozzle (the chief function of which is to accelerate the exhaust gases to the optimum velocity obtainable). As far as the propellant itself is concerned, the most important factor affecting thrust is the relationship between the flame temperature of the burning propellant and the molecular weight of the exhaust products. The higher the temperature within the combustion chamber, and the lower the molecular weight of the particles ejected through the nozzle, the higher the velocity of the exhaust stream will be. And the higher the exhaust velocity is, the greater the thrust.

The exhaust products ejected from the nozzle of a rocket motor may consist of a variety of compounds of the basic elements which go to make up the fuel and the oxidizer, and in many cases they cannot be isolated and identified before they are converted to other compounds by changes in temperature and pressure during the exhaust process. For this reason it is impossible, at the present stage of technological progress in rocket science, for researchers to make a complete chemical analysis of the products of combustion that are formed in the combustion chamber and flow through the nozzle of the rocket. However, the bulk of the exhaust products can be identified as they emerge from the nozzle exit. These products represent matter with measurable mass, weight and chemical composition.

The molecular weight of any substance is the sum of the products of the atomic weights of each element in the compound multiplied by the number of atoms of that element in one molecule.

$$\text{Molecular weight} = \text{atomic weight} \times \text{no. of atoms}$$

This weight is expressed in pounds (merely as a standard of measurement, for this standard bears no relationship to the *actual* weight of a molecule).* As an example, the molecular weight of water (H_2O) would be calculated as follows:

$$M\,(H_2O) = (1 \times 2) + (16 \times 1)$$
$$M = 18 \text{ lbs.}$$

This does not mean that a molecule of water weighs

* If the weight is expressed in grams it is referred to as the gram-molecular weight of the substance.

eighteen pounds; but it does mean that eighteen pounds of water consists of sixteen pounds of oxygen and two pounds of hydrogen. And it means, further, that the distribution of weight among the elements in any given quantity of matter is based upon the atomic weights of those elements and the number of atoms of each that are contained in one molecule of the substance. In the case of water, the equation above illustrates that each molecule of water contains two atoms of hydrogen with an atomic weight of 1, and one atom of oxygen with an atomic weight of 16.

Wherever the combination of low molecular weight and high flame temperature exists, the specific impulse is high. Where flame temperature is low, or molecular weight is high, the specific impulse rating is correspondingly low. In other words, some correlation exists between the molecular weight of the propellant, the flame temperature, and the specific impulse obtained. Bear in mind, however, that the molecular weight that is important here is the molecular weight of the *exhaust products*—not that of the original propellant combination.

The specific impulse (or specific thrust) of a propellant is probably the most important and most frequently used index of its efficiency. We will consider it again when we deal with amateur rocket propellants. There are a number of different ways of computing it, depending on the type of data that you start with, and it might be well to present one of the formulas used for liquid propellants while we are discussing them. Assuming that you do not know the total amount of thrust developed by the propellant, or the exhaust velocity, but you do know certain other basic data concerning the propellant and the motor in which it is to be used, you may find the specific impulse by the following formula:

$$I_{SP} = \sqrt{\frac{2}{k-1}\,\frac{RT_c}{M_w g}\left[1-\left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}}\right]}$$

where: g = acceleration of gravity
k = specific heat ratio (the ratio between the amount of heat required to raise the tem-

perature of one pound of a substance 1 degree centigrade when it is under constant pressure, and the amount required when it is held at constant volume: $\frac{C_p}{C_v}$)

R = universal gas constant (1544)
T_c = combustion temperature (absolute)
M_w = mean molecular weight
P_c = combustion chamber pressure
P_e = nozzle exit pressure

This is a fairly complicated formula, but by studying it closely you can see that specific impulse is related to the performance of a propellant *in a particular rocket motor.* In other words, a propellant combination does not have a specific impulse of its own, entirely independent of any motor system. Rather, it may produce quite a range of values for specific impulse depending on the design of the motor system in which it is burnt; for such values as combustion chamber pressure and nozzle exit pressure will vary with each motor design. The values for specific impulse shown in the table (Illustration 8) are the highest obtainable for each propellant combination, and assume that the motor involved is of optimum design permitting a maximum acceleration of the expanding gases through the nozzle.

There are several ways of defining what is meant by the term *specific impulse,* because it represents a relationship involving many factors which are under constant change during the process of combustion and ejection. One way of expressing the meaning of the term is to say that it represents *the rate of change of momentum* of the gases, or the rate of acceleration of the gases through the nozzle. This definition is fairly good; but we are not only concerned with acceleration of the gas particles. We are also concerned with the rate at which the gases *expand* as they leave the nozzle. The two things are interrelated, of course, and it might be said that one follows the other logically. However, the ability of a gas to expand is largely a property of the gas itself, whereas the acceleration of the particles through the throat of a nozzle is partially affected by the design of the nozzle and the combustion chamber.

Nevertheless, there is a simple and direct relationship between specific impulse (or thrust) and the exhaust velocity; and if the exhaust velocity of a particular motor and propellant combination is known, then the specific impulse can be calculated by use of a very simple equation:

$$I_{sp} = \frac{v_e}{g}$$

where: g = the acceleration of gravity
v_e = the exhaust velocity

The presence of the term *g* in this equation should indicate to you that specific impulse is not just a measure of velocity, but of *the rate of change in velocity*—since *g* is a measure of acceleration in terms of feet/second/second. This means, then, that *thrust* is not a matter of the velocity of the gases escaping from the nozzle exit, but is determined by the *rapidity* with which they reach that velocity. Thrust is accounted for by the fact that the gas particles in the combustion chamber initially have a zero velocity, but rapidly reach a very high velocity on their way to the nozzle exit. *Thrust* takes place between the combustion chamber and the nozzle exit; not *at* the nozzle exit. By the time the expanding gases reach the exit they have done their work. No matter what their velocity is at that point they can have no further effect on the movement of the rocket. From this point it is only important that they be allowed to dissipate themselves as rapidly as possible, and reach atmospheric pressure as rapidly as possible, so as to make room for the gases which are following behind them. (Failure of the gases to reach atmospheric pressure shortly after their escape from the nozzle would create a *back-pressure* which would slow down the movement of succeeding gas particles through the nozzle.) If the gas particles within the combustion chamber had a high velocity to begin with (assuming it were possible to create this condition), and they experienced no increase in velocity on their way to the nozzle exit; then no thrust would be produced at all, no matter how great the velocity was. Similarly, if the difference in velocity between combustion chamber and nozzle exit were very small, there would be no appreciable thrust.

You can demonstrate to yourself the principle that is involved in creating thrust by sitting in a swing and conducting two experiments. First, extend one leg in front of you very slowly to the limit of its reach. The swing will not move. Secondly, kick the leg out in front of you as fast as you can. The swing will be propelled backward a short distance. In both cases you have performed the same amount of work by moving the same leg the same distance. But in only one instance did a reaction take place in the swing. Does this mean that Newton's law of reaction does not always apply? No! It simply means that in the first instance the reaction was not of a high enough order to move the swing. In other words, no *thrust* was produced. In the second instance considerable velocity has been added to the movement of the leg, and the rapidity with which that velocity is reached (the rate of acceleration) will determine the size of the reaction produced in the swing. In the first instance the impulse of the leg is very low. In the second instance it is very high. Impulse is the measurement of the speed with which a given velocity is reached.

Corrosive and Toxic Effects of Liquids: Before we leave the subject of the liquid propellants it might be well to review briefly the hazardous properties of some of the chemical substances widely used in propellant combinations in order to emphasize to the reader the dangers which lie in wait for the amateur who is foolhardy enough to attempt to experiment with them. Generally speaking, amateur rocket enthusiasts simply have no conception of the extraordinary precautions which have to be observed by commercial firms, professional laboratories and the military services in the transportation, storage and handling of these substances, nor of the elaborateness of the equipment and the high degree of training of the personnel used to employ them effectively. The destructive properties of these substances affect both materials exposed to them and personnel who have to handle them, in most cases. Their effect on materials is called *corrosive action* and, generally speaking, they tend to decompose certain materials or change their physical properties. Their reaction on the human body is described as a *toxic effect* and is usually manifested in the form of burns, blisters, rashes, or in extreme cases, decomposition.

Liquid Oxygen: There is no such thing as a *safe* oxidizer, but of those presently available, liquid oxygen is the least harmful because it is nontoxic. It does not give off poisonous or otherwise injurious fumes. If spilled on the skin, it evaporates rapidly and does no harm. However, prolonged contact with it will cause severe frostbite in the member exposed, because of the extremely low temperature, and it reduces the temperature of pipes, tubing and containers to the point that they cannot be touched with the bare hand without the skin sticking. Because liquid oxygen boils at minus 183 degrees centigrade, it must be kept in vacuum insulated containers, or containers insulated with glass wool. The loss during transfer from one container to another is extreme, and the overall loss from time of manufacture to actual use runs as high as 50%. The chief danger of liquid oxygen is the fire and explosion hazard it represents. Porous organic materials exposed to it may absorb sufficient oxygen to render them highly inflammable or even explosive. The vapor given off by liquid oxygen tends to form pockets of gaseous oxygen in unventilated areas, and the presence of this gas creates a serious fire hazard. Pure oxygen lowers the ignition point of all materials with which it comes in contact and makes them burn so fiercely that even metals become combustible in its presence. Liquid oxygen also makes most metals extremely brittle. A steel pipe can be broken with a light tap from a hammer after its temperature has been reduced by contact with it.

Hydrogen Peroxide: The fumes of hydrogen peroxide are mildly toxic, and the liquid itself, if spilled on the skin, causes irritation. White patches will form, and unless the liquid is washed off immediately severe itching results and peeling of the skin follows. If the fumes are inhaled they irritate the mucous membranes of the nose and throat, causing coughing and excessive nasal and throat secretion. Damaging effects to the eyes may not be apparent until long after the exposure. Severe skin burns can result from prolonged exposure. Hydrogen peroxide may cause spontaneous combustion of porous organic substances if spilled on them. Pumps, tubes, tanks and other handling apparatus must be tightly sealed to prevent leakage of the fluid, and special outer protective clothing and eye-shields must be worn by personnel exposed to it.

Nitric Acid: White fuming nitric acid and red fuming nitric acid are both highly corrosive and extremely toxic. Gas masks must be worn by personnel handling them. Contact with the liquid causes severe skin burns, but the fumes are even more dangerous, causing irritation of the eyes, nose and throat, with resultant violent coughing, a choking burning sensation in the chest, headache and vomiting. Symptoms may not appear until long after exposure, by which time damage to internal tissues and organs may be so advanced as to be beyond treatment. Concentrated nitric acid (95% or over) will eat through virtually any metal, so that only pure aluminum can be used for containers. If the acid becomes diluted through exposure to a damp atmosphere it will even corrode aluminum, and it is very difficult to prevent its dilution because of its hygroscopic nature.

Ethyl Alcohol: This substance is like water in its appearance but causes severe irritation to the eyes and upper respiratory tract if its vapors are inhaled. Its effect on the skin is relatively mild, but prolonged contact will cause some irritation. It is not as poisonous as some other forms of alcohol if taken internally, but is nevertheless highly intoxicating and injurious to the stomach. It acts as a solvent on most organic materials and is a moderate fire risk.

Furfuryl Alcohol: This is a yellow liquid with a brine-like odor and a bitter taste. It is poisonous if taken internally, or even if absorbed through the skin. It causes irritation to both skin and eyes. Concentrations of its vapor will cause irritation to the throat and lungs.

Methyl Alcohol: This is a highly poisonous substance, colorless like water and with a smell similar to ethyl alcohol. It is harmful whether taken internally, absorbed through the skin or breathed through the lungs. It evaporates quickly and is highly flammable. Even in small amounts it will cause headache, nausea, vomiting and irritation of the mucous membranes. Larger amounts cause dizziness, staggering, severe cramps, blindness, convulsions and coma. Even a small amount taken internally may cause death. Personnel should not be exposed to it in unventilated areas, and respiratory equipment is a must when working with it.

Hydrazine: This is a colorless, alkaline, fuming liquid, which may be odorless or have the odor of ammonia. It is flammable, highly explosive and corrosive. It is poisonous by breathing, by skin contact and if taken internally. Intense skin burns result from contact with the liquid. The vapors will cause immediate and violent irritation of the nose and throat, and itching, burning and swelling of the eyes. Prolonged exposure may cause blindness. A gas mask must be worn when working with it.

Hydrocarbon Fuels: Virtually all of the hydrocarbons (gasoline, kerosene, heptane, butane, octane, pentane, etc.) give off large amounts of vapors which are heavier than air and tend to collect in low places. These vapors are instantly ignitable if exposed to a spark or flame, and are poisonous by inhalation or absorption through the skin. Prolonged exposure to the fluid can even cause deadening of the tissues of the skin.

The foregoing does not include all of the fuels and oxidizers used in liquid propellants; but it does cover the more common ones, and those having the more dangerous toxic properties. A review of the list should convince anyone that these are not substances which can be treated lightly nor handled carelessly. No amateur should experiment with any of them, either singly or in combination, and they should not be stored or handled in populated areas where other people may be exposed to their hazards. Highly trained professional personnel whose jobs require them to handle these substances wear and use elaborate protective equipment and must submit to almost daily physical examinations to determine whether they are suffering from delayed or cumulative effects of exposure.

Solid Propellants

The more commonly known solid propellants, and the substances of which they are composed, are shown in the table in Illustration 8. As we have seen in our discussion of the liquids, the solid propellants have generally lower ratings of specific impulse and burn at higher temperatures. Many of them are extremely dangerous to compound because they are based on, or contain, explosives that have been familiar to us for many years. Even though the propellant in its final form may be perfectly stable and not sensitive to shock, friction or heat, the process of compounding it can be fraught with danger. Most solid propellants must be mixed in a molten state and cast into the rocket chamber, or compacted under pressures of many, many tons in order to achieve the density required. The equipment required to do this, and do it with any degree of safety, is so costly and elaborate as to be beyond the means of any amateur group. The hydraulic presses and dies necessary for this type of work can run into the hundreds of thousands of dollars.

When one considers the vast resources, in terms of money, equipment, laboratories and research technicians, presently devoted to the development of solid propellants in this country and elsewhere in the world, it is utterly foolish to entertain the notion that some brilliant young genius working odd hours in a basement or attic might hit upon a formula that has eluded the best brains in the field. He is much more likely to blow off an arm and set his house on fire. The substances used in rocket propellants are simply not the type of thing one mixes on the kitchen stove. It is therefore wiser, and safer, for the amateur to *avoid all experimentation* with fuels and to not even attempt to mix fuels which require melting or extreme pressures to compound with an oxidizer. The zinc and sulfur combination, which has been used widely by amateurs, and which is considered in detail in this chapter, will send a rocket to altitudes far beyond the ability of the average amateur group to track it. In view of this, it seems pointless to experiment with other compounds which are more difficult and dangerous to handle.

The solid propellants possess certain very definite advantages which make them attractive to users, particularly the military services who must always be concerned with the problems of transportation and supply in distant combat areas, and the equally important problems of servicing, maintenance, and the training of personnel. The simplicity of solid propellants (which are either prepackaged or cast directly into the rocket motor, and do not require the elaborate plumbing and control mechanisms that the liquids do) gives them a practical advantage of prime importance. For military purposes, a great deal of performance can be sacrificed in favor of simplified handling, training and logistical requirements. Among the advantages of the solid propellants are:

Low toxicity—which reduces handling problems and hazard to personnel, and eliminates the need for much protective clothing and equipment.

High density—which means less bulk and a consequent saving in storage space and size and weight savings in the rocket airframe.

Ease of handling—rocket and propellant can be shipped as one unit, fueling equipment, time-consuming fueling process and elaborate countdown procedure are eliminated or reduced to a significant degree.

Lower cost—Pound for pound the solids cost less and are less expensive to handle. There is no loss through evaporation or spillage.

Ease of ignition—complicated and temperamental ignition systems are not required.

There are also certain disadvantages to the solid propellants, as compared to the liquids. They are:

Lower performance—Pound for pound the solids generally give lower thrust.

Decomposition—Whereas most liquids can be stored for indefinite periods of time (as long as they are in the proper type container), many solids tend to decompose or *age* in storage, with resultant changes in chemical structure.

Cracking—Cracks sometimes occur in cast grains, either through aging or mishandling. What is called *thermal cracking* may occur during the burning process. The presence of these cracks increases the burning surface, and consequently the temperatures and pressures created, and can cause a violent explosion.

Dangers and Hazards of the Solid Propellants

As in the case of the liquids, there are very definite dangers and hazards involved in the preparation and use of solid propellants which the amateur should be aware of, and which should convince any thoughtful person that experimentation with them is foolhardy. The amateur who ignores these hazards, or treats them lightly, is inviting disaster. A few of the more common hazardous materials, and the dangers they represent are listed here for your information:

Black Powder: This is the oldest known explosive mixture and also the most unstable. It is so unpredictable and tricky to handle that it is no longer used professionally for any serious purpose. A mixture of potassium nitrate, charcoal and sulfur, it explodes readily when subjected to heat, friction, shock or an igniting spark. Small amounts of it may be used successfully as an igniter for a more stable propellant or as an explosive charge to separate stages or eject a parachute device. No more than a few ounces of it should ever be mixed.

Match heads: These have been widely used by a great many thoughtless amateurs and juvenile "firebugs" who are interested only in seeing something explode. The friction match is obviously a highly unstable thing invented to make it easy for the housewife to start a fire. One of them does not represent much danger. But *three* match heads have been known to propel a quarter-inch bolt with enough force to send it crashing through a window and chip a concrete wall. A pound of match heads has sufficient power to blow off an arm or a leg. A container full of match heads can explode if merely shaken.

Nitroglycerine and nitrocellulose: These are used as the principal base of a great many solid propellants, but should not be handled by amateurs under any circumstances. They have a toxic effect on the human body, causing headache, nausea, vomiting and in extreme cases of exposure even convulsions and decomposition of tissue. Both are extremely sensitive to shock, friction and heat (particularly nitroglycerine), and are among the most powerful explosives known.

Chlorates and perchlorates: These should not be used by amateurs under any circumstances. The most readily available chlorates, sodium chlorate and potassium chlorate, are so friction sensitive that they will detonate when ground or rubbed in a mortar. They are not used even in professional propellants for this reason. The *perchlorates* are more stable, but are still dangerous.

Potassium permanganate: This compound has appealed to many amateurs because of its availability and its ready burning. Many have had the bright idea of using it in CO_2 cartridges and Jetex units with disastrous results. It is so friction sensitive that the slightest grinding will set it off. In one case, a young rocket enthusiast had his left hand blown off when he tried to use a nail to enlarge the nozzle aperture of a cartridge he had loaded with potassium permanganate.

Powdered metal: Virtually any powdered metal is dangerous if it is allowed to form a dust in the air. Iron, magnesium, nickel and aluminum will produce an explosive mixture with air when they are being poured from one container to another or when shaken. Some metals, such as magnesium, will ignite spontaneously when in the form of dust in the air, even though no igniting spark is present.

Generally speaking, this is true of any substance which is in powder form, whether it is classed as a combustible or not. Flour mills and cement plants have been known to explode without warning, sometimes completely demolishing a plant. On a recent television stunt program the production staff had the brilliant idea of tossing a bag of flour on a man who was impersonating a firecracker just as his wife was asked to light the fuse protruding from his head. The idea was to increase the "comic" effect; but instead, a violent flash explosion took place which gave both the man and his wife serious burns.

In addition to the dust hazard presented by finely divided metals, many of them become very shock sensitive when mixed with an oxidizer.

Spontaneous combustibles: Certain substances will ignite spontaneously when exposed to air. Among these are yellow phosphorus, metallic sodium and metallic potassium. Naturally, these materials should never be handled by amateurs. They scatter particles as they burn, and these particles will burn deep holes into flesh.

The foregoing is not intended to be a complete listing of all of the hazards one may encounter in working with solid rocket propellants. It is simply a guide to some of the more frequent and evident dangers. To ensure maximum safety in preparing and handling *any* propellant combination, it is recommended that the reader pay careful attention to the safety rules listed at the end of this chapter.

Propellant Grain Shapes and Methods of Forming

Most solid propellants are either cast or molded into a solid bar which is the exact shape and size of the combustion chamber of the motor in which they are to be used. This solid bar, consisting of a mixture of fuel and oxidizer, is called a propellant *charge* or *grain,* with the latter term being more widely used. In some cases the propellant mixture, in a molten or putty-like state, is poured directly into the combustion chamber and allowed to harden under conditions which will allow it to form a firm bond with the rocket chamber walls. This is called a *bonded grain.* In other cases, the mixture may be cast, or formed under pressure, to the exact dimensions of the combustion chamber in a mold designed for that purpose, and then is inserted into the motor when it is ready for use. In still other instances, propellant combinations may be cast or formed into cylinders or "bar stock," the approximate size of the motor chamber. The bar is then "machined" to fit any one of a variety of motor chambers by sawing, grinding or extruding it to the desired dimensions. This method may be used when it is desired to produce a propellant grain for use in a variety of rocket motors of roughly similar dimensions; but, naturally, it is only practical in the case of propellants which are not sensitive to shock, friction or pressure.

Propellant grains produced by these methods fall into three general classifications according to their burning characteristics. These are: *neutral-burning, regressive-burning,* and *progressive-burning.* Cross-sectional and longitudinal views of grain designs within each of these classifications are shown in Illustration 6.

Neutral-burning types are those in which the area of the burning surface remains more-or-less constant throughout the burning process. The amount of propellant consumed during any given period of time likewise remains constant, as does the burning pressure.

Regressive-burning charges are those in which the area of the burning surface *decreases* during the burning process, with a consequent drop in the amount of propellant burned per time period and a constantly decreasing pressure.

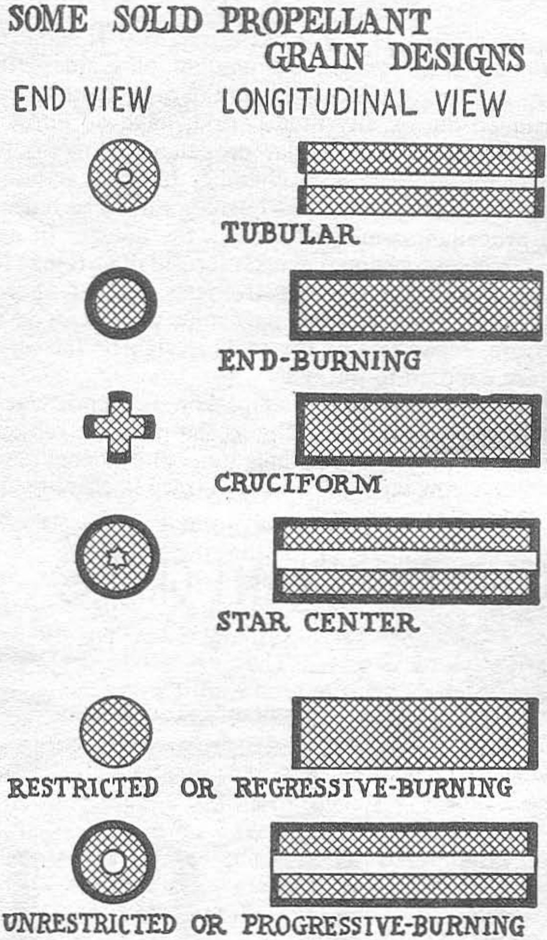
Progressive-burning charges are those in which the burning surface *increases* during the burning process, with a resultant increase in the amount of propellant burned per time period, and a constantly rising pressure.

In order to give you a better idea of what some of these grains look like, three-dimensional drawings of some popular types are shown in Illustration *7* together with a cutaway view of a concentric ring grain inserted in a rocket motor.

Restricted Burning and the Use of Inhibitors: The burning characteristics of any propellant grain are achieved through a combination of grain design and the application of *inhibitors* (noncombustible or slow-burning substances) which are applied to portions of the grain surface in order to prevent burning on that part of the surface. Grains which have been so treated are known as *restricted-burning* grains. The heavy black borders shown on various portions of the grains in Illustration *6* indicate the presence of an inhibiting material. The material used for this purpose is usually similar in nature to the propellant to which it is applied. For cordite, for instance, cellulose acetate is often used for the inhibitor coating.

In Illustration *6* you will note that the end-burning, or cigarette-burning, type of grain has a layer of inhibitor on every surface except the one end on which it is desired to have burning take place. In the case of grains which are cast into the combustion chamber so that a tight bond is formed between the grain and the chamber wall, the bond itself acts as an inhibitor, and no coating of the grain is necessary. By studying the grain designs shown in the illustration carefully you will be able to determine the type of burning that the designer is trying to achieve, i.e., the surfaces which are to be allowed to burn, and the direction in

Illustration No. 6



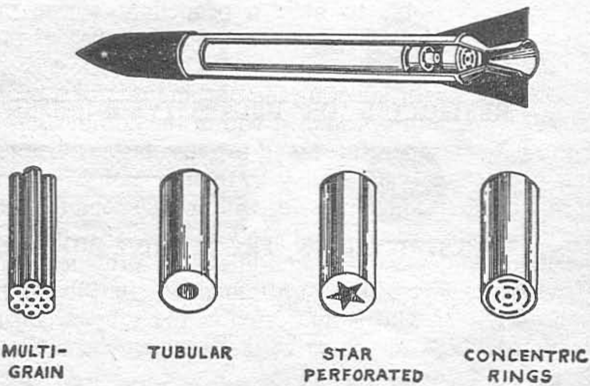
which burning is to progress. You will also note that some grains burn from the inside outward, some burn from the outer surface toward the center, and others burn in both directions simultaneously. End-burning, of course, progresses longitudinally throughout the length of the charge.

Burning Rate: The type of burning that is achieved by a particular grain design, the amount of grain surface exposed to burning, and the amount of propellant (by weight) consumed during any time period, have no effect on the *burning rate* of a particular propellant in themselves, although the differences in chamber pressure induced by a grain design may well affect burning rate. The burning rate of a propellant combination (i.e., the number of inches of it that will be consumed in each second of burning) is determined empirically by exhaustive tests, and is a figure which remains constant for that particular propellant at a given pressure, regardless of the grain design or the amount of surface exposed to burning.

Burning proceeds in a direction perpendicular to the burning surface and, as long as the pressure remains constant, it progresses at the same number of inches per second no matter how large an area of surface is burning. To illus-

ILLUSTRATION No. 7

SOLID PROPELLANT GRAINS



trate the difference between the burning rate of a propellant and the amount of propellant consumed per second, let us assume that you have a rectangular block of propellant that is one inch square and twelve inches long. The *burning rate* of the propellant is one *linear* inch per second. If you ignite just one end of the block and allow it to burn, the burning surface exposed amounts to one square inch. Since the block is twelve inches long, and the burning rate is one inch per second, it will obviously take twelve seconds for the entire block to burn. If, on the other hand, you can ignite one entire side of the block you will have twelve square inches of surface exposed to burning, and since burning proceeds in a direction perpendicular to the burning surface, and the block is only one inch wide, the entire block of propellant will be consumed in just one second. In the first instance the *amount* of propellant consumed per second was one cubic inch. In the second case the amount consumed per second was twelve cubic inches. In both cases, however, the burning rate was the same: one *linear* inch per second.

As a practical matter, however, the larger the burning surface is the faster the burning rate will be; because the increased amount of propellant consumed each second generates higher pressures in the rocket chamber; and as pressure increases, the burning rate generally increases. If the propellant being used is particularly sensitive to pressure changes and its burning rate increases rapidly with increasing pressures, then the burning may get entirely out of control and produce an explosion. For this reason it is generally desirable to have a propellant whose burning rate remains fairly constant over a wide range of pressure changes.

Another factor affecting the burning rate of a propellant is the temperature produced within the combustion chamber. Higher temperatures tend to cause faster burning rates, but propellants vary widely in their response to temperature increases. Since it is not within the scope of this book to present a thoroughgoing analysis of propellants and their behavior under varying conditions of pressure and temperature changes, it is recommended that the more advanced reader who is interested in the subject consult the many excellent reference works listed in the bibliography in the Appendix.

Burning Time: It can be seen from the foregoing that it is a very simple matter to calculate the burning time for any propellant charge once the burning *rate* is known, and the chamber pressure is known (the first being dependent on the second). The burning time for any propellant grain is equal to the *web thickness* of the grain divided by the burning rate.

$$\text{Burning time} = \frac{\text{web thickness}}{\text{burning rate}}$$

The web thickness is the linear distance measured in a perpendicular direction from the burning surface to the surface opposite. If you have an end-burning grain, then the web thickness is the length of the entire grain. If, on the other hand, you have a tubular grain which is three inches in diameter and has a one-inch diameter hole bored in the center, then the web thickness is one inch. If this grain had a burning rate of one inch per second, then the entire grain would have a burning time of one second, regardless of how long it was.

It should be noted here that this discussion of burning rates and times applies only to solid propellants which are compacted into a solid grain, whose density is known. It is impossible to predict, with any degree of accuracy, the burning rates or burning times of solid propellants in loose powder form, for several reasons. For one thing, no two compositions will ever be precisely the same. Density, crystal size and the amount of air trapped in pockets will vary with every mixture. For another thing, there is no means of controlling the area of the burning surface with inhibitors, or by bonding, with the result that the flame front tends to shoot out at random throughout the mixture and cause erratic burning. For this reason, the burning rates and times that are given for the zinc and sulfur combination discussed later are only approximate and represent average performance figures taken from a great many tests.

The burning rates shown for the solid propellants listed in the table in Illustration *8* are valid only for a chamber pressure of 1000 psi. Higher or lower pressures will vary these rates.

Solid Propellants for Amateur Use: There have been many propellant combinations used by amateur groups in the unending search for the "ideal propellant." Some have been very dangerous combinations that have caused accidents because the people using them were unfamiliar with their properties. Had they known a little more about the ingredients they were using, they probably would not have attempted the foolhardy experiments which ended in disaster. But some people learn only by trying and are never content to listen to the advice and counsel of others, nor do they bother to research available information on a subject before attempting to find out for themselves by experimentation. This type of person will find no place in the scientific community of the future because his working habits and thought processes are not consonant with sound scientific procedure; indeed, it is highly probable that he will blow himself up at an early age, long before he can cause a major disaster to others.

All accidents are regrettable and the possibility of serious injury or death is not pleasant to contemplate. But any accident, whether it injures anyone or not, causes public alarm over the hazards of amateur rocket activity, and increases the possibility of restrictive measures against further rocket experimentation. Amateur rocket societies, if they expect the public to take them seriously, must do everything they can to promote the confidence of public officials and civic organizations who are in a position to render them valuable assistance. A record of serious scientific achievement unattended by foolhardy risks is the best recommendation a group can have when it seeks the support it needs from the community.

Consequently, no amateur group should attempt to mix or use propellants which are obviously beyond its capacity to handle. This includes all of the propellants listed in the table in Illustration *8*, except the zinc-sulfur. As previously mentioned, the equipment necessary to handle and mix these materials properly costs hundreds of thousands of dollars. The best professional know-how in the country is devoted to the task, and accidents still occur. Amateurs attempting such a job are flirting with certain disaster.

There is a great deal of development work yet to be done before any amateur rocket society in the country can boast that it has exhausted the potential of the two propellants to which the rest of this chapter is devoted. This is true both in the case of rocket motor design and in the development of the propellants themselves. In the case of the zinc and sulfur combination it is safe to say that the average amateur rocket does not utilize more than ten per cent of the power this propellant can develop. Of the hundreds of amateur rockets and rocket designs the author has seen, only two could be said to make efficient use of it.

Why, then, should amateur groups be obsessed with the notion of experimenting with ever more powerful and dangerous propellants when they cannot, as yet, effectively utilize the most readily available one? The answer, of course, is that those who are constantly seeking a more powerful propellant are merely trying to achieve something the easy way. They conceive of the science of rocketry as a quest for altitude—and altitude alone. And they have very little appreciation for the design problems involved in creating an efficient propulsion system.

If there are members of your groups who are inclined to put the major emphasis on experimentation with propellants, and less on the challenge of design, let them consider this:

> The zinc and sulfur combination is capable of sending a properly designed amateur rocket to altitudes in excess of 100,000 feet.
>
> 98% of the amateur groups using this propellant have failed to get a rocket beyond 3,000 feet.

The conclusion that can be drawn from this is obvious. The average amateur group hasn't even begun to learn anything about motor design, nor bothered to develop a zinc and sulfur grain that will give optimum performance. If your own group has advanced to the point that it is capable of producing rockets which will reach 100,000 feet consistently, then perhaps it is ready to move on to development work utilizing a more powerful propellant. But not until then. And since there are very few places in the country where it is possible to launch a rocket to such heights, it would seem safe to assume that amateur rocket operations will be confined to altitudes below this figure, and that the zinc and sulfur propellant (or something similar to it) will be the standard propellant for most amateur purposes for a long time to come.

The "Caramel Candy" Propellant: Of the two most widely-used amateur propellants, the mixture of potassium nitrate (KNO_3), commonly known as saltpeter, and sugar, is probably the most readily available. Called "Caramel Candy" by many young rocketeers, it delivers a fair impulse, ignites readily, and will send a one-foot rocket to a height of about a thousand feet. However, it is somewhat messy to use and must be melted to mix properly. Any melting operation can be dangerous, and this one is no exception, even though there is a fairly wide margin between the melting point (350°F.) of the mixture and the flash temperature (600°F.).

Mixing must be done under carefully controlled conditions and should be supervised by an expert chemist. The molten mixture must be poured directly into the rocket motor chamber while at melting temperature. This means that the rocket motor and any ladles or funnels used in the pouring process must be preheated to the melting temperature (350°F.) in order to prevent premature cooling during pouring. If the pouring process is interrupted, partial cooling of the mixture will cause cracks and air bubbles to develop which will increase the burning surface of the grain. The resultant uncontrolled and erratic burning will produce pressures and temperatures beyond design maximums, and may cause an explosion, or at the least, a rupture of the motor chamber wall.

Besides the dangers of a flash explosion from overheating of the mixture and the likelihood of cracks and air bubbles developing in the grain, there are other hazards that must be carefully guarded against when preparing this mixture. For one thing, the mixture is sticky and syrupy, like molasses, and adheres to any surface it touches. Consequently, everything that has come in contact with it must be thoroughly cleansed with hot, soapy water after pouring of the grain has been completed. This includes all utensils used, and protective equipment such as asbestos gloves, aprons, face shields, etc. Particular attention must be paid to the seams of gloves and other wearing apparel, and to cracks and crevices in table tops and floors where small amounts of the propellant are apt to gather and crystallize. Secondly, extreme care must be exercised to avoid the accumulation of small particles in threaded sections of the rocket motor. If the nozzle of the rocket screws on to the rocket body, or is bolted to it, then tiny grains of propellant embedded in the threads can detonate when subjected to friction or pressure. *Never pour any propellant, molten or powdered, through a threaded section* without first covering the threads with masking tape, and then wiping them clean and inspecting them carefully after the pouring is completed. A funnel should always be used when pouring through a threaded section.

The potassium nitrate and sugar combination can be ignited with an electrical squib, Jetex fuse, or the standard black powder fuse that is used for fireworks. In all cases, of course, the fuse itself must be ignited by an electrical firing circuit similar to those described in Chapter 8. You can make a reliable electrical squib by simply dipping a piece of nichrome wire (or a piece of any heating element) into the propellant mixture several times, allowing each coating to dry partially between drippings. The squib is sometimes coated with a putty-like mixture made of black powder and a little water. Remember that black powder is only recommended for ignition charges, and only a few ounces of it should be mixed at one time.

The proportion most frequently used in mixing the "Caramel Candy" propellant is 60% potassium nitrate and 40% sugar by weight. Other proportions may give effective results, and if your group has a qualified chemist adviser it might be worth your while to undertake a development project on this particular propellant with a view to determining an optimum proportion for the mixture under varying chamber conditions. It also would be worthwhile to investigate the feasibility of cold-casting the mixture, using some type of binder or solvent, and producing prepackaged grains which do not have to be cast in the rocket motor. This work should not be attempted, however, unless you do have a competent adviser and laboratory facilities which have been approved for such a purpose by local fire and police officials. Not too much experimental work has been done with this propellant and it is not known how shock-sensitive or friction-sensitive it is under varying temperature, pressure and humidity conditions. The potassium nitrate, at normal room temperature, can be ground lightly to break up large crystals, for the ingredients must be well mixed and sifted before they are melted. It is known, however, that the mixture absorbs moisture readily from the air, and therefore grains made from it cannot be stored for any length of time.

The mixture described here has not been fired successfully as an end-burning grain. A larger burning surface is required to develop sufficient chamber pressure, and the grain is usually cast in the rocket motor with a pintle (or slender rod), approximately one third the inside diameter of the motor chamber, being used to form a hole through the center of the grain. This gives a *tubular* grain such as the one shown in Illustrations *6* and *7*.

Zinc and Sulfur—or Micrograin: By far the most widely used amateur rocket propellant is the combination of zinc dust and powdered sulfur which many amateurs refer to as "micrograin." The latter term, which is not particularly descriptive and could be applied to any propellant in fine powder form, was popularized by amateur rocket societies on the West Coast who were among the first to conduct extensive experiments with the combination. Very little authentic, or well-substantiated data is available on it; and it is understandable that the average amateur rocket enthusiast is pretty well confused by the widely-varying and sometimes conflicting claims made for it. As examples: it is credited with specific impulse ratings as low as 20 seconds and as high as 150 seconds; and burning rates are given for it which range all the way from 14 inches per second to 290 inches per second. Obviously something is wrong in this situation, and obviously there is a need for definition.

The fact of the matter is that probably all of the widely disparate performance claims made for this propellant are reasonably true. That is, they are true if you adopt the same criteria and conditions as the person making the claim, *and* if you can duplicate precisely the combination he used and the motor in which he fired it. The performance of a propellant is affected by many variable factors —in the composition of the propellant itself, in the design of the propulsion system, and in the atmospheric conditions surrounding the test. To attempt to compare performance figures from any two tests when none of these variables can be controlled is sheer nonsense. No basis for comparison exists.

Let us consider the one simple factor of the proportion of the ingredients used in a propellant combination. Zinc-sulfur has been loaded into a rocket and fired successfully in the simple proportion of one part zinc to one part sulfur, by weight. It has also been fired successfully using a proportion of *eight* parts zinc to one part sulfur. It has even been fired using a proportion of one part zinc to *three* parts sulfur. In all these cases the rocket performed satisfactorily, so far as the observer was concerned. Whether the performance obtained was an *optimum* performance is another question. With this wide a variation in just the *proportion* of the ingredients used you can appreciate how futile it is to attempt to establish reliable performance parameters for the propellant. You might just as well try to estimate the weight of a bag of feathers without knowing whether the bag contained two feathers or two million, whether they were tightly packed or loose, whether they were wet or dry, and with no information as to the size and weight of one feather.

Another reason why no firm performance parameters have been established for zinc and sulfur is that it has been most frequently used in loose powder form. It has already been stated that burning rates for powdered materials cannot be established because there is no controlled burning surface. More often than not, powders tend to burn all at once rather than in an orderly progression. A fourteen-inch rocket packed with zinc and sulfur has been known to burn for seven seconds on a test stand. On the other hand, a fourteen-foot rocket with a combustion chamber measuring twelve feet by three inches, fired in California, had a total burning time of one-half second. If the density of the mixture is known, however, an approximate burning rate can be calculated.

Among the many other factors which vary greatly in powdered mixtures and make it impossible to compare performance data reported from various sources are:

The purity of the ingredients
The particle size of the ingredients
The density to which the ingredients are compacted
The conditions of humidity to which the ingredients have been exposed, both in storage and in use
The thoroughness with which the ingredients are mixed
The amount of air present in the chamber
The conductivity of the chamber walls

The efficiency of the propulsion system in which the mixture is fired

In addition to its use in loose powder form, amateur groups have fired zinc and sulfur packaged in cartridges, pressed into a solid grain under high pressure, and cold cast into a solid grain by use of a solvent such as alcohol. There is a limited amount of information available on its performance in these three forms and this will be discussed briefly at the end of the chapter.

The only reliable data on zinc and sulfur in loose powder form is that developed by the Army Artillery and Missile School at Ft. Sill, Oklahoma, as the result of extensive tests conducted there for the purpose of establishing some standards for the propellant which could be recommended to amateurs. The optimum mixture arrived at in these tests consists of 2.04 parts of zinc combined with 1 part sulfur by weight, compacted to a density of 161 pounds per cubic foot. (On the density scale this would mean a density or specific gravity of 2.58 compared with water which has a density of 62.4 pounds per cubic foot.) Based on this ratio of ingredients and this density the following performance factors were found applicable when burned in a combustion chamber at a pressure of 1,000 p.s.i.:

Burning rate—90 in/sec.
* Effective exhaust velocity—1,490 ft/sec.
Flame temperature—3,060°R. (2,600°F.)
Specific heat ratio—1.25
Molecular weight—97.45 lbs per mole
Specific Impulse—46 sec.

* (Ideal theoretical exhaust velocity actually works out to 2,980 feet per second. However, a total correction factor of 50% was applied because one of the exhaust products, zinc sulfide, has a heat of sublimation of 2,600°R. (Rankine); which means that this portion of the gas would convert to a solid at any temperature above 2,600° and would no longer expand to produce thrust. The degree to which this occurs, and whether it actually occurs, are matters of some dispute, however. Consequently the figure of 1,490 ft/sec. can be regarded as a very conservative estimate of exhaust velocity. The calculations necessary to determine effective exhaust velocity, specific heat

ratio, and specific impulse will be discussed in Chapter *4)*

The ensuing discussion of the zinc and sulfur propellant combination, and the criteria presented in Chapter 5 are based on the performance factors listed above for the 2.04 to 1 mixture.

Handling: Zinc and sulfur in combination will burn readily in open air (not a desirable characteristic for a professional propellant), and can be ignited easily with an electrical squib, a small charge of black powder, or a bare nichrome wire from a heating element. It is relatively shockproof and when solidified can be lightly machined. Its chief hazard is that of all powders and finely divided metals. It creates a suspension of dust in the air when it is being poured from one container to another, and a sufficient concentration of this dust in an unventilated area may result in an explosion. Neither zinc nor sulfur is particularly toxic, but the dust can cause irritation of the eyes and nasal passages. It is best to avoid prolonged contact with the dust and to wear a respirator and face mask when handling the propellant in powder form.

Mixing: Since zinc and sulfur will ignite easily, even from a random spark, all utensils used in mixing the ingredients should be made of nonmetallic materials. The mixing can be done either in a wooden rotating drum, a glass jar or a cloth bag. Continuous rotation and shaking of the container is normally sufficient to produce a smooth blending that is uniform in color and texture. It is not usually necessary to sift or grind the ingredients, but if small lumps appear in the sulfur they should be broken up with a wooden spoon or stick, or eliminated from the mixture prior to weighing of the ingredients. Mixing should be very thorough. Uneven mixing or lumpiness will cause erratic burning, or "chunking," in the combustion process, and is one of the many reasons why there is such a wide variation in the performance of this propellant.

Prior to the mixing, the quantities of each ingredient must be carefully weighed out on an accurate scale such as is used in a school chemical laboratory. In order to determine the amount of propellant that you need you must know the volume of the chamber you are filling and the density to which you wish to pack it; then you can calculate the weight of propellant necessary to achieve that density. But first let us consider how to determine the relative amounts of each ingredient of the mixture.

The recommended proportion of 2.04 parts zinc to 1 part sulfur is calculated on the basis of the atomic weights of the two elements.

The atomic weight of zine (Zn) is 65.38

The atomic weight of sulfur (S) is 32.07

In the reaction which takes place in the combustion chamber one atom of zinc combines with one atom of sulfur to produce the compound zinc sulfide:

$$Zn + S \rightarrow ZnS + \text{heat}$$

Knowing this we can determine the formula weight of a mixture which will produce a complete reaction, i.e., a reaction in which all of the fuel (Zn) consumes all of the oxidant (S). The formula weight is determined by multiplying the atomic weight of each ingredient in the formula by the number of atoms of that ingredient which are required for a complete reaction, and then adding the totals together:

$$\text{Formula weight: } \overset{\textit{Zinc}}{\overline{(1 \times 65.38)}} + \overset{\textit{Sulfur}}{\overline{(1 \times 32.07)}} = 97.45$$

To find the amount (or percentage) of each chemical, divide the atomic weight of that chemical by the total formula weight.

$$\text{Zinc} = \frac{65.38}{97.45} = 67\%$$

$$\text{Sulfur} = \frac{32.07}{97.45} = 33\%$$

In other words, to mix one pound of propellant you will need 0.67 pounds of zinc and 0.33 pounds of sulfur. To mix ten pounds of propellant you need 6.7 pounds of zinc and 3.3 pounds of sulfur. Whatever the total weight of propellant you need, multiply that weight by 0.67 to get the weight of the zinc you should use, and by 0.33 to get the weight of the sulfur.

To determine the total propellant weight needed to fill a rocket chamber you must first calculate the volume of the chamber and then multiply that volume by the density of the propellant you wish to use. Normally rocket motor chambers are cylindrical in shape and flat at both ends. The volume is calculated by the simple formula you probably have already learned in high school geometry.

$$V = AL$$

where: V = volume
A = area (of one end)
L = length of the cylinder

To find the cross-sectional area of one end of the cylinder use the formula for finding the area of a circle:

$$A = \pi_r{}^2$$

As an example, find the volume of a cylindrical rocket chamber with a diameter of 3 inches and a length of 40 inches (not necessarily desirable design dimensions):

$A = \pi_r{}^2$ (and r = ½ the diameter or 1½")
$A = 3.1416 \times 2.25$
$A = 7.07$ inches
$V = AL$
$V = 7.07 \times 40$
$V = 282.2$ cu. in.

If the rocket chamber is not perfectly cylindrical in shape (such as a chamber with tapered ends) you can determine its volume without any calculation by simply filling the chamber with water and then pouring it out into a graduated beaker. If the beaker is graduated in cubic centimeters you can convert the cubic centimeters to cubic inches by multiplying by the factor 0.061. (I.e., 10 cc. × .061 = .61 cu. in.)

In order to determine the propellant weight needed to fill the chamber we have now only to multiply the volume by the density of the propellant being used, being careful to use consistent units (e.g., if the volume of the chamber is expressed in cubic inches we must multiply by the density expressed in pounds per cubic inch). Using the previous example of a chamber 3 inches in diameter by 40 inches in length (282.2 cu. in.) let us calculate the total propellant weight and the weight of each ingredient necessary to fill it to the desired density of 161 pounds per cubic foot (0.0932 lbs. per cu. in.).

$W = V$ (282.2 cu. in.) $\times$ D (0.0932 lbs./cu. in.)

$W = 282.2 \times 0.0932$ lbs.

$W = 26.3$ lbs.

$Zn = 26.3$ lbs. $\times\ 0.67 = 17.62$ lbs. zinc

$S = 26.3$ lbs. $\times\ 0.33 = 8.68$ lbs. sulfur

This means that in order to fill a chamber 40 inches long and 3 inches in diameter to a density of .0932 pounds per cubic inch, using a combination of 67% zinc and 33% sulfur, you need 17.62 pounds of zinc and 8.68 pounds of sulfur. When mixed together they give a total propellant weight of 26.3 pounds. Using this amount of propellant, simply continue filling the chamber, tamping as necessary, until all of the propellant has been loaded. You then have the desired propellant density.

Loading and Compaction: The loading of a rocket motor chamber with a loose powder propellant is best accomplished by simply pouring the mixture through a funnel using a ladle or cup to pour with. This must be done in the open air, or in a well-ventilated enclosure (see illustration of fueling pit in Chapter 8). Whether loading is done through the nozzle end or the front end of the chamber is immaterial, and will depend on the type of rocket you have constructed. The propellant should be poured into the chamber in small amounts, with each increment being carefully compacted as it is added. Powdered fuel may be compacted by several methods. Among these are tamping with a rod or pestle, shaking or vibrating the rocket, and applying mechanical pressure. The most effective means has been found to be vibration applied to the outside of the rocket body. This can be done by simply tapping vigorously with a wooden mallet, or by using an electric vibrator. If an electric vibrator is used (such as a small sander, or body massage vibrator) it should be covered with a plastic bag to prevent sparking. Simply hold the vibrator against the body of the rocket for brief periods of time, and add the propellant gradually. Follow the directions given in Chapter 8 in respect to positioning of the rocket, use of protective clothing and barriers, etc., for complete safety. It is imperative that the accumulation of dust in the air be avoided.

Ignition: The igniter should not be inserted in the rocket until it is placed on the launching rack. However, if your rocket is of the nose-loading type, and the diaphragm and igniter are combined into one unit, then this unit must obviously be inserted before loading commences. It is recommended that in such cases the igniter be of the plain nichrome-wire type in order to reduce the possibility of a premature ignition of the rocket. The types of igniters suitable for the zinc and sulfur combination have already been indicated and are illustrated in Chapter 5.

Other Compositions of Zinc and Sulfur: Considerable work has been done by some advanced amateur groups and individual experimenters in the direction of increasing the power yield of zinc and sulfur. Although some of this experimentation has been conducted for several years, progress has been slow because amateurs simply do not have the time, the facilities nor the funds to conduct the enormous number of tests under controlled conditions that would be necessary to establish valid comparative data on the performance of various mixtures and types of compositions. Nevertheless, enough progress has been made to indicate that there is a potential in this propellant which may be three or four times as great as its normal rating.

One method of packing zinc and sulfur developed by California groups is known as "cartridge" or "capsule" loading. The method consists of packaging the powder in small cardboard capsules with tissue paper ends. The capsules are approximately one inch deep and the same diameter as the interior of the rocket chamber. The alleged purpose of capsule loading is to establish some measure of control over burning rate and to prevent packing of the propellant in the front end of the chamber as the result of the pressure build-up during combustion. Whether it accomplishes either of these objectives is open to question. The same groups that complain of the propellant packing under pressure, also complain that it tends to fall out of the nozzle end as the result of acceleration. It can hardly do both of these things at the same time, obviously. Considering the pressures generated in even a small rocket chamber burning zinc and sulfur (300 p.s.i. to 1000 p.s.i.) it is doubtful that a flimsy material like cardboard could prevent packing very effectively.

The idea appears to have some merit, however, and apparently has worked with reasonable success. But it is a troublesome and time-consuming method of preparation, and it stands to reason that it can only act to reduce the power of the propellant if for no other reason than the fact that it uses up a lot of space in the chamber which could otherwise be filled with propellant. As an example, a three-foot rocket designed by one California group and loaded in this manner, has a design altitude between 500 and 1000 ft. claimed for it. Yet rockets of similar dimensions packed with loose powder have risen above 3500 feet. No specific performance data is available on zinc and sulfur packaged in this form, but groups using it generally credit it with a specific impulse of about 20 seconds.

Another California group has done considerable work in forming solid grains by simply pressing the dry powder mixture of zinc and sulfur in a hydraulic press, using a piston the size of the inside diameter of the rocket chamber. The group claims to have subjected the mixture to pressures as high as thirteen tons, but this has been done using professional equipment provided by an aircraft company with adequate safety measures being taken. The mixture used is 85% zinc and 15% sulfur compressed to a density of 0.141 pounds per cubic inch as compared with the 0.06 to 0.093 pounds per cubic inch achieved by hand tamping or vibration. When compressing the propellant under such high pressures the group uses a chrome-molybdenum steel casing with a .125 inch wall thickness and an inside diameter just slightly larger than the rocket chamber for which the grain is intended. The grain produced can be shaved or machined lightly, but has not been subjected to any definitive tests for shock sensitivity. It will not burn at atmospheric pressure, which is a desirable property of any solid propellant, since it not only reduces hazards but also means that the propellant cannot be made to release its energy at low chamber pressures which are insufficient to produce effective thrust. It does burn well at high pressure, according to the group that has developed it, but again, no controlled experiments have as yet been conducted to establish reliable parameters for its performance.

By far the most interesting and potentially productive work on the zinc and sulfur combination has been done by groups who have developed methods of cold-casting the mixture by using some solvent such as alcohol. A small amount of alcohol added to zinc and sulfur produces a putty-like mixture which can be stuffed into a rocket chamber or casting mold. It generally takes five or six days to cure properly, but the resultant grain is a smooth, hard metallic substance which will not burn in open air and can be sawed or machined to fit. As in the case of the pressed grain described above, however, no tests have been performed to determine whether it will detonate under extreme pressure, impact, or the heat of prolonged machining. One group has tested such a mixture for impact sensitivity by dropping a 25-pound weight on a small amount of it from a height of about 15 feet. So far, they have not been able to make it detonate.

Some grains have also been produced using acetone and similar substances as the binding agent. Some of these grains have dried within a few hours and cross-sectional cuts made in them to inspect the grain composition. They appear to have a smooth, uniform composition, and densities in the neighborhood of 0.139 pounds per cubic inch have been achieved. One group in Brooklyn, New York, has had excellent results in casting such grains, using certain other additives, which they hope to produce in quantity for commercial sale. When actual burning tests are completed and firm performance parameters are obtained, the group will apply for an Interstate Commerce Commission rating on the propellant and further information on it may then be available.

A group in Colorado has conducted experiments for several years with cast grains of zinc and sulfur, using alcohol as the solvent. The work of this group has been outstanding, and while their findings are by no means definitive, as yet, the results they have achieved have been spectacular in some instances. If nothing else, they serve to point up the fact that there is a much greater potential in zinc and sulfur than most people believe. Here are some of their findings (tentative of course):

All cast grains require more burning surface than end burning affords. Therefore the group casts most of its grains in the tubular configuration shown in Illustration 6.

Specific impulse ratings as high as 125-150 seconds have been obtained.

A tubular cast grain has sent 24-inch rockets to altitudes of 7,000-10,000 feet, compared with only 1500 feet for the same rockets loaded with loose powder.

Two-stage rockets employing these grains have attained altitudes in excess of six miles.

The group claims to have fired a three-stage rocket to an altitude of 80,000 feet; which, if true, is far above any previous amateur record, so far as the author is aware.

Exhaust velocities between 4,000 and 5,000 feet per second have been obtained.

Density of the grains has been about 0.139 pounds per cubic inch.

Rockets 24 inches in length, 1½ inches in diameter, with a nozzle throat-diameter of ½ inch have developed 500 pounds thrust with a burning time of 0.7 seconds.

Considering the progress that has been made by groups such as those cited in the foregoing examples, it would appear that there is much room for effective development work in this area, and that cast grains of zinc and sulfur may well prove to be a far more effective propellant than the loose powder has proved to be. It would also appear that cold-casting of the mixture can be accomplished with safety and with relative ease (none of these groups has ever had an accident, but that is no reason for not observing all of the precautions that are recommended here).

It is the opinion of the author that an orderly development project undertaken by any amateur group, with qualified assistance and good equipment, will eventually produce a zinc and sulfur grain which will easily satisfy the requirements of the most advanced amateurs. Do not undertake such a project, however, unless you are well equipped to pursue it, and observe the safety rules which are appended here.

II SAFETY RULES—PROPELLANT HANDLING

Following is a summary of the more important safety rules you should observe whenever members of your group handle, mix or experiment with propellant ingredients. Read the rules carefully and often. Insist on their observance by all members of your group.

A. *Handling and Storage*

Do not allow chemical substances, liquid or solid, to come in contact with your skin. If some does, wash it off immediately with soap and water, or follow the directions in the first-aid section of the appendix.

Always have a fire extinguisher on hand.

Always have a readily available source of water.

Always have the antidotes on hand that are recommended in the first-aid appendix.

Always have a first aid kit on hand.

Always have a telephone at hand.

Always have another person with you.

Always have a heavy blanket (preferably asbestos or impregnated canvas) to wrap about a person whose clothing may catch fire.

Do not use metal objects that will cause sparks when handling or mixing fuels.

Do not smoke or permit open flames in any area where chemicals are handled or stored. *Remember that water heaters, oil and gas, furnaces, ovens, space heaters, etc., have open pilot flames burning all the time—even in summer.*

Do not use electric motors or open electric coils (such as in electric heaters, toasters, etc.) in an area where chemical dust may be present. If necessary to use one—to operate a fan, for instance—cover the motor casing with a plastic bag to prevent sparking.

Do not store large amounts of propellant ingredients in one place. Break up your storage area into small "dumps," widely separated. Store ingredients separately, not together. Provide protective barricades.

Avoid storing propellant ingredients in shatterable containers which will produce fragments in the event of an explosion. Use cardboard cartons, wooden boxes, plastic or cloth bags as much as possible.

Follow the Quantity—Distance Table and Thickness of Protective Barriers Table (Chapter 8) for safe storage of propellants.

Do not use match heads for any purpose.

Do not use chlorates, picrates, iodates or fulminates for any purpose. Beware of the dangerous properties of the following substances and avoid their use:

Potassium Chlorate / Sodium Chlorate	Explode readily when rubbed, ground or mixed. Not even used professionally.
Powdered Metals:	Small-grained powders of pure iron, magnesium, lithium, beryllium, zirconium, and aluminum will ignite spontaneously when dispersed in the air. All of these are extremely shock-sensitive when mixed with an oxidizer.
Metallic Sodium:	Can ignite spontaneously in the air if moisture is present.
Metallic Potassium:	Ignites spontaneously in the air.
Yellow Phosphorus:	Ignites spontaneously in the air.
Fluorine:	Extremely toxic. Will react violently with anything containing carbon; such as human flesh, wood, paper, etc. Its fumes are toxic and can form a deadly gas.
Hydrazine:	Will spontaneously ignite in combination with many substances. Fumes are toxic.
Nitrocellulose (Gun cotton) and Nitroglycerin:	Both extremely shock sensitive as well as toxic.
Potassium Ferrocyanide / Potassium Ferricyanide	React violently with oxidizers and explode when mixed with chlorates.

Do not attempt to transport propellants, or explosive propellant ingredients, in a vehicle or on a public highway without getting a permit from your State Police and the Interstate Commerce Commission. *You must abide by the conditions they impose.*

B. *Mixing and Loading*

Do not mix chemical substances whose properties and behavior you are not familiar with.

Do not attempt to melt, or heat, chemicals unless:

a. you are positive of the melting temperature and the