FUNDAMENTALS OF MODEL ROCKETRY

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To the enduring memory of my beloved Son, Capt. Vyom, whose spirit forever flies higher than any rocket.

To my elder brother, ***Ajay Vikram Singh****, whose selfless support was the solid fuel that sustained my journey, making my professional studies of rocketry in Ukraine possible.*

And to the countless dreamers—the passionate builders, the tireless experimenters, and the visionary designers whose eyes are fixed on the heavens. To the underground rocketeers, whose relentless, dedicated pursuit in workshops and garages turns sparks into flame and dreams into flight.

For all who live by the creed: to fire, to fly… up, up, and up, away.

FOREWORD

Rajesh Muneshwar's "Fundamentals of Rocket Modelling" is a significant and timely contribution as an accessible literature on small-calibre rocket technology from India. Drawing upon his extensive hands-on experience, Rajesh has consolidated decades of his expertise in building sophisticated rocket models and their motors in this essential volume.

The book is deeply interwoven with India's advancements in rocket technology. It places the author's work within a pioneering context: a time much before the Indian government unveiled the privatisation of the Indian space sector, he achieved breakthroughs— such as the successful testing of India's first privately-built liquid-propellant rocket engine, the Shivendra-1 in 2010—and simultaneously, Rajesh Muneshwar's Rocket group of experimenters had been leading the development of Solid Rocket Motors. These motors, extensively used sucrose-based potassium nitrate propellant grains, were foundational to High Power Rocketry, Experimental Rocketry, and the emerging field of Rocket Modelling.

A Legacy of Innovation

An enterprising innovator, Rajesh established close collaboration with international aerospace corporations, prominently including the legendary "KB Yuzhnoe" Design Bureau's Rocket Propulsion department of the Scientific Committee of Dnipropetrovsk in Ukraine. He later co-founded Vihaan Spacetech in India, a venture envisioned for developing private commercial space launch vehicle technology and promoting small-scale rocketry to STEM education, weather modification (Artificial Rain rockets) and specialised small-calibre armament rockets for military application. This ongoing work has advanced both the promotion of rocket technology and the foundational theory of spaceflight.

Over the past two decades, *Rajesh Muneshwar* has introduced and mentored hundreds of young students and enthusiasts to the fascinating field of rocket modelling. He has developed numerous original designs for rocket model motors, as mentioned in this book; all have been successfully adopted by aspiring teenage rocket builders in school clubs and Enthusiasts' Rocket Groups.

The core strength of this book is the mathematical modelling and subject knowledge of the ballistic equations, practical procedures of assembly practices, and motor designing. The section on rocket model motors features original work based on the author's own developments over the past 15 years, seamlessly integrating these advancements with successful, classical designs rooted in the heritage of the erstwhile Soviet Union. The method for calculating flight altitude is primarily inspired by Bohdan Wegrzyn's "Modelarstwo Rakietowe" (Warsaw, 1963).

Furthermore, a significant portion of the trajectory simulations and motor performance predictions leverages the author's professional work in high-power rocket design. This comprehensive guide empowers a beginner to a confident and safe approach to the world of rocketry while providing the structured, advanced knowledge an intermediate rocketeer needs to master the craft. Even where certain topics may not be exhaustively covered, this book serves as an outstanding resource for leaders of model rocketry clubs in schools, colleges, and STEM education programs, as well as an essential companion for independent novice amateur rocket builders and experimenters from India and across the world.

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FROM THE AUTHOR

Hello, future rocket scientists and space Entrepreneurs!

India achieved its phenomenal success in recent decades. Indian Space Research Organisation (ISRO) has completely transformed India into one of the leading nations with spectacular space launches, successful interplanetary missions to Mars and Chandrayan-III's autonomous Moon landings near the South Pole. These milestones are a testament to the nation's profound scientific and technological zeal.

To secure our sustainable progress in the space sector, a crucial, often-overlooked factor will be the Hands-on space education by practical work with a model rocket. It is a vital training ground—a launchpad—for the next generation of spacecraft designers, Propulsion engineers, technicians, test pilots, and Astronauts.

While Model Rocketry has been popular globally, it is now rapidly capturing the creative imagination of our nation, especially among students in secondary, technical, and vocational schools. Since 2010, clubs and specialised technical laboratories have proliferated, fuelled by a passion for crafting and testing homegrown rockets.

Your Guide to Competent Rocket Construction

The Objective of this book is simple & Crystal clear: to help every curious beginner, student, and experimenter build their own Model Rockets and their motors.

I've tried to compile the fundamentals of Model Rocketry into this compact guide. You can literally build and launch your first small rocket after reading just 20 pages of construction & Assembly guidelines that focused and emphasise your rocket's stable Flight. An excellent model will only tumble without proper alignment of its centre of gravity and centre of pressure—a crucial factor I tried to decipher in more details.

Every rocketeer asks: "How high will it fly?"

This book provides the answer. You will find detailed discussions on factors influencing flight, an overview of domestic solid-propellant motors (SPRE), essential calculations for flight trajectory, and methods for determining altitude during all phases. We even include an elementary derivation of K. E. Tsiolkovsky's velocity equation.

Dive in, build, and launch—and take the first step in realizing India's Space future.

Rajesh N. Muneshwar

Kyiv,
Ukraine

Contents

1. AN INTRODUCTION TO MODEL ROCKETRY

Welcome to the exciting world of model rocketry! Have you ever looked up in the sky and dreamed of building something that could fly high above the clouds? Well, this is your chance. This book is your personal guide on an adventure to design, build, and launch your very own model rocket.

Model rocketry is an engaging hobby that combines the disciplines and theories of aerodynamics, physics, Mathematics, Electronics, metallurgy, computer programming, combustion science and craftsmanship. At its core, every well-functioning model rocket is a complex miniature system, comprising three essential elements: a primary structure, one or more Motors for propulsion, and *integrated systems*—such as a recovery system (e.g., a parachute) to ensure a safe return to ground.

The most amazing part? There is no single "right" way to do it. Just like scientists at ISRO have different ideas for a mission, you also have choices to make. This book will walk you through the general steps and show you the different paths you can take. Your mission, should you choose to accept it, is to create a rocket that is uniquely yours.

For beginners, a less complicated but equally amazing starting point is the single-stage model rocket. Its design simplicity provides a foundational understanding of rocketry principles and construction techniques. This chapter will guide you through the designing of a classic beginner's rocket, often referred to as the "Pioneer" model—a project well-suited for a school workshop, a modelling club, or a summer camp.

Your Rocket, Your Rules!

One of your first and most important decisions is how you want to build. Do you like the idea of buying a readily available rocket from online store and modify to its even better version? Or does the challenge of building everything from scratch, from individual parts, sound more exciting to you?

If you choose to *modify a ready-made kit*, you will become an upgrade expert. You can supercharge your rocket by integrating it with a bigger Rocket Motor, adding a booster stage for more height, or even clustering multiple Rocket Motors together for a powerful lift-off!

If you opt to *build from scratch*, you become a chief designer of your Rocket Launch Project. You have complete control on your development program. You can either buy a mixed bag of parts (often called a 'Designer Special') or get creative with 'Kit Bashing'. Kit bashing is a fun way to mix and match parts from two or more different rocket kits to invent a brand-new design. It's like being a rocket chef, following your own special recipe!

Safety First, always!

No matter how cool your rocket looks, its journey isn't complete until it lands safely back on the ground. That's why the recovery system—usually a parachute—is so important. Remember, every part must work together. Even if your parachute perfectly opens up, a broken shock cord (the string that holds it all together) means your mission is a failure. So, always check your work, add that extra drop of glue, and make it strong.

The Real Goal of Your Mission

As you begin, always keep this in mind: the true success of your project isn't just about how high your rocket flies. It's about the knowledge you gain, the problems you solve, and the skills you learn. A cleverly designed, smaller rocket can often outperform a bigger, more expensive one. Remember the wise words: "*Bigger is not better, but bigger is usually more expensive!*"

There might be reasons to build a larger rocket, but a cleverly designed, smaller rocket with an A-C Motor (18mm) can easily compete with—and even beat—a bigger rocket with a D-E Motor (24mm). It's all about your smart design, not just the size!

So, turn the page, and let's ignite your imagination. Get ready to learn, build, and launch. Your journey to the stars starts now!

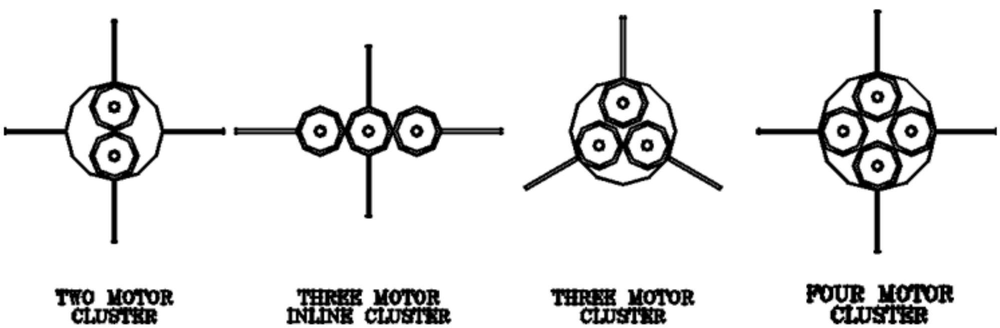
Clustering

Want to launch a heavier rocket or carry a special payload? *Clustering* is a cool technique. In clustering you use two or more rocket motors at the simultaneously to add that extra power boost for lift-off! Using two or more rocket motors at once, allows you to lift heavier rockets and payloads off of the ground.

When you are clustering black powder motors, it is very important to have a launch controller of a minimum voltage supply to the igniters of 12 Volts DC. This ensures all the motors light up together at the same time. Another important thing, when you use clustering technique, try to keep the motors as close to the rocket's central axis as you can. Vivid unexpected issues you can face with clustering techniques. Some of which could be an ignition failure of the motor, then the rocket's ascent flight achieving an altitude much lower than your design estimates. Sometimes, the recovery system can deploy too late or the rocket itself can get slammed into the ground while still under power.

Now, here is an important point: if you cluster motors with different nozzle sizes, the one with the smaller diameter will ignite first, followed by the larger one. Please refer to the example of the rocket below. It uses two C6-7 and one D12-5 motor with friction motor mounts. As expected, the C6-7s lit first, and then the D12-5 was to follow. The picture on the left shows a perfect flight where all three motors are in line and burning. But the picture on the right is from a failed launch. In that case, the owner forgot to properly friction-mount the central D12-5 motor. So, the C6-7s ignited and took off, simply leaving the D12-5 behind! You can even see it lit in the smoke below the rocket. Just after this photo was taken, the loose D12-5 motor struck the rocket, made it flip over, and it slammed into the ground.

Here are a few typical clustering arrangements for your reference. And one more thing you must keep in mind that if you align your fins with the motors, your rocket will structurally become much stronger



Rocket Staging: Principles and Design Considerations

In a staging technique of rocket design configuration empty fuel tanks and rocket motors, stages are discarded in a sequential order during the flight. This design technique increases the total impulse and thus the Rocket's overall thrust, simultaneously reducing its final weight. This leads to a higher velocity and altitude.

Rocket Staging burns two or more Motors that ignite in sequence. The lower stage, also referred to as a booster stage, is jettisoned once it burns out and is followed by the ignition of the next upper-stage motor.

Motor Selection for Staged Rockets

This project focuses on model rockets using solid-propellant motors. For staging, *black powder motors and Sugar propellant (KNSB) motors* are recommended. These motors are safe and compatible with standard 6 or 9 VDC launch controllers and do not require complex ignition systems.

Although it's technically possible to stage more powerful *composite propellant rocket motors,* it is not recommended for your rocket modelling project. These motors require at least a 12 VDC higher-voltage ignition source, as well as a sophisticated electronic trigger — *timers, altimeters, or G-switches* to reliably ignite the upper stage. Due to this increased complexity, it becomes unsuitable for this application.

Risk Analysis: Upper-Stage Ignition Failure

Staging introduces an additional point of failure: the ignition of the upper-stage motor. This underscores the critical consequences of a misfire on your mission planning and safety procedures.

Single-Stage Rocket Misfire: If the motor fails to ignite, the rocket remains on the launch pad. The issue can be safely corrected by replacing the igniter.

Two-Stage Rocket Misfire: the flight sequence is disrupted if the *upper-stage* motor fails to ignite after the booster burns out and separates. The rocket will be at an altitude of 400-600 feet and will begin to fall, typically nose-first, without its recovery system (like a parachute) being deployed. This will almost certainly result in the destruction of the rocket upon impact. Once the rocket leaves the pad, you have no control over its flight, so this risk must be accepted when choosing to stage.

Stability and Centre of Gravity (CG)

For a stable flight, you must ensure each vehicle configuration is aerodynamically stable. This requires marking the Centre of Gravity (CG) and Centre of Pressure (CP) for all flight configurations.

For example, a two-stage rocket requires two sets of marks:

1. One set for the fully assembled rocket on the launch pad (booster + sustainer).
2. One set for the sustainer section alone, after the booster has been jettisoned.

Always prioritise safety. Carefully consider these technical requirements and risks before proceeding with a staged rocket design.

Compound Staging

Compound staging incorporates both clustering as well as staging and obviously comes with all of the inherent complexity & failure modes of both the staging techniques.

The rocket illustrated below was built for a rocket challenge by high school students; the challenge was to launch two eggs 2,000 feet. It had to carry an altimeter and have at least two stages. The booster carried two D12-3s and a D12-0 with parachutes; the sustainer carried an E9-5 and a 24” nylon parachute. This is where a bigger vehicle was required to lift the two-egg payload.

The rocket shown below was built for high school students; the challenge was to launch two eggs 2,000 feet. It had to carry an altimeter and have at least two stages. The booster carried two D12-3s and a D12-0 with parachutes; the sustainer carried an E9-5 and a 24” nylon parachute. This is where a bigger lift was required to lift the two-egg payload.

Parallel Staging

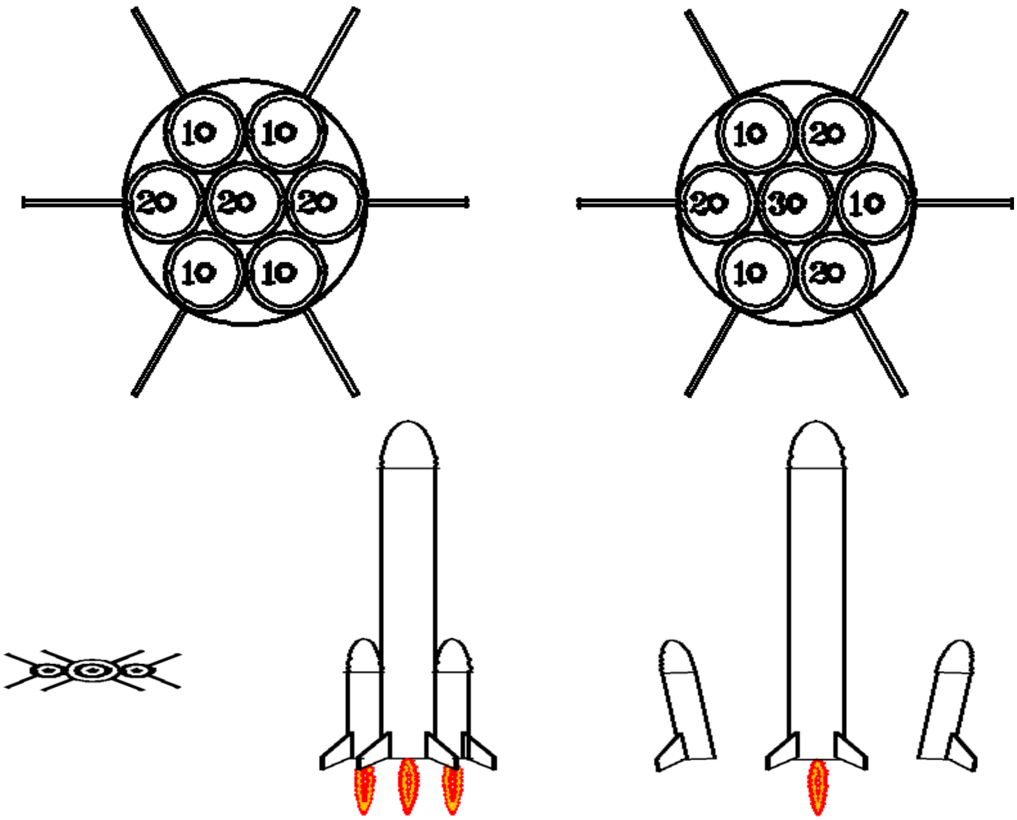
Parallel staging closely resembles clustering, but the sustainer has a longer burn time, and the boosters have more thrust but a shorter burn. The boosters are ejected after their burn time and, in this case, have their own recovery systems. This is usually controlled by timers or altimeters, but it can also be done by other means.

Staged clusters

Using staged clusters involves air-starting the additional motors. Note that on the rocket on the left, the first phase has four motors and three in the second. The rocket on the right has three in the first phase, three in the second, and one in the third. The spent motors are still carried by the rocket along with the additional drag of the larger body tube to house them. This is controlled by using either timers or altimeters.

1.1: The Single-Stage "Pioneer" Model Rocket

The "Pioneer" is a classic design that elegantly demonstrates the basic components of a rocket. Its simplicity makes it an ideal first build. As illustrated in Figure 1, the model is composed of the following structural parts:



The Nose Cone (or Ogive): This is the forward-most section, consisting of a *conical* part (1) and a cylindrical base (2). Its streamlined shape is crucial for piercing through the air with minimal resistance.

The Body Tube: Marked as component (3), this is the main airframe of the rocket, housing the Motor and recovery system.

The Stabiliser Fins: Designated as assembly (5), these are attached to the base of the body tube and provide aerodynamic stability during flight, keeping the rocket on a straight course.

Essential Equipment and Payload

To transform this structure into a flying model, it must be equipped with the following:

Rocket Motor (10**):** The propulsion unit. In this design, the Motor casing is a repurposed *12-gauge hunting cartridge.*

Recovery System: A parachute (8) is packed into the body tube, which deploys at the apex of the flight to slow the rocket's descent.

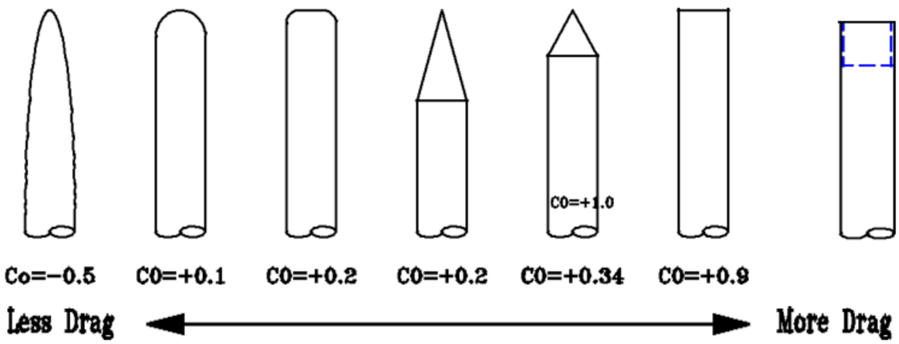
Wadding (9): A protective wad of flame-resistant material (e.g., cellulose or felt) placed between the Motor and the parachute to prevent the hot ejection charge from damaging the parachute.

Launch Guides: Two *guide rings* are attached to the body tube, which slide onto a launch rod to stabilize the rocket during the critical initial acceleration.

1.2: Construction Techniques

A. *Fabricating the Nose Cone*

The nose cone is typically constructed from sturdy writing



paper.

1. A sheet of paper is uniformly coated with adhesive.
2. It is then carefully wound in two tight, overlapping layers around a forming tool known as a *mandrel (13)* to create a consistent cylindrical shape.
3. As an alternative to paper, the conical tip can be carved from a lightweight block of balsa wood or shaped from plastic for greater durability and a finer finish.

4. *Finishing:* Regardless of the material, the surface must be smooth. Any imperfections should be sanded away, and the final piece can be polished to a sleek finish for optimal aerodynamics.
5. *Critical Fit:* The internal diameter of the cylindrical base must be *slightly larger* than the external diameter of the body tube. This "loose" fit is intentional, ensuring the nose cone can be easily ejected by the Motor's charge to deploy the parachute.

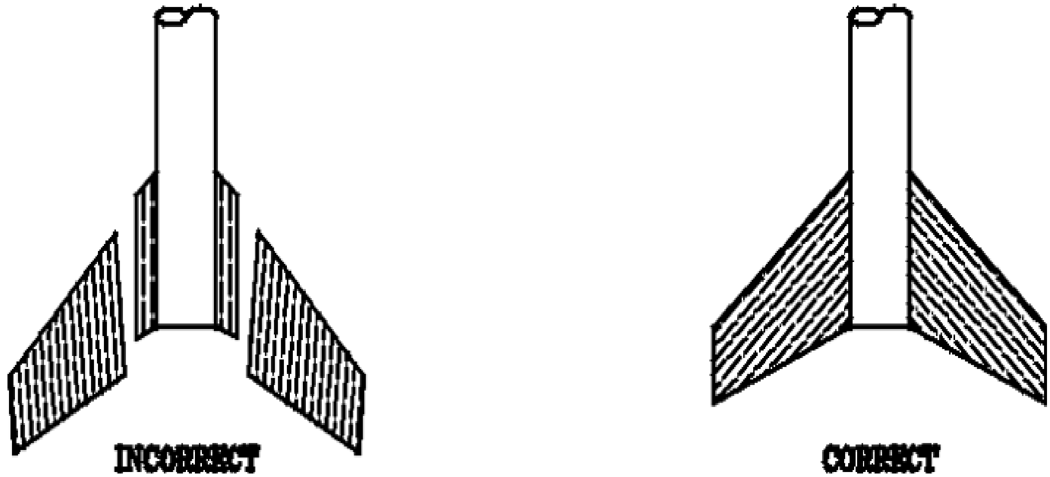
Options for nose cones include the ones pictured below and others, all of which create certain amounts of drag. The ones pictured here are arranged in order of increasing drag, with the drag coefficients appearing below each drawing. As you design your rocket, be aware that there is more to nose cone selection than appearance.

B. Construction of the Fins

Balsa wood fins are adequate for all forces exerted on a rocket using black powder motors, but only if the wood grain is running in the proper direction. When laying out your fins on your material, pay close attention to the direction of the wood grain. The most efficient way to save material is often incorrect. Fins with the grain running parallel to the body tube break under the stresses of flight. (See drawing labelled “Incorrect.”) With most fins, the grain running with the leading edge is much stronger. (See drawing labelled “Correct.”) Grain direction is important for balsa or basswood fins only; if you are using plywood fins, it won’t be a problem.

For composite motors you must either 1) reinforce the balsa wood by painting the raw wood with Epoxy glue, or 2) change the material to basswood or plywood. Reinforced balsa fins are structurally strong but are difficult to sand to a smooth finish.

The images below show the optimal direction of the grain for numerous fin shapes.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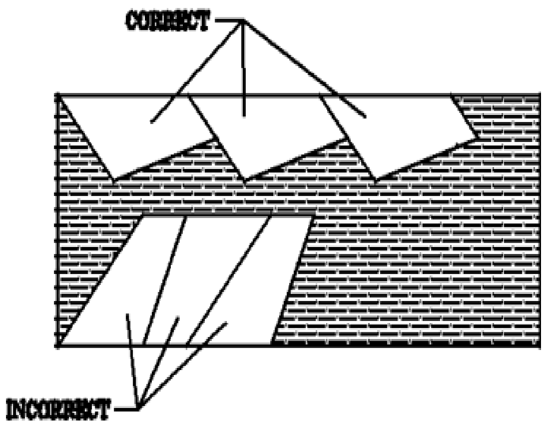
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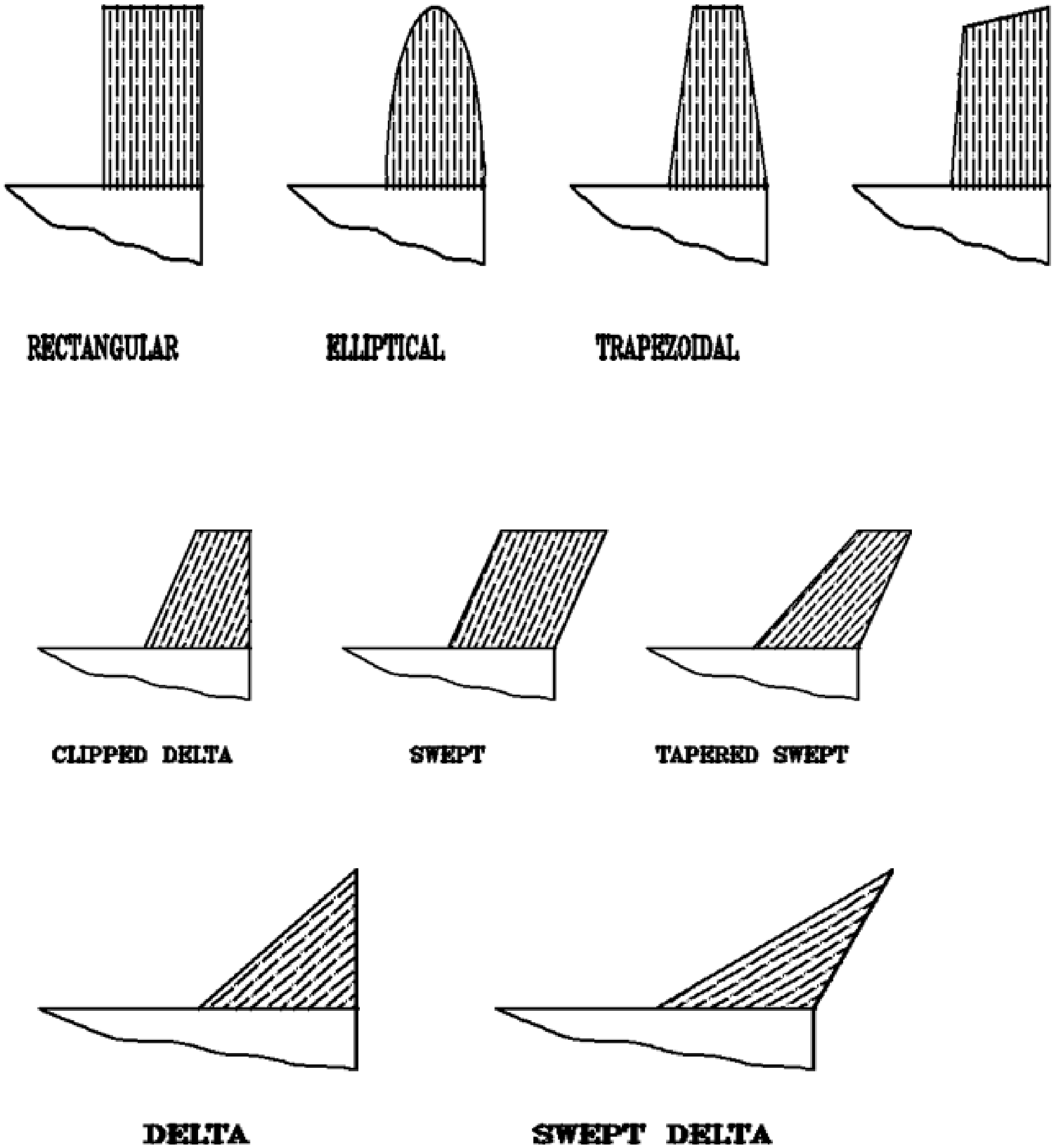

RECTANGULAR
ELLIPTICAL
TRAPEZOIDAL
CLIPPED DELTA
SWEPT
TAPERED SWEPT
DELTA
SWEPT DELTA

C. Constructing the Body Tube

The main body of the rocket forms its structural backbone and must be both strong and lightweight.

1. Following a similar process to the nose cone, a sheet of writing paper is coated with glue.
2. It is then wound tightly and evenly onto the same mandrel, this time in **two to three layers** for added rigidity. The even application of pressure during this winding process is key to creating a perfectly round and strong tube that can withstand the forces of launch and flight.

You see, rockets with a larger diameter naturally have a lot of Base drag in their design. If you add a boat tail, you can actually reduce this base drag. A boat tail is basically a tapered section where the smaller end faces the rear of the rocket. However, do note: if you are putting a boat tail on a short, stubby rocket, you must be careful. The reason is, some of these designs depend on that base drag to remain stable during flight.

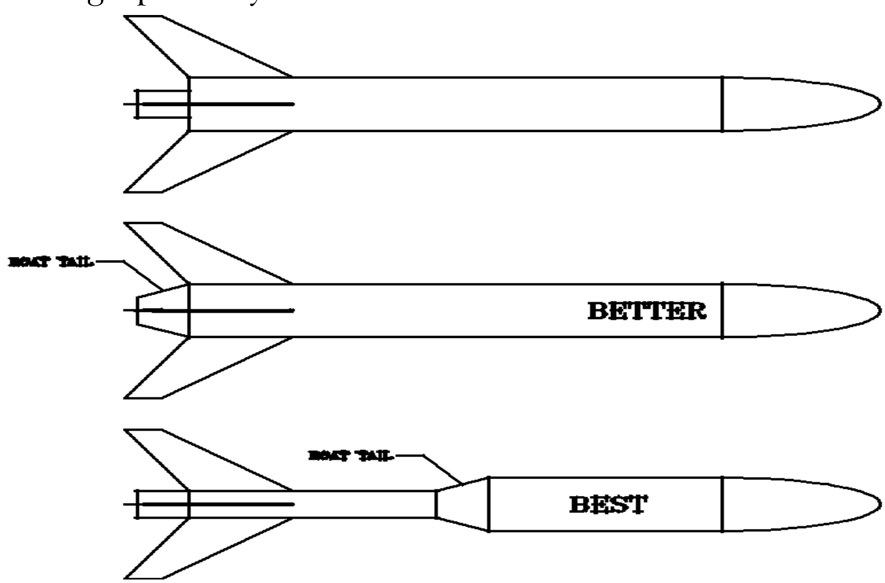
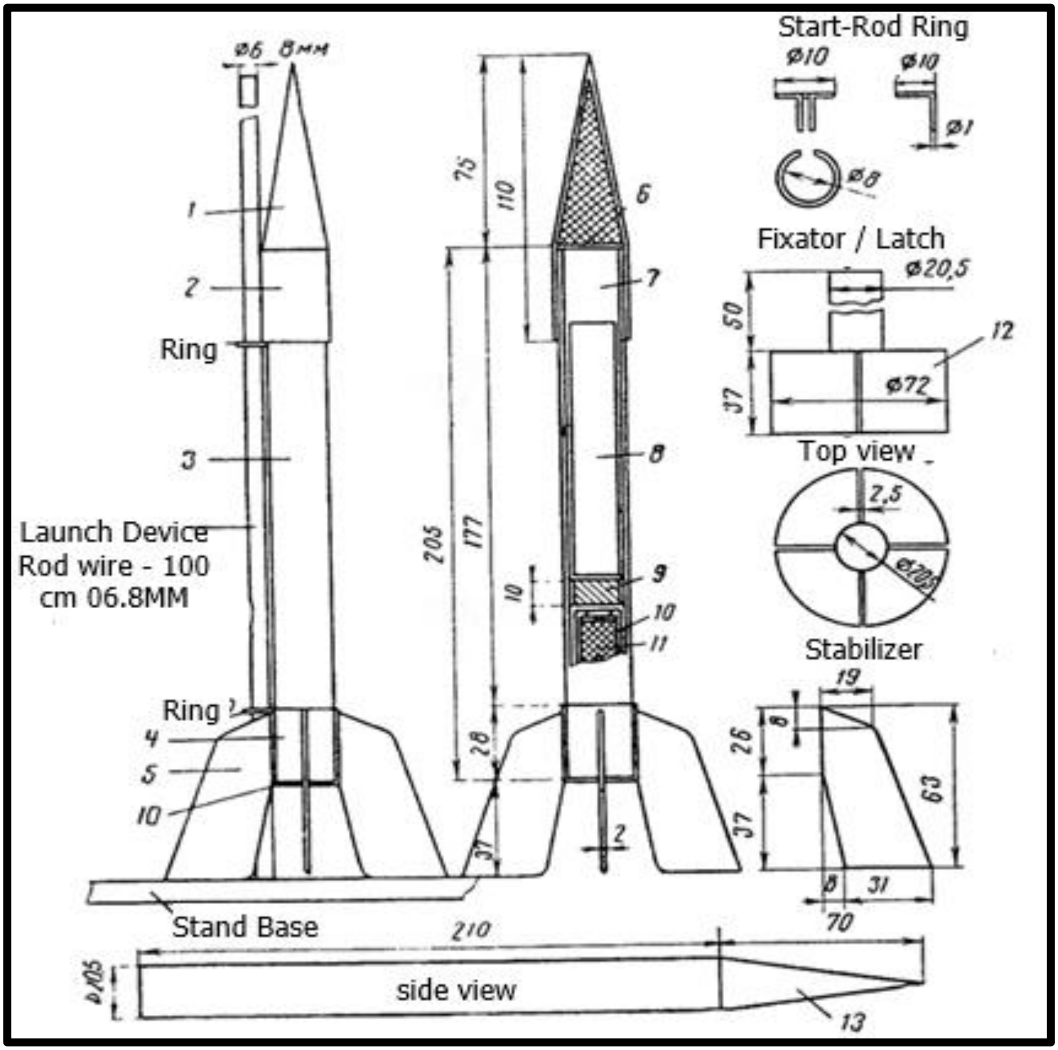


Fig. 1: Single-Stage Model Rocket:



…turns. To ensure a reliable bond for the stabilizer fins, a paper band 25-28 mm in width is affixed in five to six layers to one end of the finished and dried fuselage.

The stabiliser fins for the model consist of four plates, cut from plywood or sturdy cardboard, with a thickness not exceeding 1.5 mm…2 mm.

Conical section of the nose cone.:2Cylindrical base of the nose cone; 3. Fuselage of the model rocket.; 4. Reinforcing band to increase the thickness of the rocket's aft section; 5. Stabiliser fin. 6. Support the bulkhead of the nose cone.; 7. Parachute shroud lines; 8. Parachute; 9. Protective wadding. 10. Micro solid-fuel rocket Motor, 11. Solid-propellant charge for the micro Motor; 12. Launch Pad: Base

Launch rod (wire), Length = 100 cm, Ø 6-8 mm; Launch lug ring; 13. Mandrel; 14. Alignment Jig (for fuselage and stabiliser assembly): Side view; Top view

It is not allowed to make stabilisers from metal. Irregularities are smoothed with sandpaper, first on all plates simultaneously, and then on each one individually. The cleaning is done until a completely smooth surface is obtained. The size and weight of the stabilisers must be the same, and their edges must fit flush against the body of the Model Rocket along their entire surface. For the precise installation of the stabilisers on the body of the model, a special assembly tool intended for this purpose is used - a mandrel and fixture 12.

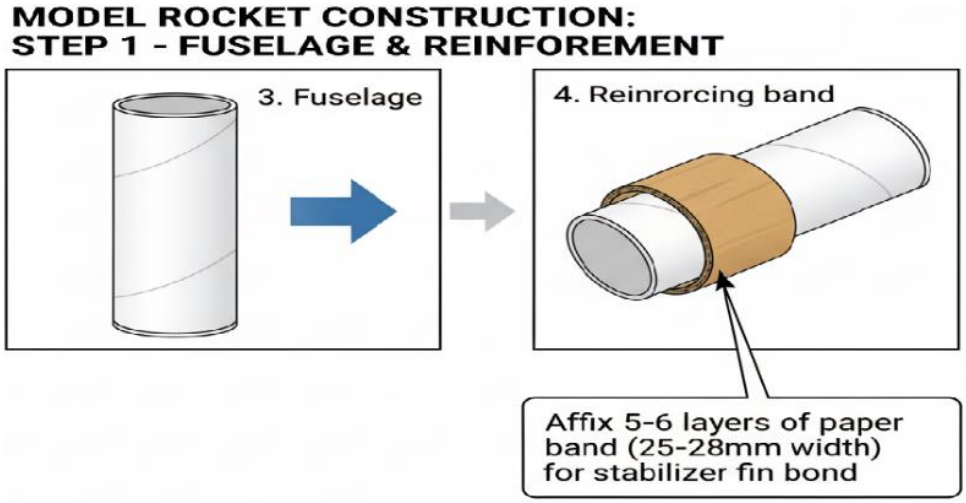
The dried body is placed onto the fixture with the end where the paper tape is glued. Through the slots in the fixture, cuts are made in the body of the Model Rocket using a saw. Their depth is no more than 1 mm. The stabilisers are glued into these cuts. Casein, woodworking, stationery glue, or enamel can be used as the adhesive. After the stabilisers have dried, the body of the Model Rocket is removed from the fixture, now with the tail assembly attached. It is advisable to glue the guide rings at the same time as the stabilisers.

One ring is attached to the lower part of the Model Rocket, and the second one - slightly below the nose cone. After thorough cleaning of the Model Rocket's body, you can proceed to its painting. The model is predominantly painted in bright colours. A model painted silver looks good. The parachute is made from lightweight fabric (silk, percale) or tissue paper. Its diameter is no more than 300 mm, the number of shroud lines is not less than 6, each 300-400 mm long. All shroud lines are joined into a common knot, which ends with a strong thread (a bridle) for attachment to the body of the Model Rocket. The bridle is attached to the upper end of the Model Rocket's body and is usually located under the nose cone cap. It is also recommended to attach the nose cone itself to the body of the Model Rocket with a thread 50-60 mm long, so as not to lose it after launch. Then, they proceed to equip the rocket. The rocket Motor is inserted into the finished and painted body of the Model Rocket from the tail end, so that it goes in all the way.

The rocket Motor must be held securely in the rocket body tube of the model, which is important for the parachute to deploy at the highest point of the flight. From the front side of the Model Rocket, a felt wad is inserted and pushed down to the rocket Motor. Then the parachute is placed inside. The shroud lines are laid on top of it, and the nose cone is put on. To launch the Model Rocket, a launch device must be prepared. The simplest launch device can be made by securing a wire with a diameter of 6 mm and a length of 1000-1500 mm into the ground or onto some kind of stand. The launch wire is installed vertically or with a slight tilt, taking into account the wind direction. The launch of Model Rockets without guide devices is not permitted by the "FAI Rules," just as launching without remote electrical ignition of the Motor is not allowed.

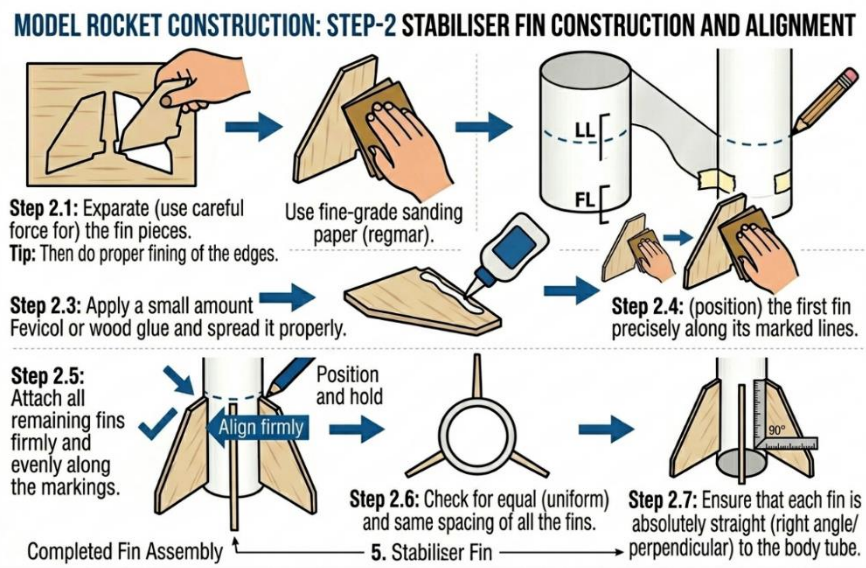
1. *Preparing the Fuselage and Reinforcing Band*

First, create the fuselage (3) of your model rocket. Then, to ensure a strong bond for the fins, apply a paper band (4) 25-28 mm in width in five to six layers to one end of the dried fuselage. The fuselage (3) is the main body tube. To ensure a reliable bond for the fins, a *reinforcing paper band (4),* 25-28 mm wide, must be affixed in five to six layers to the aft (rear) end of the dried fuselage.



2. *Stabiliser Fin Preparation*

Cut four stabiliser fins (5) from plywood or sturdy cardboard, no thicker than 1.5-2 mm. Smooth out any irregularities with sandpaper until you achieve a completely smooth surface. Ensure all fins are the same size and weight, and their edges fit flush against the rocket body.

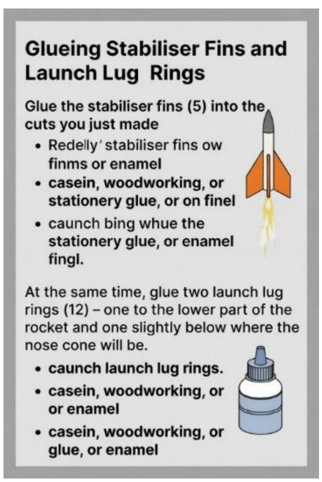


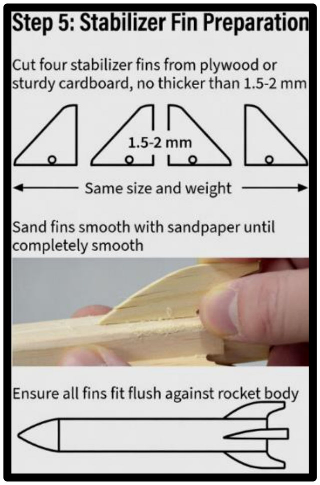
3. Using the Alignment Jig for Fin Installation

Place the dried fuselage onto the Alignment Jig (14) (also referred to as fixture 12 in the text) at the end with the paper tape. Use a saw to make cuts no deeper than 1mm in the fuselage through the slots in the jig

4. Glueing Stabiliser Fins and Launch Lug Rings

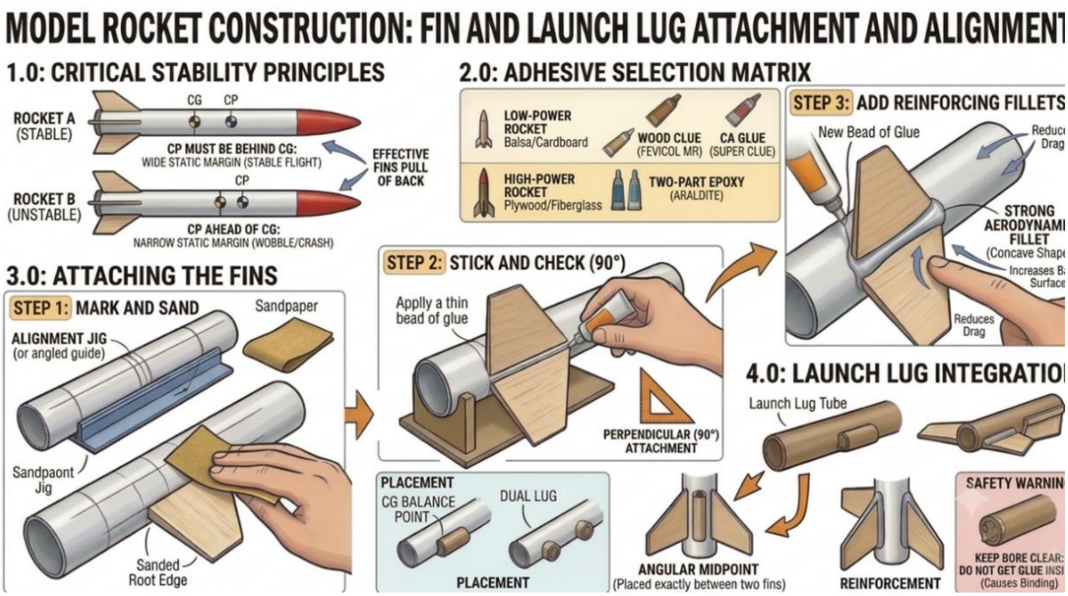
Glue the stabiliser fins (5) into the cuts you just made using casein, woodworking, stationery glue, or enamel. At the same time, glue two launch lug rings (12) – one to the lower part of the rocket and one slightly below where the nose cone will be.

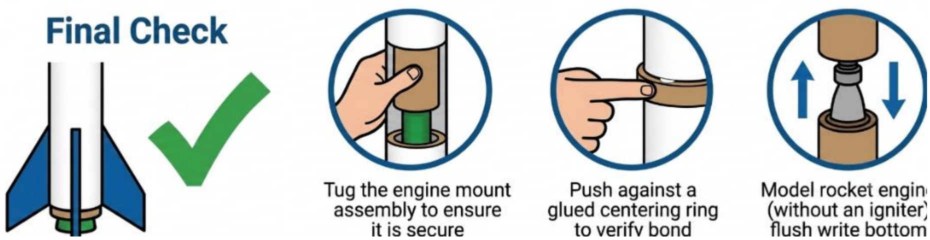




5. Painting the Rocket Body

Once the fins and rings are dried and the body is removed from the jig, thoroughly clean the rocket body. Then, proceed to paint it in bright colours. Silver is also a good choice.





2. THREE-STAGE MODEL ROCKET

A functioning three-stage model rocket is made entirely of paper. Figure 2 shows the general view of a "Strela" (Arrow) type model rocket and its parts. The model consists of three stages and a nose cone. The model rocket's propulsion consists of rocket Motors, whose bodies are 12-gauge hunting cartridges. For the manufacture of the model rocket, the same special tool is used as for other types of schematic model rockets. The manufacturing technology is the same as for a single-stage model.

The conical part and the ring of the nose cone (Fig. 3) are made from semi-Watman paper in 2 layers. A cardboard frame (circle) is inserted into the nose cone, pushing it to the base of the nose cone (stop).

The manufacture of the stabilisers is not difficult but requires care. The material for them is mainly 2-mm plywood, less often, plastic or linden wood. Making them from metal is prohibited.

The stabiliser Fins, cut out with a jigsaw, are first processed simultaneously along the contour, and then each one individually. The edges of the stabilisers are rounded and made streamlined.

The individual stages of the model rocket, made in accordance with the dimensions indicated on the drawing, are assembled in pairs, i.e., tube 2-a is inserted with glue into tube 2-b, tube 3-a into tube 3-b, tube 4-a into tube 4-b. When assembling, arrange the tubes as shown in the drawing. To avoid mistakes, it is recommended to perform the final assembly of all stages of the model with empty cartridge cases inserted, having previously cut them to a length of 60 mm.

All three assembled stages are placed on the mandrel from the first stage side, and with its help, the locations for gluing the stabilizers are marked on the model rocket's body. To more reliably glue the stabilizers to the model rocket's body, grooves 159 mm long and 2 mm wide are made along the markings with a sharp knife. Their depth should be no more than 1 mm. The groove is filled with glue, and the edge of the stabiliser is also coated with it. Then the stabiliser is inserted into the slot of the mandrel and pressed with its edge against the groove. In doing so, care must be taken to ensure that its lower edge is pressed against the table on which the assembly is being carried out. During drying, the plates should be pressed against the model rocket's body with a rubber band.

When the glue has dried, the model rocket body with the glued stabilisers is removed from the mandrel. Then, each plate, depending on the stage, is marked with a pencil using a special template and cut along the marking with a jigsaw. The templates are prepared in advance. Their configuration is shown by a dashed line on the

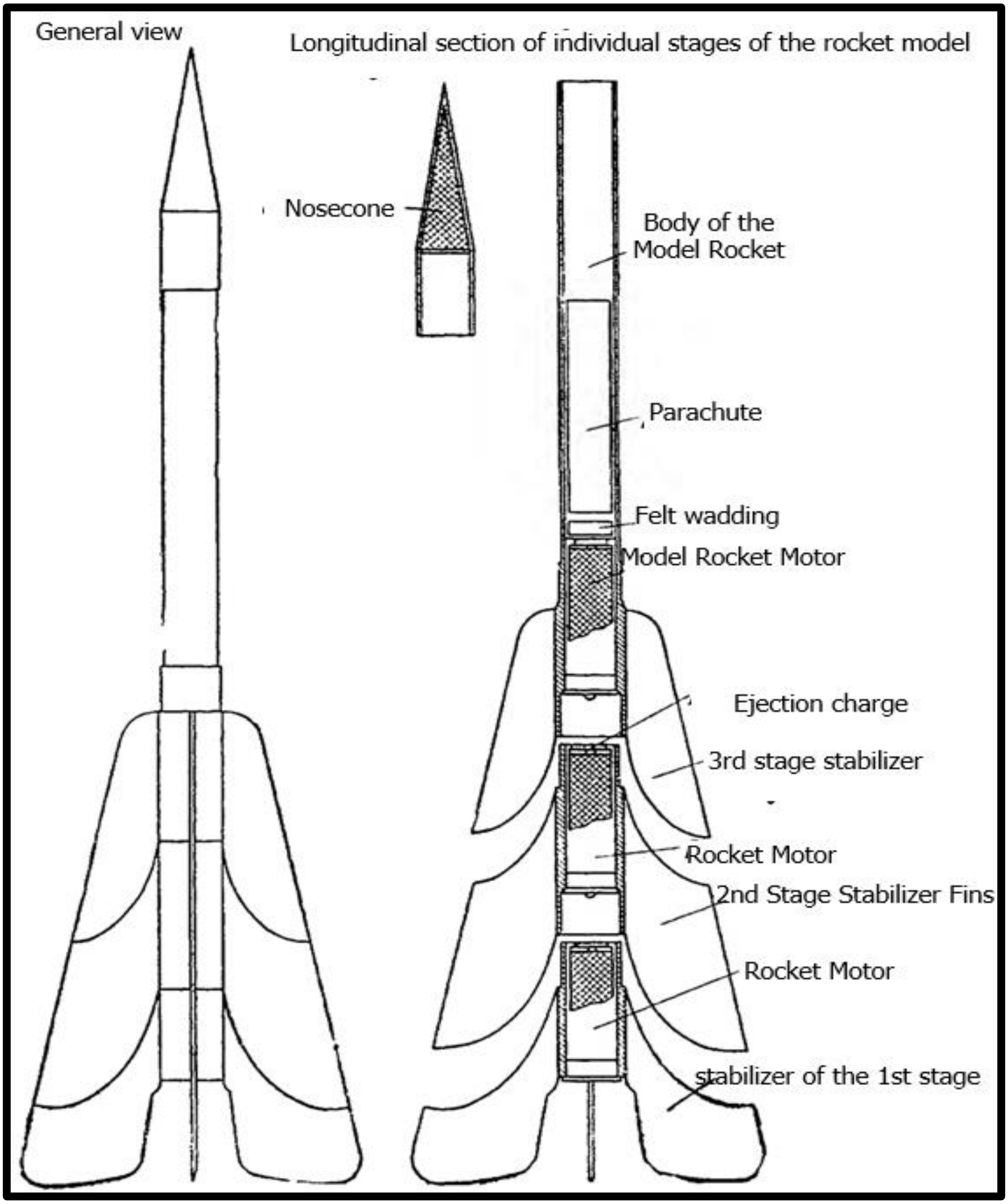


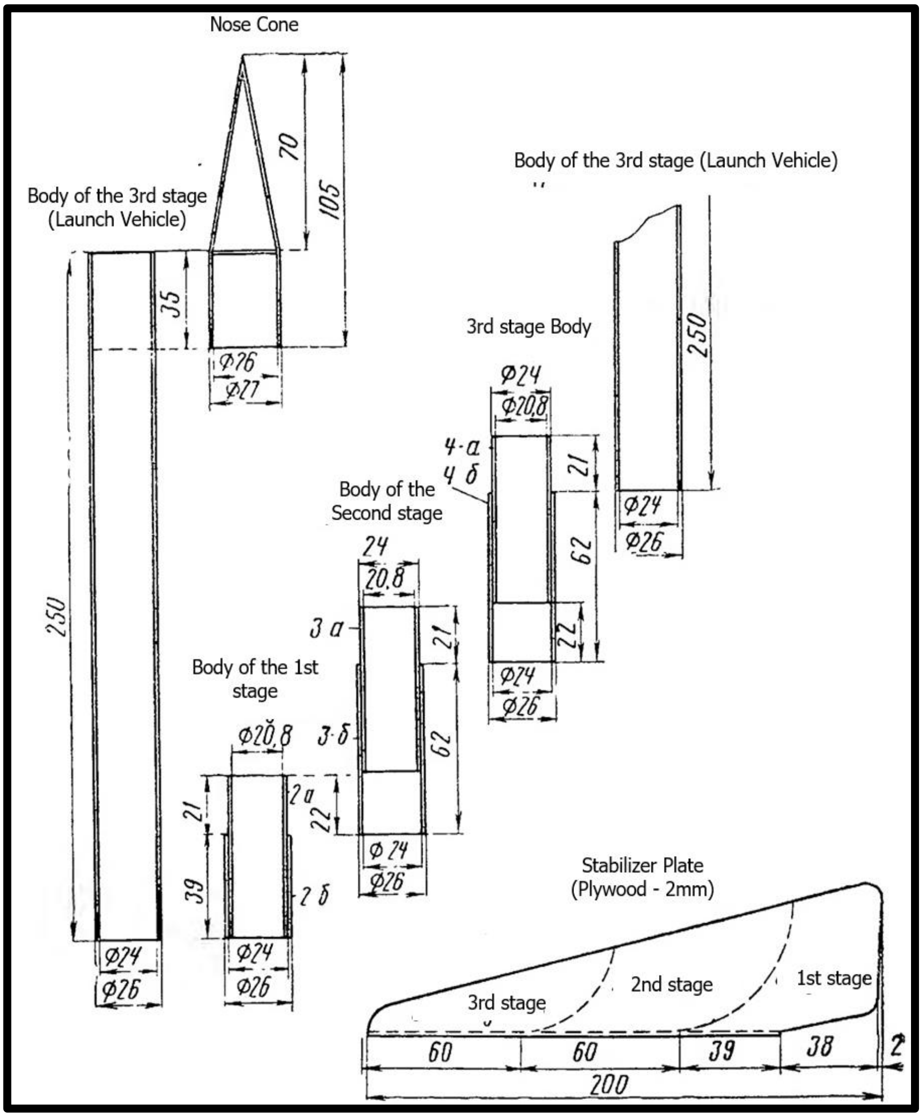
Fig:3, Three Stage Model Rocket "STRELA"

Fig. 3. For the assembly and disassembly of the rocket model, the initial positions of the stages are marked.

The finished and thoroughly dried body of the rocket model is carefully smoothed with fine sandpaper and then coated with colourless varnish. It is recommended to paint the model in bright colours to make its individual stages easier to find after launch.

The rocket model is equipped in the following order:

Fig.4 Details of the "STRELA" Model Rocket



A rocket motor is placed into the first-stage body, then a motor with a piece of visco fuse (a special igniting means) is inserted into its nozzle is placed into the second-stage body, and a rocket motor with an inserted piece of visco fuse is also placed into the third-stage body. The stages, equipped with rocket motors, are connected according to alignment marks, and they proceed to equip the Model Rocket with a parachute.

To protect the parachute from the gases of the ejection charge, a felt wad is inserted into the third-stage body of the Model Rocket, pushing it down to the rocket motor. Then, the parachute is attached by one end of its shroud line to the Model Rocket's body and packed in such a way that the lines are laid on top of it and are facing towards the nose cone. After packing the parachute, which should fit easily into the rocket body, the launch lugs are installed, and the nose cone is put on.

After its rocket motor burns out, the first stage separates, simultaneously igniting the second-stage motor. The Model Rocket continues to gain speed and separates the second stage after its motor burns out, simultaneously igniting the third-stage motor. When the Model Rocket loses speed, the parachute is ejected.

To prevent the nose cone of the Model Rocket from being lost when the parachute deploys, it is secured according to "FAI Rules" with an 80 mm long thread. The launch is performed in the same way as the launch of single-stage Model Rockets, in compliance with all safety rules.

The design of this three-stage Model Rocket allows for it to be additionally equipped with a device, for instance, a simple gyroscopic mechanism for better stabilisation of the Model Rocket in flight, etc. Radio control of the Model Rocket's flight and its launch by radio presents great interest. Young radio technicians can work on creating a miniature radio receiver, utilising the achievements of modern semiconductor technology.

§ 3. TEST-MODEL ROCKET

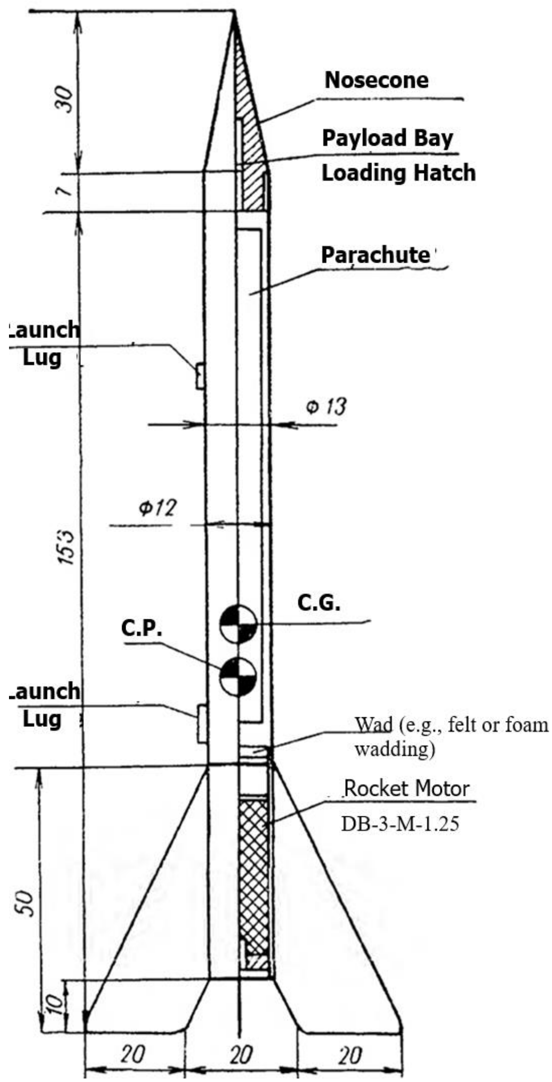
The micro-Model Rocket (Fig. 4) can be used both as an independent model for training flights and testing motors with an external diameter of 12 mm, and as the upper stage for the models described above.

The model has a launch weight of 15 g; a Diwali rocket motor or the motor of the type DB-3-SM-1.25 is installed on it. The body of the Model Rocket is made from writing paper in two layers on a 12 mm diameter mandrel, and the nose cone is made of wood, preferably lime (linden). The nose cone is made with an internal central hole for payload.

and is attached to the Model Rocket's body with a 100 mm long thread. The parachute, with a diameter of 150 mm and shroud lines 200 mm long, is made from microlent paper*; the launch lugs are made of cardboard.

The finished body of the Model Rocket is carefully smoothed with fine sandpaper and painted with coloured nitrocellulose lacquer. Instead of

Fig. 4. Model of a rocket with a 12mm diameter micro-Motor



...Instead of painting, the model can be covered with microlent paper and, after applying a thin layer of enamelite, polished.

§ 4. LAUNCH BOOSTER

The launch booster is designed to accelerate the Model Rocket and launch it to a specific height with maximum speed at the end of the boost phase. The launch booster (Fig. 5) is a casing (15) containing six motors (17).

The booster body consists of the following parts: a bushing, turned from linden wood on a lathe (Fig. 6, cross-section C-C); a booster frame disc (Fig. 5, 4) made from 5-mm plywood; motor frames (7, 14) also made from 5-mm plywood; and the booster body (15), made from Whatman paper in two layers with glue.

The conical bushing of the booster is glued to the booster frame disc at its lower base. After drying, the lower base of the bushing is marked into four sections along its circumference, and axial lines are drawn on its body. Following these markings on the bushing body, cuts are made with a saw up to the disc (4), with a width equal to the thickness of the stabiliser fins.

Two identical frame discs with seven holes each are mounted inside the launch booster body and secured using glue. The holes must be positioned opposite each other, and the axis of each pair of holes must be parallel to the main axis of the booster. The final operation is attaching the booster body to the conical bushing. The disc is inserted into the body with glue to a depth of 5 mm. The purpose of the seventh, central hole in the booster is special. A 12-gauge paper cartridge is inserted into it, metal end up, containing a parachute packed inside, which is intended for the booster's safe recovery to the ground.

The cartridge with the parachute is constructed as follows:

A 10 mm length of safety fuse (also known as Bickford fuse) is inserted into the hole in the metal base. To ensure the fuse is held very securely in the hole of the cartridge, it is best to insert it with glue. The glue must not get on the combustible material (powder pulp), otherwise, the ignition may fail. Then, 1 gram of black granular powder is poured into the cartridge, followed by a 1 mm thick cardboard wad, and on top of that, a silk parachute with six shroud lines. Its diameter is 200 mm, and the shroud lines are no less than 500 mm long. Another 1 mm-thick cardboard wad is placed on top of the parachute.

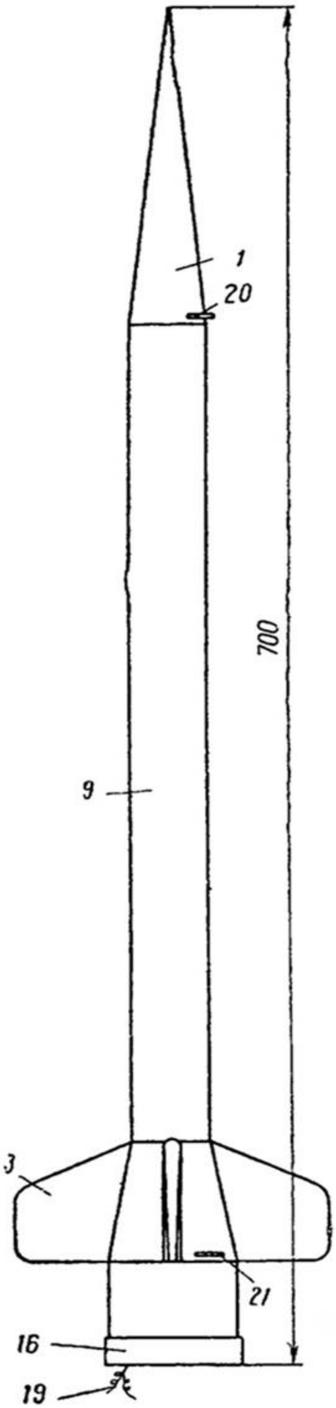
The standard-type motors, inserted into the booster casing from below, must be held firmly. 2-3 grams of powder pulp are poured into the top part of the motors, which is intended… for simultaneously igniting the motor of the model rocket's upper stage and the safety fuse of the parachute, as well as for separating the booster from the system. The parachute should open one second after the booster separates from the model rocket.

for the simultaneous ignition of the upper-stage model rocket's motor and the parachute's safety fuse, as well as for separating the booster from the system. The parachute must deploy one second after the booster separates from the model rocket.

§ 5. EQUIPPING THE UPPER STAGE OF THE MODEL ROCKET

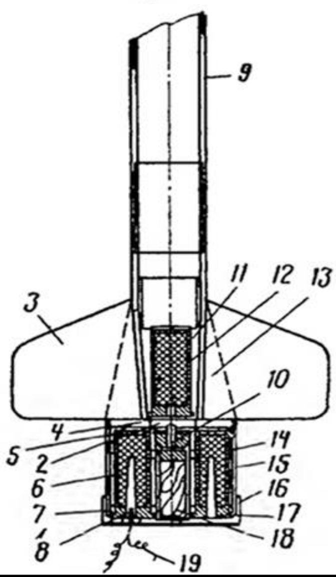
The upper-stage model rocket has a casing with a diameter of 20.5 mm and allows for the use of standard-type motors. A parachute and a miniature semiconductor radio receiver are placed into the body of the upper-stage Model Rocket; the design...

The design of which is proposed for rocketeers to develop independently. The dimensions of the upper-stage Model Rocket allow for the placement of a small-sized and lightweight radio receiver, operating on at least one command (for example, a command from the ground to deploy the parachute).

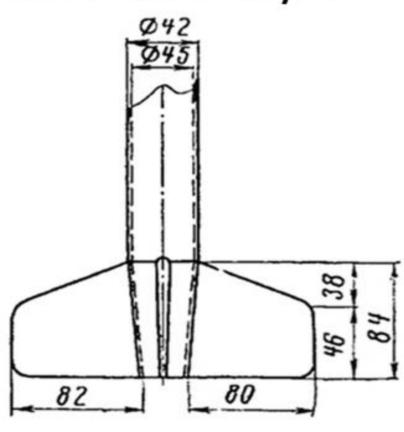


Nose Cone
Powder Pulp (Propellant grain)
Stabilizers (Fins)
Booster Frame
Nozzle End of the Micro-Solid Rocket Motor
Propellant Grain of the Micro-Solid Rocket Motor
Booster Motor Frame (This label seems to point to the area, while item 14 is the specific part)
Igniter
Rocket Model Body (Fuselage)
Safety Fuse (Igniter Cord)
Tailing Cone of the Rocket Model
Micro-Solid Rocket Motor of the Rocket Model
Booster Slots for the Rocket Model's Stabilizers (Fins)
Booster Motor Frame
Booster Body (Casing)
Base Tray of the Pyrotechnic Cross (Note:is likely a specific term for an igniter array)*
Micro-Solid Rocket Motor of the Booster
Booster Recovery System Parachute
Electrical Wiring to the Igniter
Launch Lugs
Launch Lugs (second instance)

Cross Section



Stabilizer Fin Assembly set



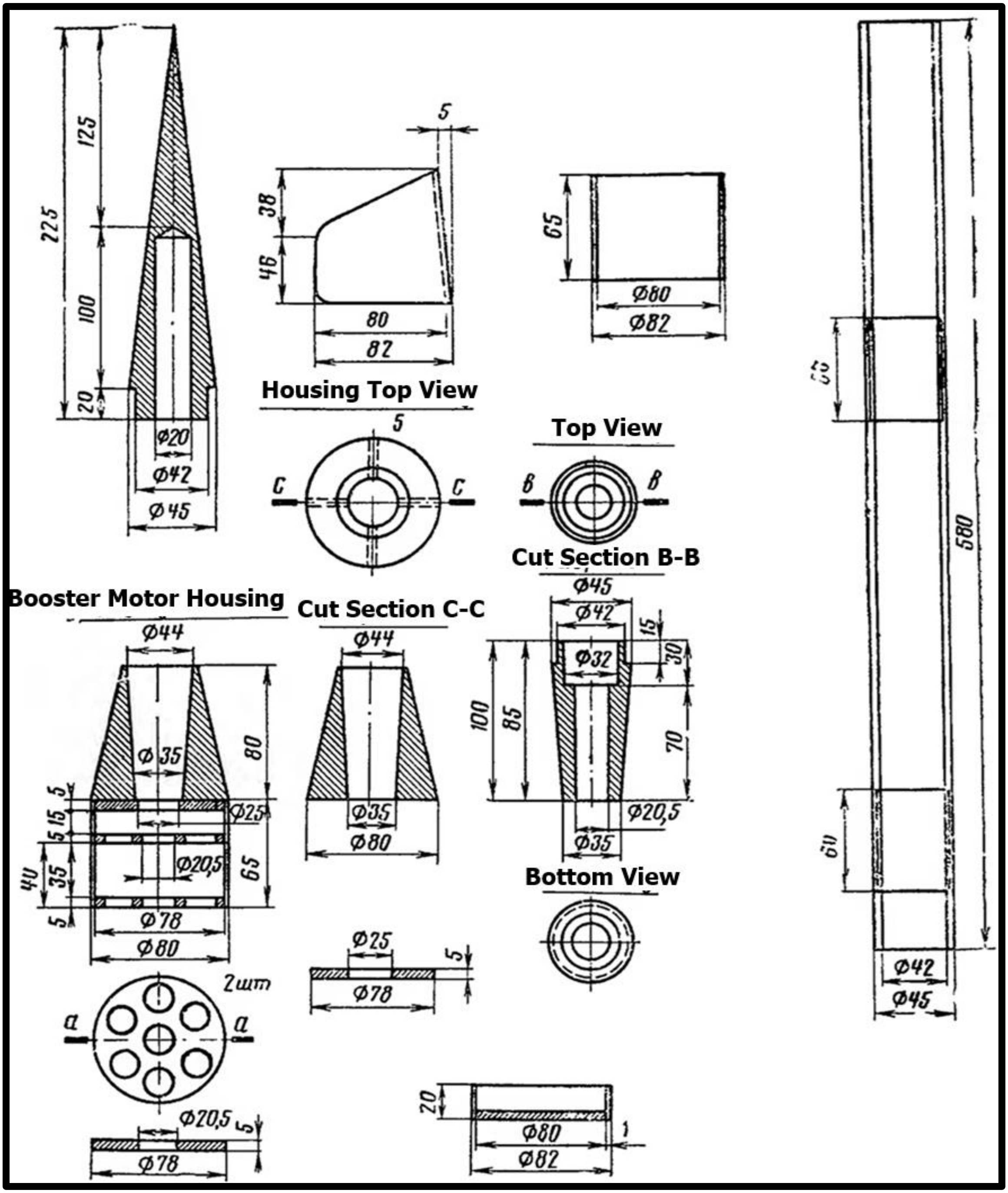


Fig.6 Parts of a model rocket with a booster motor

The upper-stage rocket motor must be ignited promptly, while the model is still moving by inertia with sufficient speed; otherwise, it may deviate from the intended course. Many young model rocket builders have probably learned from constructing two- and three-stage models the consequences of an untimely ignition transfer to the next stage. In such cases, the model rocket is thrown off course.

Instantaneous transfer of ignition flame to the motor of the subsequent stage is ensured by fire-conducting paper tubes, each containing two strands often called an E-match or a Chinese fuse. These tubes are used when the next motor is located at some distance from the motor of the lower stage.

§ 6. SCALE MODEL OF THE "VOSTOK" ROCKET LAUNCH VEHICLE

A scale model (Fig. 7) of the launch vehicle for the "Vostok" satellite-ship at a 1:50 scale was first built in December 1967 by Mikhail Kulashev, a student of the Kuibyshev Aviation Institute. After many highly successful flights of this scale model, its single-stage version was replicated by many Model Rocketeers.

The materials used for the model are: Whatman paper, cardboard, foam plastic, wooden blocks, FRP plastic and other materials.

The motors of the side blocks (Fig. 8, 12) are installed at an angle to the Model Rocket's axis, which ensures precise centring of the first-stage motors (boosters) and reduces the impact of inevitable thrust variations from the Motor cluster.

The main axial loads are borne by the central load-bearing tube (4), which also serves to conduct the thermal impulse to the ejection charge (17) of the recovery system (parachute) located in the model rocket's nose section.

The tube serves as a convenient centring element during the model's assembly. The main requirement for the tube is high Strength. The wall thickness of the tube should not be less than 1 mm. This allows the remaining elements of the model's body to be made from a single layer of Whatman paper, significantly reducing the model's launch weight.

The external design of the scale model serves the purpose of achieving a more accurate and realistic replica. The truss (7), connecting the model rocket's nose section. The design which is proposed for rocketeers to develop independently. The dimensions of the upper-stage Model Rocket allow for the placement of a small-sized and lightweight radio receiver, operating on at least one command (for example, a command from the ground to deploy the parachute).

The upper-stage rocket motor must be ignited promptly, while the model is still moving by inertia with sufficient speed; otherwise, it may deviate from the intended course. Many young model rocket builders have probably learned from constructing two- and three-stage models the consequences of an untimely ignition transfer to the next stage. In such cases, the model rocket is thrown off course.

Instantaneous transfer of ignition to the motor of the subsequent stage is ensured by fire-conducting paper tubes, each containing two strands of visco fuse. These tubes are used when the next motor is located at some distance from the motor of the lower stage.

§ 6. SCALE MODEL OF THE "VOSTOK" SPACECRAFT LAUNCH VEHICLE

A scale model (Fig. 7) of the launch vehicle for the "Vostok" satellite-ship at a 1:50 scale was first built in December 1967 by Mikhail Kulashev, a student of the Kuibyshev Aviation Institute. After many highly successful flights of this scale model, its single-stage version was replicated by many Model Rocketeers.

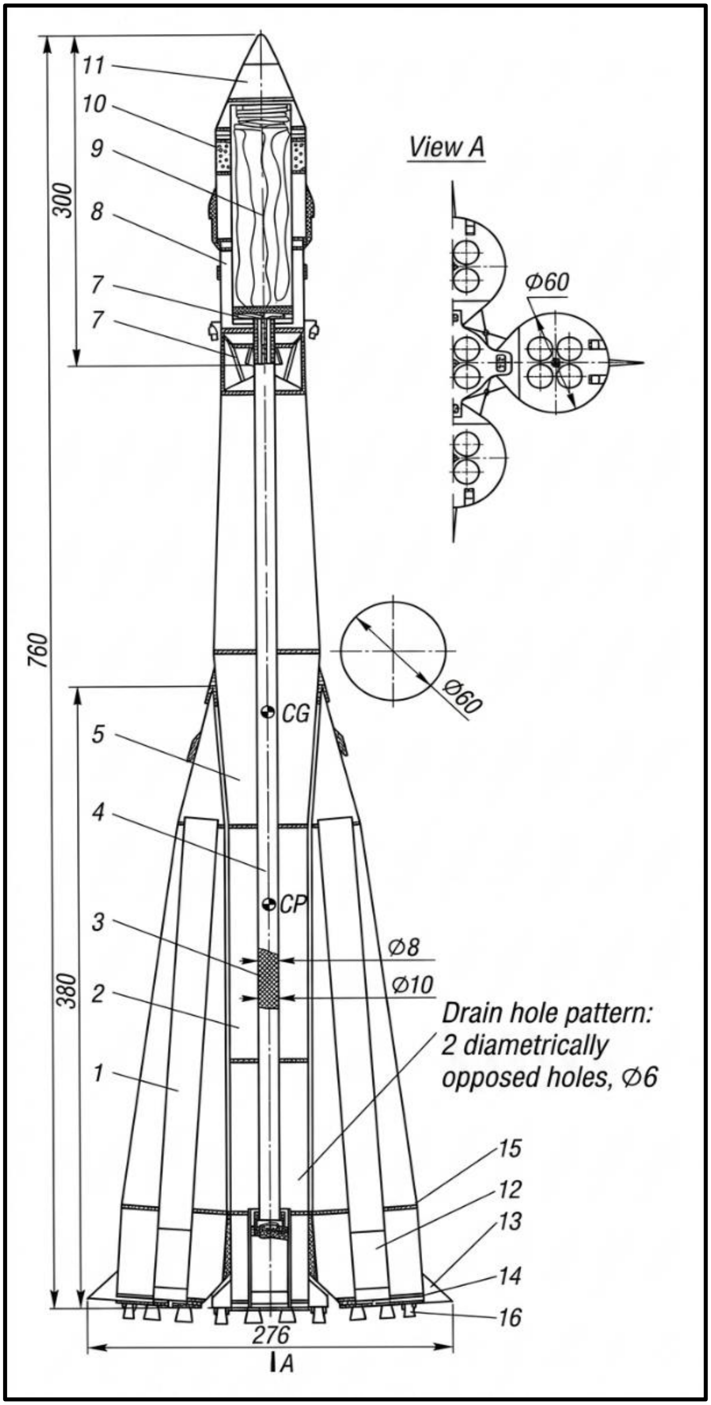
The materials used for the model are: Whatman paper, cardboard, foam plastic, wooden blocks, and other materials. The motors of the

side blocks (Fig. 8, 12) are installed at an angle to the Model Rocket's axis, ensuring precise centring of the first-stage motors (boosters) and reducing the impact of inevitable thrust variations from the Motor cluster.

The main axial loads are borne by the central load-bearing tube (4), which also serves to conduct the thermal impulse to the ejection charge (17) of the recovery device (parachute) located in the model rocket's nose section.

The tube serves as a convenient centring element during the model's assembly. The main requirement for the tube is high Strength. The wall thickness of the tube is made no less than 1 mm. This allows the remaining elements of the model's body to be made from a single layer of Whatman paper, significantly reducing the model's launch weight.

The external design of the scale model serves the purpose of achieving a faithful replica. The truss (7), connecting the model rocket's nose section (16)



Auxiliary Booster of the First Stage

Central Block of the Second Stage

Strand of Visco Fuse

Central Load-Bearing Tube

Nose Cone of the Central Block

Model Recovery System Parachute

Truss

Third Stage Body

Payload

Nose Cone (Fairing)

First Stage Micro Solid-Rocket Motor

Stabilizer (Fin)

Side Booster Frames (Bulkheads)

Steering Nozzle

Recovery System Ejection Charge

However, the second stage did function, albeit for a short time.

Currently, variants of a three-stage model of the "Vostok" spacecraft launch vehicle have already been developed. For example, M. F. Kulashev conducted a series of sequential experiments. The designer launched the second stage separately, combined with the third. The launch was carried out without stabilizers; the stability of the tube was maintained solely through proper balancing.

The model's recovery system could be parachute-based, rotor-based, ribbon-based. Although some innovate recovery solutions are also proposed, like a paraglider-based recovery systems in which the rocket stages are recovered with the help of an inflated flying wing.

This new branch of model building is undoubtedly of significant interest. Whereas it was previously considered as just one more branch of Model Rocketry, the field is now more accurately referred as aerospace modelling, as it includes not only rocket models but also Spacecraft models.

The Model Rockets presented herein should be regarded as examples of various historical stages in the development of domestic Model Rocketry. Currently, domestic aerospace modelling has been advancing to such a degree that these models, or certain of their structural components, can be recommended primarily for educational purposes. It must be noted that not all the models discussed conform to IN-SpAce Regulations and, consequently, are not eligible for official intercollegiate competitions.

Chapter II. MODEL ROCKET MOTORS

The development of a flawless functional Model Rocket is intrinsically related to its propulsion system problems. *Which Motor is most suitable for a given model*? *Which of its specifications are suitable? What is their fundamental nature?* A comprehensive understanding of these issues is essentially important for every Model rocketeer.

This chapter will provide you an elementary explanation of Motor Performance specifications. i,e the parameters that define its performance of the rocket motor. A clear conceptualisation of Motor thrust, burn time, total impulse, specific impulse, and their effect on a model rocket's flight stability, trajectory will enable the designer to make an appropriate Motor selection, thereby ensuring a success in the competition.

The main specifications of the rocket Motor are as below:

1.	Motor Thrust		F (kg)
2.	Burn Time		t (sec)
3.	Specific Impulse	I_{sp}	Kg.sec/kg (equivalen t to Sec)
4.	Total Impulse	I_{Total}	Kg.sec
5.	Fuel Weight	M_{Prop}	kg
6.	Mass Flow Rate	kg/sec	Kg/sec
7.	Exhaust Gas Velocity	V_e	m/sec
8.	Motor Weight	M_{eng}	kg
9.	Motor Dimension s	L, d	mm, (Length and Diameter)

§ 1. THRUST

Let's consider the principle of thrust generation in a rocket Motor. In the burning operation of a solid rocket motor, the hot combustion gases, are constantly produced from the propellant combustion in the combustion chamber.

Assume that the chamber containing pressurised gases is a closed vessel (Fig. 11, a). In this case, it is easy to understand that *no thrust is produced* in this chamber because the pressure is distributed equally over the entire internal surface of the closed vessel, and all pressure forces are mutually balanced.

However, in the case of an open nozzle (Fig. 11, b), the gases inside the combustion chamber under pressure rush out through the nozzle at high velocity. As a result, the part of the chamber opposite the nozzle becomes unbalanced.

The pressure forces acting on the part of the chamber's base area that is opposite the nozzle opening are also unbalanced, and this is what generates thrust.

If we consider only the translational motion of the gases along the combustion chamber and nozzle, then the distribution of velocity of gases along this path can be characterized by a curve (Fig. 12, a). The pressure on the elements of the chamber and nozzle surface is distributed as shown in Fig. 12, б.

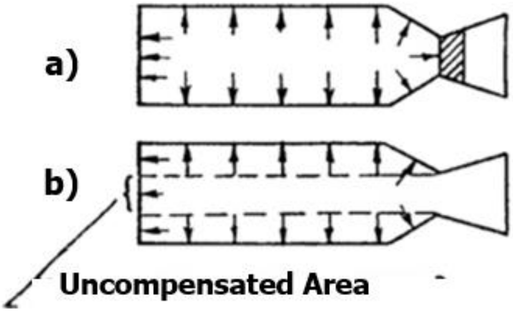


Fig. 11. Diagram of reactive thrust generation in a rocket engine

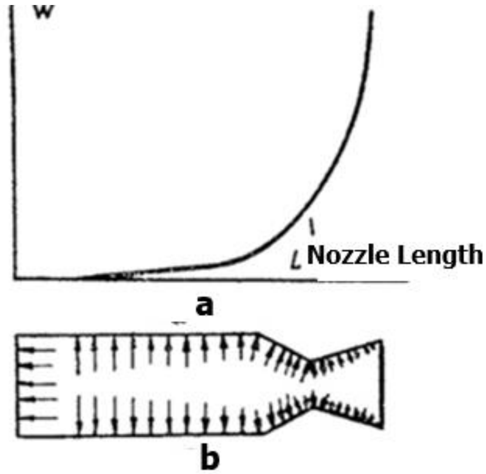


Fig. 12. Diagram of gas flow velocity variation in the combustion chamber

The magnitude of the uncompensated area of the combustion chamber base is equal to the area of the smallest cross-section of the nozzle (the throat). Obviously, the larger the area of this cross-section, the greater the amount of gas that can leave the combustion chamber per unit time. Thus, it can be concluded that the Motor's thrust depends on:

1. <u>The amount of gas leaving the combustion chamber per unit time (due to the uncompensated area). The velocity of the gas outflow, caused by the pressure imbalance.</u>

In order to derive a quantitative relationship, let us consider the change in the momentum of the gases as they flow out of the combustion chamber. Assume that over a time *t*, a certain amount of gas with a mass *m* leaves the Motor's combustion chamber. If we assume the translational velocity of the gases in the combustion chamber is zero and at the nozzle exit it reaches a value of V_e m/sec, then the change in the gas velocity will be W m/sec. In this case, the change in momentum (ΔQ) of the mentioned gas mass is given by the equality:

$$\Delta Q = m \times V_e \qquad (1)$$

However, a change in the momentum of the gases can only occur if a certain force F acts on the gas over a period of time *t*. Then

ΔQ = J, where I = F ×t is the impulse of the force acting on the gas. (2)

$$\Delta Q = \sum \quad J$$

(2) Replacing the value of ΔQ in equation (1) with the equal value J = P · t, we get: F × t = m× V_e hence F = (m / t) ×V_e (3), (4)

$$F \times t = m \times V_e \quad , \quad (3)$$

We have obtained the expression for the force with which the walls of the combustion chamber and nozzle act on the gas, causing its velocity to change from 0 to V_e m/sec.

$$F = \frac{m}{t} \times V_e \quad (4)$$

In accordance with the laws of mechanics, the force with which the walls of the chamber and nozzle act on the gas is equal in magnitude to the force P with which the gas, in turn, acts on the walls of the chamber and nozzle. This force F is the Motor thrust. $F = (\frac{m}{t}) \times V_e$ (5)

$$F = \frac{m}{t} \times V_e \quad (5)$$

It is known that the mass (m) of any body is related to its weight (in this case, the weight of the fuel in the Motor, M_{Prop}) by the relation:

$$m = \frac{M_{Prop}}{g} \quad (6)$$

M_{Prop} - Propellant Mass

g – Acceleration due to gravity, substituting in equation no. 5, mass flow, weight of the exhaust gas, and the analogous term calculated from equation 6. We obtain the following:

$$P = \frac{M_{Prop}}{gt} \times V_e (7)$$

Quantity - $\frac{G_T}{t}$ represents itself the weight of the quality of exhaust gas.

The quantity $\frac{G_T}{t}$represents the *weight of fuel (gas)* leaving the Motor's combustion chamber per unit time (1 sec). This quantity is called the *weight-based mass flow rate* and is denoted as G sec. Then:

$$F = \frac{\dot{m}}{g} \times V_e \quad (8)$$

So, we have derived the Motor thrust equation. It is necessary to note that the equation can have this form only in the case when the gas pressure at the moment it passes through the nozzle exit plane is equal to the ambient pressure. Otherwise, an additional term is added to the right side of the equation: (9)

t

where:

A_e - area of the nozzle exit cross-section (cm^2);

Pe- gas pressure in the nozzle exit cross-section (kg/cm^2);

P_0 - ambient (atmospheric) pressure (kg/cm^2).

Thus, the final equation for the thrust of a rocket Motor is:

$$F = \frac{\dot{M}_{prop}}{g} \times V_e + A_e(P_e - P_o) \quad (10)$$

The first term on the right side ($\frac{M_{prop}}{g} \times V_e$)is called the *dynamic component of thrust,* and the second term A_e ×*(Pe - P₀)* is the *static component*. The latter constitutes about 15% of the total thrust, so for simplicity, it will not be considered in the following discussion.

For thrust calculation, a equation with a meaning analogous to equation (5) can be used, for F= const:

$$F_{avg} = \frac{I_{Total}}{t} \qquad (11)$$

where:

F_{avg} - average Motor thrust (kg);

I_{total} - total impulse of the Motor (kg·sec); t - Motor operating time (sec).

With a constant thrust value, the equation is often used:

$$F = I_{sp} \times \gamma \times \dot{r} \times A_b \qquad (12)$$

This section completes the fundamental derivation of rocket thrust and introduces key concepts.

1. *From Mass to Weight Flow Rate:* The transition from $\frac{m}{t}$(mass flow rate) to $\frac{Gsec}{g}$ is made to use the more commonly measured "weight" of fuel. Since weight G = m × g, then $m = \frac{G}{g}$ Therefore, $\frac{m}{t}$ becomes $(\frac{G}{t})$ / g, or G_sec / g.
2. *The Complete Thrust Equation (Equation 10)*: This is the most important result.

Dynamic Component $\left(\frac{M_{pro}}{g}\right) \times V_e$: This is the thrust produced by the momentum change of the exhaust gases, as derived from Newton's 2nd and 3rd laws. It's the primary source of thrust.

Pressure Thrust Component ($A_e \times (P_e - P_0)$: This accounts for the force due to the pressure difference between the exhaust gas and the ambient atmosphere. If the nozzle is *underexpanded* (P_k > P_0), this term is positive and adds to the thrust. If it's *overexpanded* (P_k < P_0), the term is negative, reducing thrust. A nozzle is ideally optimised for a specific altitude where $P_k \approx P_0$, making this term zero.

3. *Simplification:* Pressure thrust is often a small fraction (~15%), allowing it to be ignored for basic calculations and conceptual understanding, simplifying the equation to $F = \left(\frac{\dot{m}}{g}\right) \times V_e$

4. *Alternative Equation (11 & 12):*

Equation 11 ($F_{avg} = \left(\frac{I_{total}}{t}\right)$.): This is a definition. Total Impulse (I_{total}) is the integral of thrust over time. For constant thrust, it simplifies to $I_{total} = F \times t$, so $F = \left(\frac{I_{total}}{t}\right)$.

Equation 12 ($F = I_{sp} \times \dot{m}$: This is a direct consequence of the definition of *Specific Impulse* (I_{sp}). Specific impulse I_{sp} listed as I_{sp} in the initial parameters, is defined as thrust per unit weight flow rate: $Isp = \left(\frac{F}{\dot{m}}\right)$ Rearranging this gives $F = I_{sp} \times \dot{m}$. This is an extremely practical equation used extensively in rocketry.

Important Thrust Equations

Equation	Application & Notes
$\boldsymbol{F = \left(\frac{m}{t}\right) \times V_e}$	Basic thrust from momentum change (mass flow).
$\boldsymbol{F = \left(\frac{\dot{m}}{g}\right) \times V_e}$	Basic thrust from momentum change (weight flow).
$\boldsymbol{F = \dot{m} \times V_e + A_e \times (P_e - P_0)}$	Complete Thrust Equation. Accounts for pressure.
$\boldsymbol{F = I_{sp} \times \dot{m}}$	Practical equation using Specific Impulse (I_{sp}).
$\boldsymbol{F_{avg} = \frac{I_{Total}}{t}}$	Relates Average Thrust to Total Impulse and burn time.

where:

I_{sp} is the specific impulse of the Motor (sec);

γ is the specific weight of the fuel (g/cm³);

r is the burning rate of the fuel (cm/sec);

A_b is the burning surface area (cm²);

F is the Motor thrust (kg).

In cases of a variable thrust, for example, while determining the initial, maximum, average thrust, and the thrust at an instantaneous moment of a Rocket motor burning, the actual true values of $\dot{r}$ and A_b for the given Motor must be substituted in this Equation.

So, thrust is the product of the effective exhaust gas velocity V_e and the mass flow rate of the Propellant.

Problem 1. Calculate the thrust of a rocket Motor of the type DB-3-SM-10, given the following data:I_{Sp}= 45.5 kg·sec/kg; M_{Prop} = 0.022 kg; t = 4 sec.

Solution.
The effective exhaust gas velocity from the nozzle is:

$$V_e = F_{Spec} \times g = 45.5 \times 9.81 = 446\, m/sec$$

The mass flow rate of the fuel is:

$$\dot{m} = \frac{M_{Prop}}{t} = \frac{0.022}{4} = 0.0055\, kg$$

The Motor thrust is:

$$F_{avg} = \frac{V_e}{g} \times V_e = 0.0055 \frac{0.0055}{9.81} \times 446 = 0.25\, kg$$

Note: For the DB-3-SM-10 Motor, this is the average thrust.

Problem 2. Determine the thrust of a rocket Motor of the type DB-3-SM-10, given the following data: $I_{total} = 1\, kg.sec$; $G_t = 0.022\, kg$; $t = 4\, sec$.

Solution.
We use the Equation

$$F_{avg} = \frac{I_\varepsilon}{t} = \frac{1}{4} = 0.25\, kg \qquad (11)$$

§ 2. EXHAUST GAS VELOCITY

The velocity of the gases exiting the Motor nozzle, just like the mass flow rate of the fuel, has a direct influence on the magnitude of the thrust. As can be seen from equation (8), the Motor thrust is directly proportional to the exhaust gas velocity. Thus, the exhaust velocity is the most important parameter of a rocket Motor.

The exhaust gas velocity depends on various factors. The most important parameter characterising the state of the gases in the combustion chamber is the temperature (T°K). The exhaust velocity is directly proportional to the square root of the gas temperature in the combustion chamber. The temperature, in turn, depends on the amount of heat released during fuel combustion. Thus, the exhaust velocity depends primarily on the quality of the fuel, its energy resource.

§ 3. SPECIFIC THRUST AND SPECIFIC IMPULSE

The perfection of an Motor and the effectiveness of its operation are characterized by its specific thrust. Specific thrust is the ratio of the thrust force to the weight-based fuel consumption per second.

$$I_{Sp} = \frac{F}{M_{Prop}} \qquad (13)$$

The dimension of specific thrust will be (kgf * sec) / kg or sec. In foreign publications, the dimension of I_{sp} is often written as (sec). However, the physical meaning of the value is lost with such a dimension.

Modern model solid-propellant rocket motors (SRMs) have low specific thrust values: from 28 to 50 sec. There are also new Motors with a specific thrust of 160 sec and higher, with a lower pressure limit not exceeding 3 kg/cm^2 and a relatively high specific fuel density of more than 2 g/cm^3.

Specific thrust shows the efficiency of using one kilogram of fuel in a given Motor. The higher the specific thrust of the Motor, the less fuel is consumed to obtain the same total Motor impulse. This means that for the same fuel weight and Motor sizes, the one with the higher specific thrust is preferable.

Task 3. Determine the weight of fuel in each of the four Motors with a total impulse of 1 kgf · sec, but with different specific thrusts: a) I_{sp} = 28 sec; b) I_{sp} = 45.5 sec; c) I_{sp} = 70 sec; d) I_{sp} = 160 sec.

Solution. The fuel weight is determined from the equation: $I_{Total} = I_{sp} \times M_{Prop}$,

from which

$$M_{Prop} = \left(\frac{I_{total}}{I_{sp}}\right) \quad (14)$$

a) $M_{Prop} = \frac{1}{28} = 0.0357kg = 35.7\ g$;

b) $M_{Prop} = \frac{1}{45.5}$=0.0357kg=22.2 g;

c) $M_{Prop} = \frac{1}{70}$= 0.0143 kg = 14.3

g;`

d) $M_{Prop} = \frac{1}{60}$= 0.00625 kg = 6.25 g.

The obtained results clearly show that for model rockets, it is more advantageous to use Motors with a higher *specific impulse* (to reduce the model's launch weight).

The *specific impulse* I_{sp} is understood as the ratio of the total thrust impulse over the Motor's operating time to the weight of the propellant M_{Prop} consumed during that time.

$$I_{sp} = \frac{I_{Total}}{M_{prop}}$$

With constant thrust, i.e., with constant pressure in the combustion chamber and with the Motor operating at ground level, $I_{sp} = P_{sp}$.

§ 4. CALCULATION OF CHARACTERISTICS FOR THE DB-1-SM-6 MOTOR

For Motor calculations, a coefficient characteristic of the propellant and determine the optimal regime in the combustion chamber:

$$K = \frac{Ab_{max}}{A_t}$$

where:

K is a constant coefficient for the propellant,

Ab_{max} is the maximum burning surface area in the combustion chamber;

A_t is the critical cross-sectional area of the nozzle (throat).

Problem 4. Calculate the main characteristics of the *DB-1-SM-6 Motor*, whose body is a 12-gauge paper hunting cartridge case. The propellant is mixture No. 1 (75 parts potassium nitrate, 12 parts sulphur, 16 parts charcoal). The compaction density (specific weight of the fuel) $\gamma = 1.3 - 1.35\, g/cm^3$, $K = 100$.

The maximum pressure in the combustion chamber is set within the limits of $8\, kg/cm^2$. The burning rate of this fuel, depending on pressure at normal ambient temperature, is presented in the graph in Fig. 13.

Y-axis: $\dot{r}_g$ - Burning Rate (cm/sec)

X-axis: P - Pressure (kg/cm²)

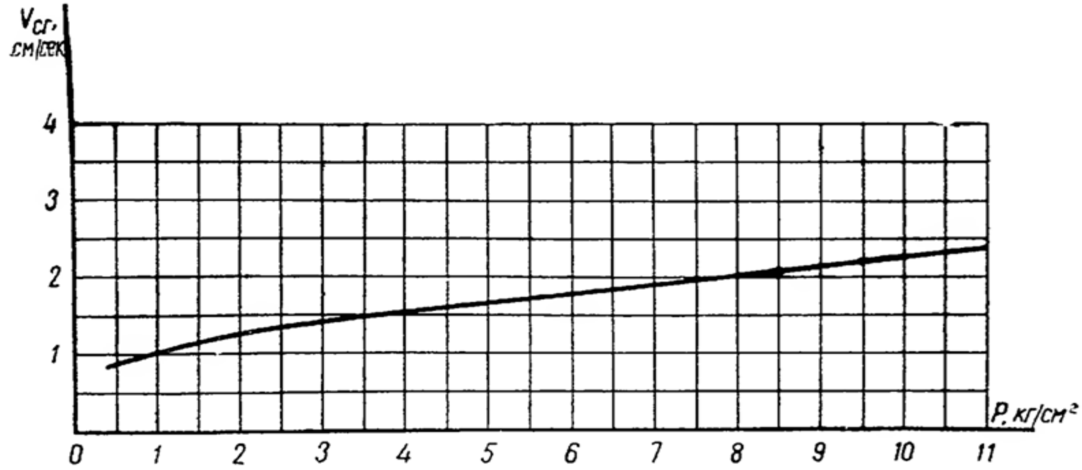


Fig. 13. Graph of the change in burning rate of fuel No. 1 depending on pressure in the combustion chamber for the DB-1-SM-6 Motor.

The graph shows a curve starting just below 1 cm/sec at 1 kg/cm^2, rising smoothly to about 1.6 cm/sec at 4 kg/cm^2, and then more steeply to approximately 3.8 cm/sec at 8 kg/cm^2.

Important core Concepts

1. *Specific Impulse (I_{sp}):* This is the most important efficiency metric for a rocket Motor. It's like the "mileage" of the Motor. A higher I_{sp} means the Motor produces more thrust for a longer time from each kilogram of fuel, which is why it's advantageous for reducing the model's launch weight.

2. *Characteristic Coefficient (K):* This is a key design parameter for solid rocket motors.

Ab_{max} (Max Burning Area): In a simple cartridge-like motor, this is the initial surface area of the fuel grain exposed for burning.

A_t (Nozzle Throat Area): This is the area of the narrowest part of the nozzle. It acts like a choke, determining how much gas can flow out and thus controlling the pressure inside the chamber.

The ratio $K = Ab_{max}/A_t$ essentially balances the gas generation rate (from burning) with the gas exhaust rate (through the nozzle). A specific K value (100 in this case) is required to achieve the desired chamber pressure (8 kg/cm^2) for a given fuel.

3. *Burning Rate Graph (Fig. 13):* This graph is crucial for prediction. It shows that the fuel burns faster as pressure increases. This relationship is fundamental for calculating how the Motor will behave over time. The data from this graph would be used to determine the initial burning rate at the target pressure of 8 kg/cm^2, which appears to be about 3.8 cm/sec.

Solution. First, it is necessary to draw the Motor casing, i.e., the 12-gauge (Jevelo) cartridge case, which makes it possible to visually follow the calculation process (Fig. 14). The Motor casing (cartridge) already has a ready-made nozzle (the hole for the Jevelo primer). The diameter of the hole is 5.5 mm, the case length is 70 mm, the inner diameter is 18.5 mm, the outer diameter is 20.5 mm, and the nozzle length is 9 mm.

The Motor's fuel grain must have a free space—a longitudinal channel—which makes it possible to bring the burning surface area of the fuel in the Motor to its maximum value. The shape of the channel is a truncated cone, whose smaller base corresponds to the size of the case hole (5.5 mm), and after calibration can be equal to 6 mm. The diameter of the upper base is 4 mm. The upper base is made somewhat smaller due to manufacturing considerations and safety techniques when removing the metal cone from the powder mass.

To determine the length of the cone (mandrel), initial data are required, which are obtained in the following order.

(A detailed diagram should be here showing the paper casing with dimensions like 70mm length, 18.5/20.5mm diameters, and the internal truncated cone fuel channel with bases of 6mm and 4mm.)

Concepts Explained

1. *Motor Casing*: The foundation of the motor is a standard 12-gauge paper shotgun shell ("Jevelo" brand). This is a common, readily available component used in amateur rocketry for its Strength and suitable size.

2. <u>*Nozzle:*</u> The existing primer hole in the base of the shotgun shell is utilized as the rocket Motor's nozzle. Its dimensions are critical for the motor's performance.

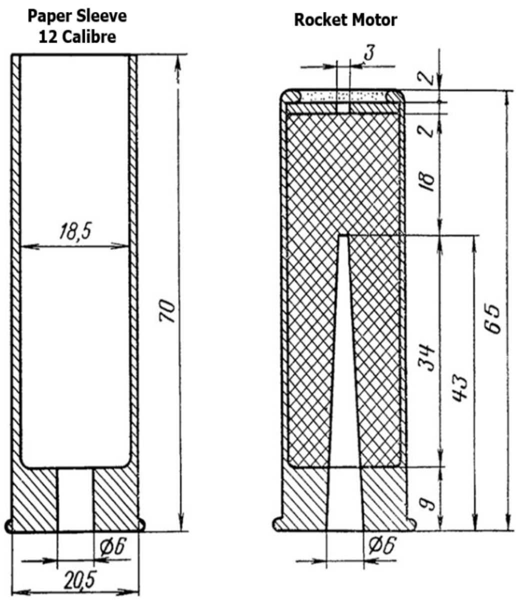


Fig. 14. Casing and DB-1-SM-6 Motor

$$Ab_{Max} = \pi \times D \times h_1 + \frac{\pi \times D^2}{4}$$

$h_1 = \frac{F_{max} - \frac{\pi D^2}{4}}{\pi D} = \frac{28.3 -- 3.14 \times 1.9^2}{3.14 \times 1.9} =$ $4.27\ cm.$

$$Ab_{max} = k \times F_{cr} = 100 \times 0.283 = 28.3\ cm^2$$

$$A_t = \frac{3.14 \times 0.6^2}{4} = 0.283\ cm^2;$$

$$K = 100$$

Diameter: 5.5 mm (can be calibrated to 6 mm)

Length: 9 mm

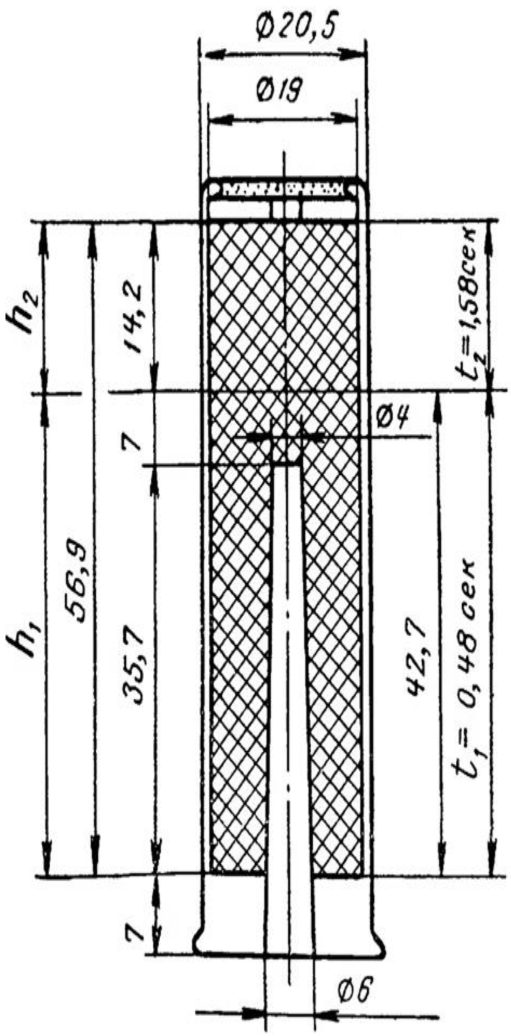
3. <u>*Propellant Grain & Perforation:*</u>

The solid propellant is cast into a shape with a central, longitudinal channel. This is standard practice in solid rocket motors.*Purpose of the Channel:* It significantly increases the initial burning surface area (Ab_max in the previous text). Instead of just burning from one end, the fuel burns from the entire internal surface of this channel, generating gas much more quickly.

<u>*Channel Shape - Truncated Cone:*</u> The channel is not a straight cylinder but a cone, wider at the nozzle end (6 mm) and narrower at the top (4 mm).

Reason 1 (Manufacturing)**:** A tapered mandrel (the mould that creates the channel) is easier to remove from the solidified fuel grain.

Reason 2 (Safety): A smaller top diameter might help control the initial burn rate and pressure buildup.



Reason 3 (Performance): This geometry helps control how the burning surface area changes as the fuel burns, which affects thrust over time.

Next Steps: finalize the design (specifically, the length of this conical channel), by performing a series of calculations using the initial data just described. These would involve the K coefficient, desired pressure, and the burning rate graph from the previous section to determine the correct grain geometry that will produce the intended thrust profile.

Using equation (15), the maximum possible burning area is determined:

where $A_t = \frac{\pi \times D^2}{4} = \frac{(3.14 \times 0.6^2)}{4}$ =*0.283 cm²* and K = 100.

The maximum burning area of the fuel (Fig. 15) is formed by pressing the fuel along the radial inner wall of the combustion chamber (case) and across the entire thickness of the fuel charge along its full length *h1*, i.e., it is given by

$$Ab_{max} = \pi D h_1 + \frac{\pi D^2}{4}$$

Substituting the values:

$$28.3 = \frac{(\pi \times 1.9 \times h_1 + (\pi \times 1.9^2)}{4}$$

we solve for h1:

$$h_1 = (\frac{\frac{(28.3-(3.14 \times 1.9^2)}{4}}{(3.14 \times 1.9)}) = 4.27 \text{ cm}$$

The internal diameter of the case is 18.5 mm. However, it must be considered that during the pressing of the fuel, the case is deformed: its diameter decreases to 19 mm (1.9 cm), and the height of the base (bottom) is reduced to 7 mm.

The average thickness of the fuel charge r is found from the expression: $r = \frac{D - \frac{d_1 + d_2}{2}}{2} = \frac{1.9 - 0.5}{5} = 0.7\ cm$

r = (D - (d1 + d2)/2) / 2 = (1.9 - 0.5) / 2 = 0.7 cm, (16)

where:

r is the average web thickness of the propellant grain (cm);

d1 is the diameter at the base of the cone (cm);

d2 is the diameter at the top of the cone (cm).

The length of the channel *l* is:

l = h1 - r = 4.27 - 0.7 = 3.57 cm.

The obtained dimensions are immediately transferred to the drawing (Fig. 15). The length of the mandrel *L* for pressing is:

L = l + r = 3.57 + 0.7 = 4.27 cm (where 0.7 cm is the height of the case base).

We proceed to determine the height of the charge...

Fig. 15. Scheme of fuel burning in the model rocket Motor DB-1-SM-6

(The diagram would show the case with a truncated conical channel, indicating dimensions D, d1, d2, h1, l, and r.)

Explanation of Concepts and Calculations

1. *Maximum Burning Area* (Ab_{max}):

This is the initial surface area of the fuel exposed for combustion. It is critical for determining the Motor's thrust profile.

It is calculated using the empirical relation $Ab_{max} = K \times A_t$ where:

K is a constant specific to the fuel (here, 100).

A_t is the cross-sectional area of the nozzle throat, which regulates gas flow and chamber pressure.

2. *Nozzle Throat Area* (A_t):

Calculated as the area of a circle with diameter *d = 0.6 cm:* $A_t = \pi \times (0.6)^2 / 4 \approx 0.283\ cm^2$.

3. *Propellant Grain Geometry:*

The propellant is pressed into a cylindrical case with a *truncated conical core.*

D is the internal diameter of the deformed case (1.9 cm).

<u>The burning area includes:</u>

- The lateral surface of the cylinder: $\pi \times D \times h_1$
- The forward end surface of the fuel: $\frac{\pi \times D^2}{4}$.

Solving for h_1 gives the length of the fuel grain that provides the required F_{max}.

4. *<u>Avg. Propellant Web Thickness (r):</u>*

The fuel burns radially inward from the case wall and outward from the channel surface.

The average thickness *r* is the radial distance between the case wall and the average channel diameter.

The channel is tapered: *d1 = 0.6 cm* (base near nozzle), *d2 = 0.4 cm* (top). The average channel diameter is *(0.6 + 0.4) / 2 = 0.5 cm.*

Thus, *<u>r = (1.9 - 0.5) / 2 = 0.7 cm.</u>*

5. *<u>Mandrel Design:</u>*

The mandrel forms the conical channel in the fuel grain.

Its length **L** is the sum of the channel length **l** and the base height **r**, ensuring the channel is properly formed during pressing.

This calculation ensures the fuel grain geometry produces the desired burning area, which directly influences the Motor's thrust and performance. The next step would be to determine the exact charge height to complete the design.

Continuation of the fuel grain description. This part of the fuel grain has no channel, i.e., it is pressed solid. Its purpose is to achieve a sustainer phase with preferably constant thrust after reaching the maximum thrust value. The height of the sustainer part of the grain must be strictly defined. The combustion of the sustainer part of the rocket propellant occurs in the Motor at a low pressure of 0.07–0.02 kg/cm^2. Based on this, from the graph in Fig. 13, we determine the burning rate of the sustainer part of the fuel: *U = 0.9 cm/sec.*

The height of the sustainer part $\mathbf{h_2}$ for a burning time of $t = 1.58$ *sec** will be:

$h_2 = 0.9 \times 1.58 = 1.42$ *cm.*

The total length of the combustion chamber h is the sum of the total length of the fuel grain h_1 and the length of the sustainer part h_2:

$h = h_1 + h_2 = 4.27 + 1.42 = 5.69$ *cm.*

Let's proceed to determine the weight of the fuel.

To do this, we calculate the volume of the combustion chamber and the volume of the free space (the channel). The difference between these volumes gives the volume of the fuel. Knowing the specific weight of the fuel, we determine its total weight.

Volume of the combustion chamber:

$$V_{Cham} = \frac{\pi D^2 h}{4} = \frac{3.14 \times 1.9^2 \times 5.69}{4} = 16.15\, cm^3$$

Volume of the free space (conical channel):

$V_{sp} = (1/3) \times \pi \times h \times (r_1^2 + r_1 \cdot r_2 + r_2^2) = (3.14 \cdot 3.57) / 3 \times (0.3^2 + 0.3 \times 0.2 + 0.2^2) = 0.7\ cm^3$,

where $r_1 = 0.3$ cm (radius of the base) and $r_2 = 0.2$ cm (radius of the top).

Volume of the propellant: $V_{perfor} = V_{cham} - V_{Sp} = 16.15 - 0.7 = 15.45\ cm^3$.

Weight of the fuel:

$M_{prop} = \gamma \times V_t = 1.35 \cdot 15.45 \approx 20\ g \approx 0.02\ kg.$

Using equation (12), we calculate the initial and maximum thrust of the Motor:

Initial thrust:

$F_{initial} = F_{Spec} \times \gamma \times \dot{r} \times Ab_{initial} = 30 \times 1.35 \times 0.9 \times 5.6 = 0.204\ kg,$

where $Ab_{initial}$ is the burning area of the free space (channel) at the start.

*Note: The initial thrust in practice will be somewhat lower due to low initial pressure in the combustion chamber and, consequently, a lower burning rate. Here, the value $\dot{r} = 0.9$

cm/sec is kept deliberately to simplify the calculation.

Maximum thrust:

$F_{max} = P_{avg} \times \gamma \times \dot{r} \times Ab_{max} = 30 \times 1.35 \times 2 \times 28.3 = 2.29$ *kg,*

where $Ab_{max} = 28.3\ cm^2$ is the maximum burning area.

The burning time t is equal to the flight time of the model on the sustainer phase, determined experimentally.

Explanation of Calculations

1. *Sustainer Grain Design:*

   The fuel grain is divided into two parts:

   Main part: Contains a conical channel for high initial Boost thrust.

   Sustainer part: Solid (no channel) to provide steady thrust after peak.

   The sustainer part burns at low pressure (0.07–0.02 kg/cm^2), with a constant burning rate ($\dot{r}$= 0.9 *cm/sec*) determined from the graph.

2. *Geometry Calculations:*

   Sustainer height h_2: Calculated as $h_2 = \dot{r} \cdot t = 0.9$ *cm/sec* $\times 1.58$ *sec* $= 1.42$ *cm.* This ensures the sustainer burns for the desired time.

   Total chamber length (h): $h = h_1 + h_2 = 4.27$ *cm* $+ 1.42$ *cm* $= 5.69$ *cm.*

   Volumes:

   Chamber volume $V_{Chamber}$: Treated as a cylinder with diameter $D = 1.9$ *cm* and height $h = 5.69$ *cm.*

   Free space volume V_{perf} The conical channel volume, calculated using the equation for a truncated cone with Length $r_1 = 0.3$ *cm,* $r_2 = 0.2$ *cm,* and height 3.57 *cm* (the channel length).

   Propellant volume V_t: $V_k - V_{sp} = 16.15\ cm^3 - 0.7\ cm^3 = 15.45\ cm^3$.

Propellant weight $M_{prop}\ \gamma \times V_{prop}$ · $M_{pro} = 1.35\ g/cm^3 \times 15.45\ cm^3 \approx 20$ *g.*

3. Thrust Calculations:

Equation (12): F= $I_{sp} \times \gamma \times \dot{r} \times A_b$, where:

$I_{\_sp}$ = *30 kg·sec/kg* (specific impulse).

γ = *1.35 g/cm³* (specific weight).

$\dot{r}$= burning rate (cm/sec).

A_b = burning area (cm²).

Initial thrust: *Uses U = 0.9 cm/sec and* $F_{initial}$ *= 5.6 cm²* (area of the channel at ignition).
Result*: 0.204 kg.*

Maximum thrust: Uses $\dot{r}$ *= 2 cm/sec* (from graph at high pressure) and F_{max} *= 28.3 cm²* (maximum burning area). Result: *2.29 kg.*

4. *Unit Consistency Note:*

The thrust equation implicitly includes a unit conversion factor of *1/1000* to convert grams to kilograms, as γ is given in g/cm³. Thus, the product $F_{sp} \times \gamma \times \dot{r} \times A_b$ is divided by 1000 to get thrust in kg.

This calculation ensures the Motor design meets performance requirements, with a high-thrust initial phase and a controlled sustainer phase. The values are derived from empirical data and geometric parameters.

The propellant burn rate$\dot{r} = 2\,cm/sec$ is determined from the graph in Fig. 13. This rate corresponds to a combustion chamber pressure of $8\,kg/cm^2$, as given in the problem conditions.

The Motor operating time t is the sum of the main time t_1 and the additional time t_2 (sustainer phase):

$$t_1 = \frac{0.7}{1.45} = 0.48\,sec, t_2 = \frac{1.42}{0.9} = 1.58\,sec, t = t_1 + t_2 = 2.06\,sec.$$

Using equation (14), we find the total impulse of the rocket Motor:

Using equation (11), we calculate the average thrust of the Motor:

$$F_{avg} = \frac{I_s}{t} = \frac{0.6}{2.06} = 0.291\,kg.$$

The approximate maximum pressure in the combustion chamber is found using equation (17):

$$P_{c_{max}} = \frac{F_{max\,thrust}}{A_t} = \frac{2.29}{0.283} = 8.1\,kg/cm^2.$$

After determining the approximate maximum pressure, it is necessary to check the strength Mproph of the case wall to ensure the reliability of the combustion chamber. A safety margin must also be provided for potential pressure increases on very hot days when the burning rate of the fuel exceeds the calculated value. We take a safety factor $n = 2$.

The wall thickness of the case is determined by the equation:

$$\delta = \frac{P_{max} \cdot D \cdot n}{\sigma_b},$$

where:

- δ is the wall thickness of the case (cm);
- P_{max} is the maximum pressure in the combustion chamber (kg/cm^2);
- D is the internal diameter of the case (cm);
- n is the safety factor;
- σ_b is the ultimate tensile strength Mproph of the material (kg/cm^2).

The ultimate tensile strength Mproph of the paper from which the 12-gauge cardboard case is made averages $490\, kg/cm^2$. Good grades of kraft paper have a similar strength Mproph. Substituting the data into equation (18), we get:

$$\delta = \frac{8.1 \cdot 1.9 \cdot 2}{490} = 0.0627\, cm$$
$$= 0.63\, mm.$$

Explanation of Calculations

1. *Burning Rate and Operating Time*:

   The burning rate $\dot{r} = 2\, cm/sec$ is derived from experimental data (Fig. 13) at a chamber pressure of $8\, kg/cm^2$.

   The total operating time $t = 2.06\, sec$ is split into:

- Boost Phase ($t_1 = 0.48\, sec$): The time to burn through the fuel thickness in the high-thrust phase.

  Sustainer phase ($t_2 = 1.58\, sec$): The time for the steady-thrust phase, calculated based on the sustainer grain height $h_2 = 1.42\, cm$ and burning rate $\dot{r} = 0.9\, cm/sec$.

2. *Total Impulse and Average Thrust:*

Total impulse: This is the product of specific impulse and fuel weight $G_t = 0.02\, kg$. It represents the total momentum imparted by the Motor.

Average thrust $F_{avg} = 0.291\,kg$: This is the total impulse divided by the burn time, giving the constant thrust that would produce the same impulse.

3. *Maximum Pressure Estimation:*

Using the simplified equation $P_{max} = \frac{P_{max\,thrust}}{f_{\kappa p}}$, where:

$P_{max\,thrust} = 2.29\,kg$ is the maximum thrust,

$A_t = 0.283\,cm^2$ is the nozzle throat area.

This yields $P_{max} = 8.1\,kg/cm^2$, consistent with the design assumption of $8\,kg/cm^2$.

4. *Wall Thickness Check:*

The wall thickness $\delta = 0.63\,mm$ is calculated to withstand the maximum pressure with a safety factor $n = 2$.

The equation $\delta = \frac{P_{max} \cdot D \cdot n}{\sigma_b}$ is a simplified thin-wall pressure vessel equation, where the hoop stress is approximated as $\sigma = \frac{P \cdot D}{2\delta}$. Rearranging for δ with a safety factor gives $\delta = \frac{P \cdot D \cdot n}{2\sigma_b}$, but the text uses $\delta = \frac{P \cdot D \cdot n}{\sigma_b}$, effectively doubling the required thickness. This conservative approach ensures safety given material uncertainties and varying operating conditions.

Important Equations

Total Impulse: $I_{total} = F_{sp} \times M_{prop}$

Average Thrust: $F_{avg} = \frac{I_{sp}}{t}$

Maximum Pressure: $P_{max} = \frac{P_{max\,thrust}}{A_t}$

Wall Thickness: $\delta = \frac{P_{max} \cdot D \cdot n}{\sigma_b}$

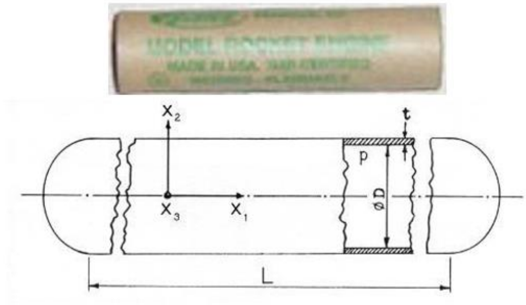
These calculations ensure the Motor design is both performant and safe, with margins for real-world variability.

The cardboard case, with an outer diameter of 20.5 mm and an inner diameter (after fuel pressing) of 19 mm, has a wall thickness of:

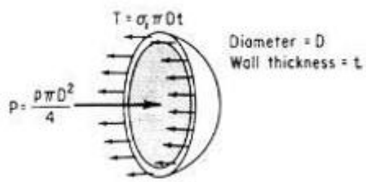
$$\delta_{actual} = \frac{20.5 - 19}{2} = 0.75\,mm.$$

The actual safety factor is $n_{actual} = 2.4$, i.e., higher than the calculated one.

The closure (bulkhead) in model Motors of this type is round with two holes, each 2 mm in diameter. It is pressed in simultaneously with the fuel. It is made from strong grades of cardboard, with a thickness of not less than 2 mm.



Model Rocket Motor Catriage - closed cylindrical vessel subjected to an internal pressure p,



A free-body diagram of a portion of the cylinder cut about a circumferential line.

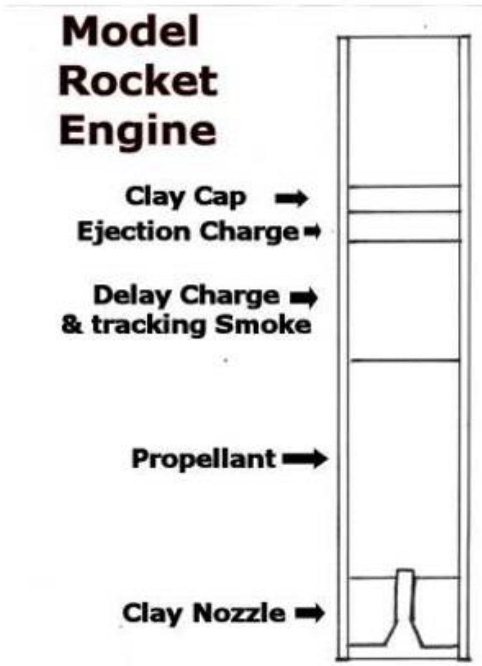


Fig: sliding-engine-into-rocket

3. MODEL ROCKET MOTORS USING SOLID PROPELLANTS (SRMs)

Commercially produced model rocket Motors of the DB* type are intended for models rockets, RC Aeromodels. The characteristics of the produced Motors comply with FAI (Fédération Aéronautique Internationale) standards. Each Motor is marked by the manufacturer. The designation indicates the Motor's name, fuel type number, purpose (launch or sustainer), and its total impulse.

For example, the designation *DB-3-SM-10* means:

1. *Motor type: DB*
2. *Propellant number: 3*
3. *SM: Launch (Boost) and Sustainer*
4. *Total impulse: 10 Newton-seconds (~1 kg·sec)*

DB-type Motors differ by their fuel number, and consequently, by their specific impulse and total impulse. They come in a wide range of thrust levels and burn times. Therefore, each Motor comes with a data sheet providing its characteristics and intended use.

The industrial manufacturing of model SRMs fully complies

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in flight. Cases where drilling out the channel led to the ignition of the fuel mixture and serious burns are not uncommon.

The reason for, for example, drilling out the channel in a fuel grain is the desire to increase the Motor's initial thrust, and consequently, to obtain greater acceleration and a higher initial velocity for the model rocket. In this case, the model rocket might indeed fly higher if the thrust-to-weight ratio is favourable. But what changes occur when the channel is drilled out?

> *First,* the thrust increases sharply, and consequently, the pressure inside the Motor rises.
>
> The specific impulse changes, and hence the total impulse changes as well, which is prohibited by the "FAI Rules."
>
> Furthermore, the Motor walls, not designed for high pressure, can fail—i.e., an explosion will occur.

§ 1. MODEL ROCKET MOTOR DB-51-S-10

The model rocket Motor DB-51-S-10 is a *launch Motor* and is intended *only for the lower stages* of model rockets (Fig. 16).

To use this Motor in single-stage model rockets or on the upper (final) stages, a standard delay element with a specific burning time, say 7 seconds, must be inserted into it.

In a 12-gauge hunting cartridge case.

In a tube with a ceramic nozzle.

Then, the ejection charge for the parachute will activate 7 seconds after the rocket reaches its maximum velocity and begins to lose it, while coasting by inertia. That is, the parachute ejection will occur approximately when the model rocket's velocity is practically zero*.

The Motor casing is a paper tube with a pressed-in ceramic or plastic nozzle. 12-gauge paper hunting cartridge cases (Jevelo) can be used as the casing (Fig. 16, a), but their use is recommended only in exceptional cases, as the thickness of the case walls does not have a sufficient safety margin, and if the pressing regime is not followed, cases of burn-through can occur.

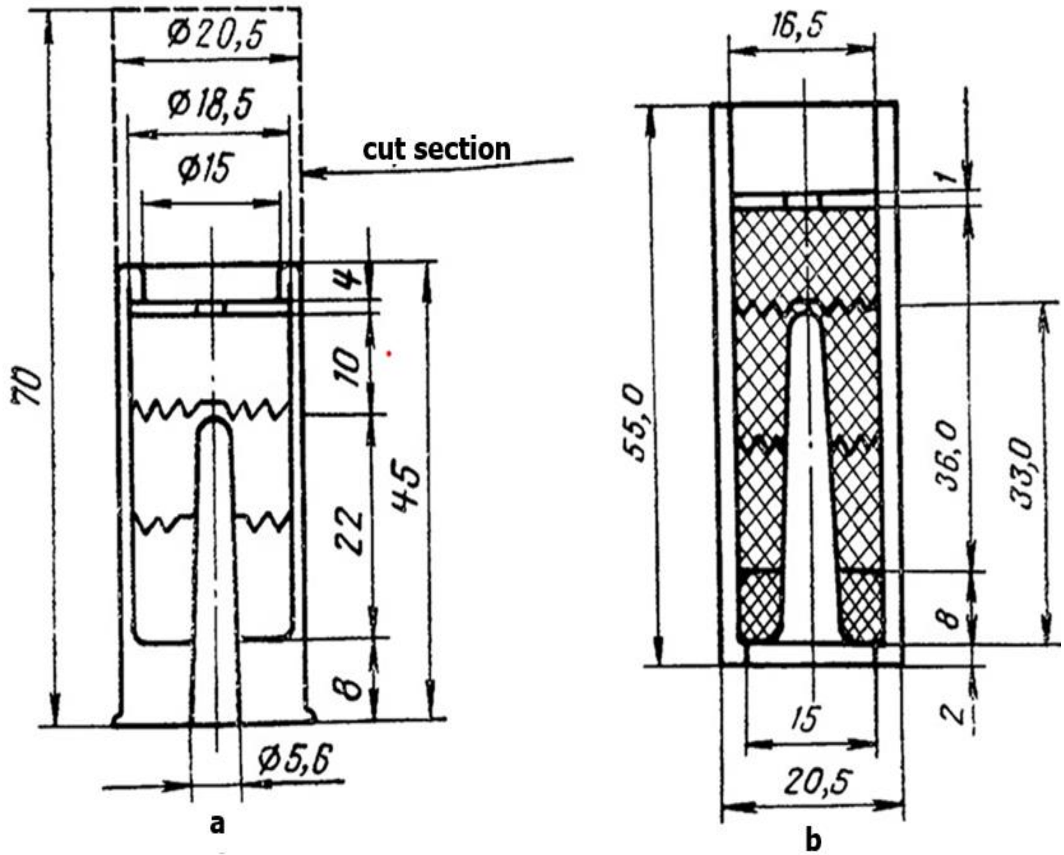


Fig. 16. Model rocket Motor DB-51-S-10:

The amateur/craft production method for such Motors is ruled out for a number of reasons, the most important of which depend on the precision of the specific pressure during fuel pressing, the degree of component fineness, humidity, and other factors. Exceeding the casing's Strength limit is especially possible in hot weather. This is why industrially manufactured Motors are guaranteed to operate normally with temperature variations from -40 to +40°C (referring to the air temperature at launch).

The above refers to Motors of the DB-1-SM-6 type. As for other Motors with more complex fuel compositions, changing the channel shape invariably leads to accidents and is penalised according to "FAI Rules".

The manufacture of Motors requires knowledge of the technological process, special equipment, tools, adherence to safety protocols, and sufficient experience. Only under factory conditions is it possible to obtain quality Motors that meet the required technical specifications. Let's consider, for example, the manufacturing process of the DB-51-S-10 Motor.

First, the tubes are inspected, and defective ones are rejected. Only high-quality tubes without any damage go into production. Dimensions are checked with limit gauges. The outside of the tubes is waxed, and the inside is coated with graphite for manufacturing/processing reasons.

The fuel is a mixture of the following components:

a) Potassium Nitrate (KNO_3) - 70%

b) Resin SM-211 - 10%

c) Powdered Magnesium (Mg) - 20% *Separately:*

Potassium nitrate and magnesium powder are ground and sieved. The resin is dissolved in a solvent, acquiring a varnish-like appearance.

The weighed magnesium is poured with the dissolved resin and mixed with it, after which the weighed nitrate is added.

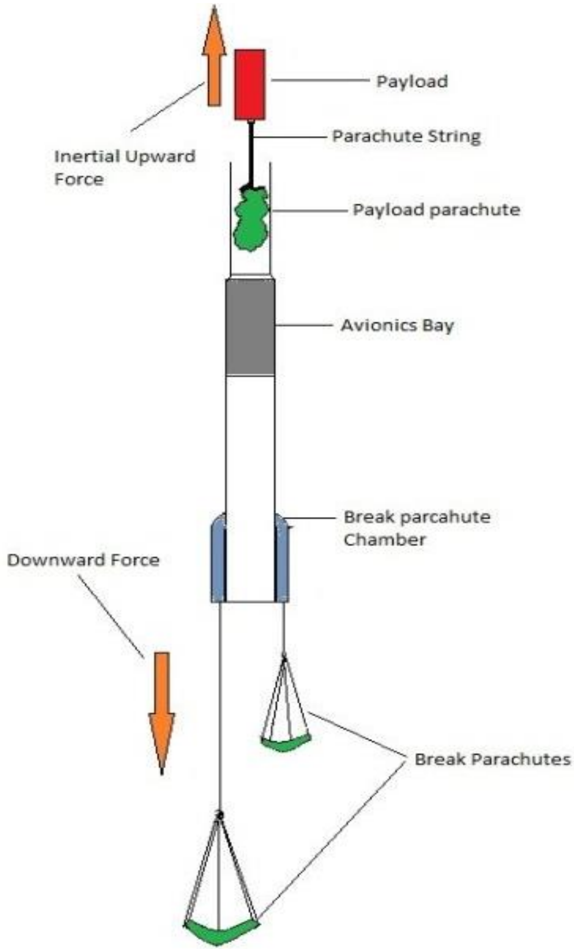
*Practice has shown that S2 class model rockets with DB-51-S-10 Motors coast on the passive segment for approximately 4 seconds. (Editor's note)

Explanation & Key Points

1. *Delay Element Function*: The text explains the practical function of the delay element. It allows the rocket to coast after motor burnout, deploying the parachute at apogee (when velocity is zero) to prevent deployment under high-speed, aerodynamic stress. The editor's note adds real-world data, showing the actual coast time for a specific rocket class is about 4 seconds, suggesting the 7-second delay might be a standard, conservative option.

2. *Casing and Safety:*

Industrial paper tubes are preferred over hunting cartridge cases due to



better, more controlled Strength properties.

It strongly reinforces that *amateur manufacturing is not feasible* due to critical, precisely controlled factors like pressing pressure, particle size, and humidity. Failure to control these leads to catastrophic failures like "burn-through."

Industrial Motors are rated for a wide temperature range (-40°C to +40°C), a key safety and reliability guarantee.

3. *Fuel Composition and Manufacturing Process (DB-51-S-10):*

The fuel is a composite propellant, not a conventional pyrotechnic black powder.

4. *Composition:*

Potassium Nitrate (KNO_3): The oxidizer (70%).

Magnesium (Mg): The metal fuel (20%). This increases energy density and burning temperature.

Resin *SM-211*: Likely a synthetic resin acting as the fuel and binder (10%), holding the mixture together.

5. *Process:* The description highlights the precision required: component preparation (grinding, sieving), dissolving the binder, and a specific mixing sequence (likely to ensure safety and homogeneity). This underscores why factory production is essential.

The mixture is again thoroughly mixed and sent for drying, after which it is ground and sieved. The finished composition goes to the laboratory, and then, if the test result is positive, to pressing.

Pressing is done in two stages: the first stage is pressing the pellets, and the second stage is loading the tube.

Pellets are pressed using special tooling: a die, a punch, and a base plate. The weight of each pellet is about *5g.* The specific pressure during pressing does not exceed *900 kg/cm²*. Pellets are made in two types: with a central hole and without a hole.

For loading, the tube is inserted into a die. The pellets are pressed into it using a set of punches.

First, a ceramic insert (nozzle) is inserted and pressed into the tube. Then, the fuel pellets *with* holes are pressed. Next, a pellet *without* a hole is placed, and a wad (nozzle closure) with a central hole is placed on top of it. This pellet is pressed together with the wad. A specific pressure of 1600 kg/cm² is required for this pressing. But even in factory conditions, it is difficult to ensure the stability of the specific pressure, which inevitably, though slightly, affects the Motor's characteristics.

§ 2. MODEL ROCKET MOTOR DB-3-SM-10

The model rocket Motor DB-3-SM-10 is combined (launch and sustainer). The Motor can be used both on single-stage model rockets and on the upper stages of multi-stage model rockets. DB-3 type Motors come in a fairly wide range of thrust and total impulse *(10; 5; 2.5; 1.25 N·sec).*

Amateur production methods are completely ruled out, primarily because their manufacture requires strict adherence to safety regulations.

The technology for producing DB-3 type model Motors is almost no different from the technology for DB-51 type Motors.

The fuel for the DB-3 series Motors is *black hunting powder,* into which a lacquer (binder) has been introduced. The number of pellets for the DB-3-SM-10 Motor is four; the weight of each pellet is 5.5 g. The pellets are pressed with a specific pressure of no more than 800 kg/cm², and they are pressed into the casing with a specific pressure of 1600 kg/cm². The total impulse of DB-3 type Motors depends on the number of pellets pressed in. So, for example:

One pellet is the DB-3-SM-2.5 Motor.

Two pellets is the DB-3-SM-5 Motor.

Four pellets is the DB-3-SM-10 Motor (Fig. 19, 18, and 17).

Summary

1. *Complex, Industrial Manufacturing:* we emphasize that these motors are not simple fireworks. Their production involves a precise, multi-stage process (mixing, drying, grinding, pressing) with strict quality control (laboratory testing) and requires specialized, high-pressure tooling.

2. *Precise Fuel Geometry:* The fuel grain is built from individually pressed pellets with specific geometries (with and without a central hole). This architecture carefully controls the initial burning surface area to achieve the desired thrust profile (high initial thrust from the perforated pellets, followed by a sustainer phase from the end-burning pellet).

3. *Safety is Paramount:* The document repeatedly stresses that amateur ("cottage industry") production is "absolutely prohibited" and "ruled out" due to the extreme dangers involved and the need for strict safety protocols, which can only be guaranteed in a commercial production factory quality standard.

4. *Motor Family (DB-3 Series):* The DB-3-SM-10 is part of a family of Motors that use a modified black powder fuel (mixed with a lacquer binder). Different impulse classes (e.g., 2.5, 5, 10 N·sec) are created simply by loading a different number of standardized fuel pellets into the same casing type. This is a classic approach for creating a product line.

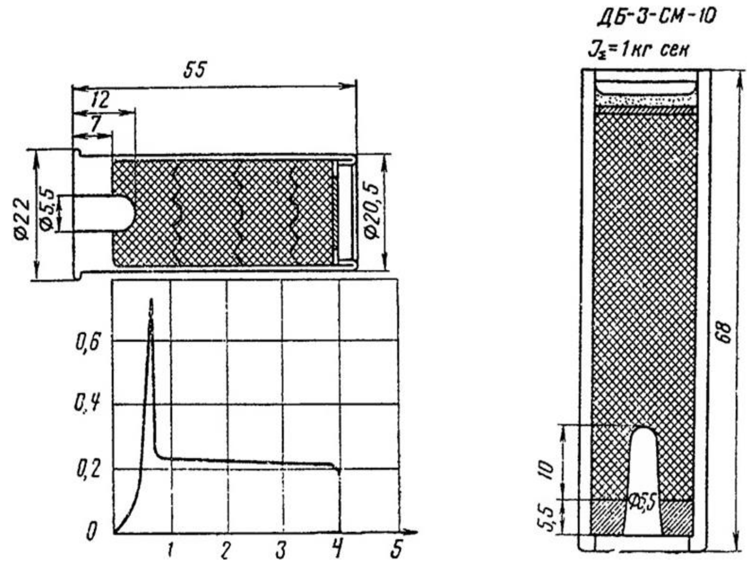


Figure 17. Model Rocket Motor DB-3-SM-10.
(The diagram shows a cross-section of the Motor with a thrust-time curve below it.)

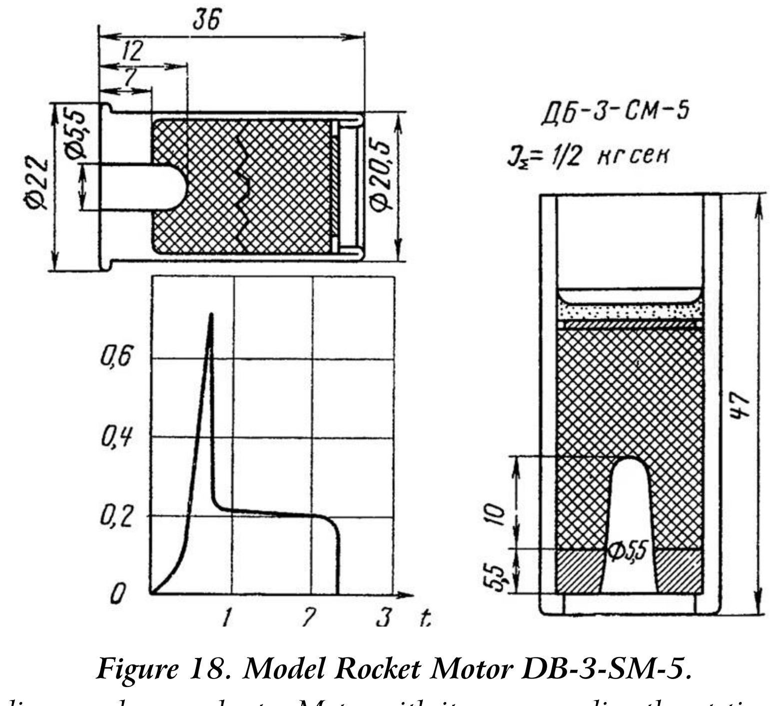


Figure 18. Model Rocket Motor DB-3-SM-5.
(This diagram shows a shorter Motor with its corresponding thrust-time curve.)

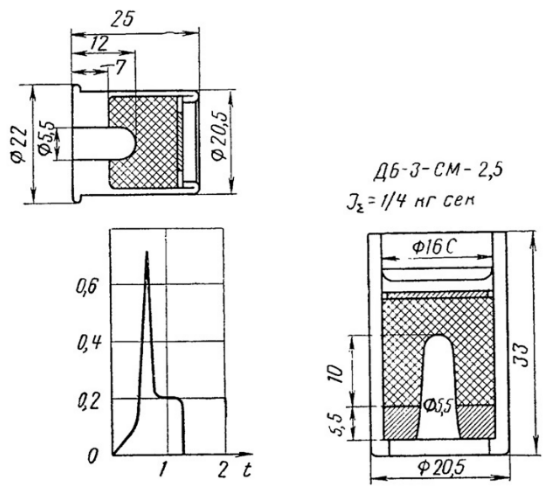


Figure 19. Model Rocket Motor DB-3-SM-2.5.

DB-3-SM-5 I~1/2 kg·sec; DB-3-SM-10; I~1 kg·sec; *(This text confirms that the total impulse (I) of the DB-3-SM-5 is approximately half that of the DB-3-SM-10.)*

The total impulse of the Motor depends not only on the quantity and weight of the pellets but also on the uniform density throughout the pellets. The manual method of manufacturing Motors does not provide high pressing quality, resulting in a large scatter of characteristics. For example, DB-1-SM-6 Motors have low quality due to their amateur/craft production method. Even the most careful manufacture of these Motors only slightly improves their quality.

§ 3. MICRO-MOTORS

The smallest Motors of the DB-3 and DB-51 types are of great interest. These are the DB-3-SM-1.25 Motor (Fig. 20) and the DB-51-CM-2.5 Motor (Fig. 21). They weigh only 5 g each, with a diameter of 12 mm and a length of 40 mm.

The specific impulse of the first Motor is 45.5 kg·sec/kg, and of the second, 70 kg·sec/kg. The launch weight of a model rocket with such an Motor is only 15 g. A model with the DB-3-SM-1.25 Motor can reach an altitude of 180 m. The launch of such models was demonstrated at the second All-Union competition of rocket modellers in the city of Kaluga. Micro-Motors with a diameter of 12 mm have a strong paper...

(The text is cut off)

(The diagram shows an even smaller Motor, consistent with the series, indicating a total impulse of I ~ 1/4 kg·sec.)

Summary

1. **Quality and Manufacturing:** The text reiterates a crucial point: consistent performance (total impulse) requires industrial manufacturing. Amateur methods cannot achieve the uniform fuel density needed, leading to unpredictable Motor behaviour. The DB-1-SM-6 is cited as a lower-quality example due to its craft production.
2. *Micro-Motors Introduced:*

   This section introduces the smallest Motors in the product line: the *DB-3-SM-1.25 and DB-51-CM-2.5.*

   They are extremely lightweight (5 g) and miniaturized (12mm diameter, 40mm length).
3. *Performance of Micro-Motors:*

   DB-3-SM-1.25: Specific Impulse (I_{sp}) = 45.5 sec. This is a black-powder based Motor.

   DB-51-CM-2.5: Specific Impulse (I_{sp}) = 70 sec. This is the more advanced composite propellant Motor (with Magnesium), offering significantly higher efficiency.

   A model rocket weighing only 15 grams at launch could reach an estimated altitude of *180 meters* with the less powerful *DB-3-SM-1.25 Motor,* showcasing the impressive performance for their size.
4. *Historical Context*: Their use was demonstrated at a major national competition in Kaluga, confirming they were recognized and used in high-level model rocketry.

   This section highlights the sophistication of the Soviet model rocket Motor program, extending down to very small, high-performance micro-Motors designed for specific, lightweight rocket models.

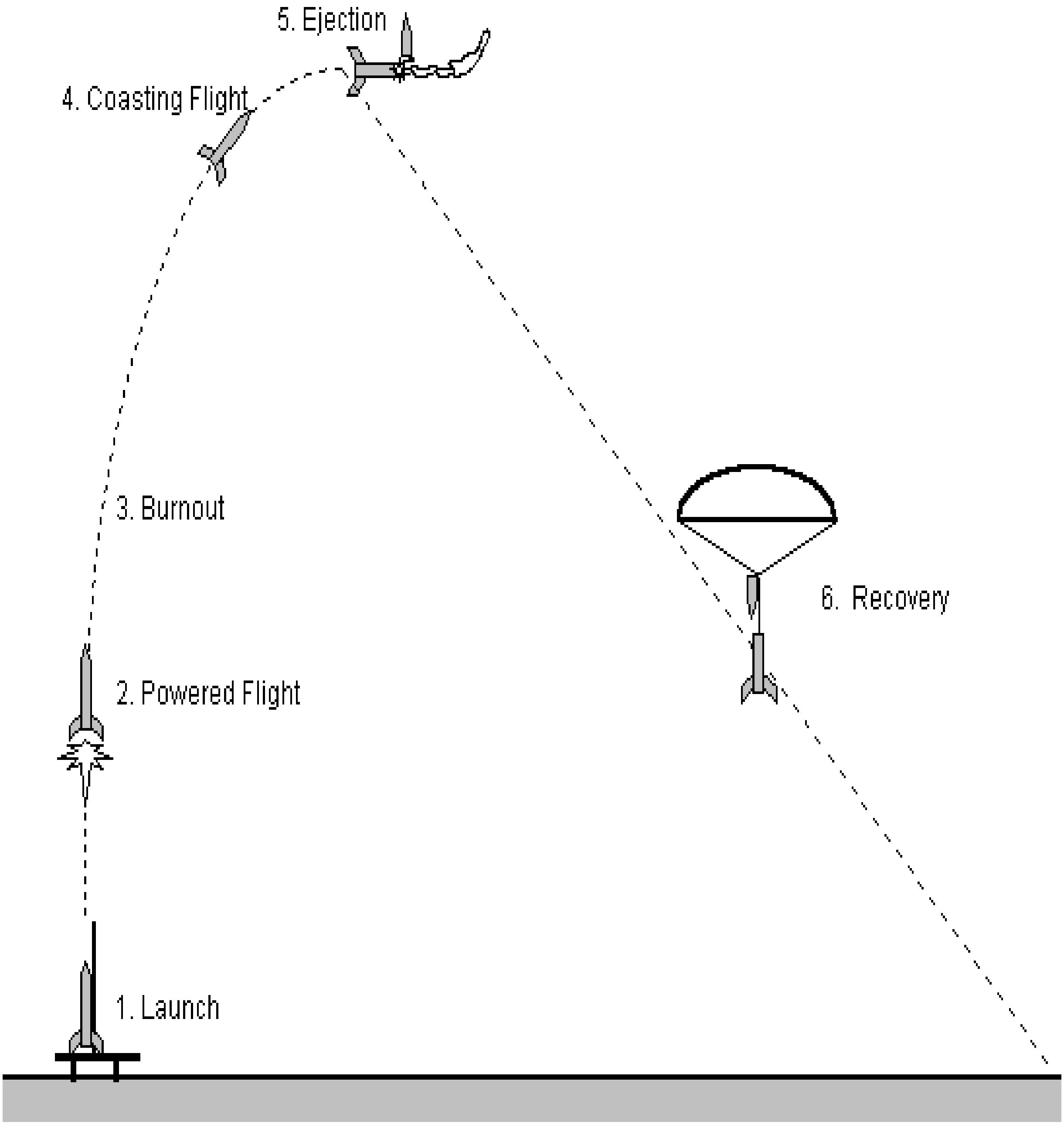


Fig. 20. Model Rocket flight with Motor DB-3-SM-1.25

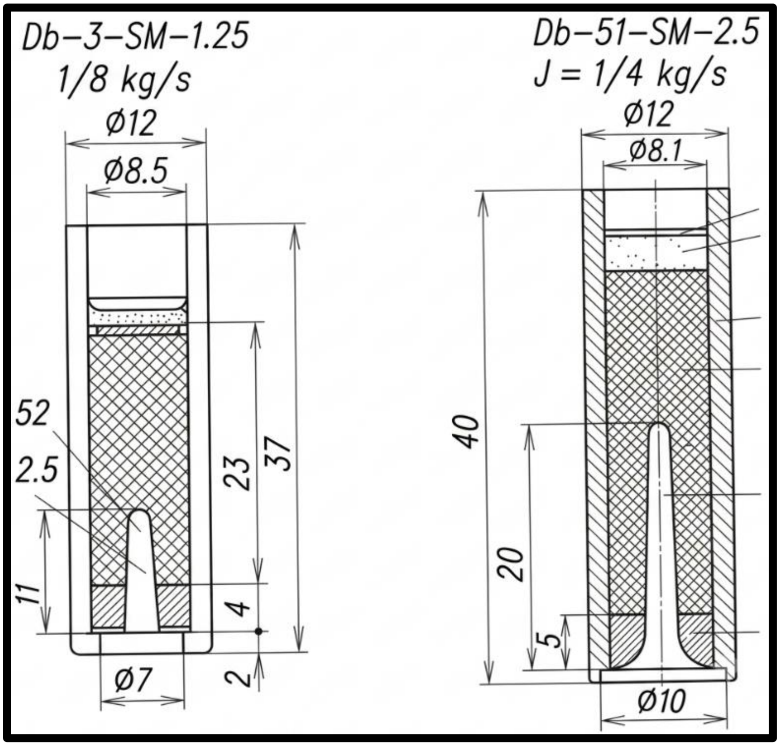


Fig. 21. Model Rocket Motor DB-51-CM-2.5

Caption: I ≈ 1/4 kg·sec

Diagram Labels:

Nozzle

Propellant grain channel

Propellant grain

Casing

Ejection charge

Base (closure)

Dimensions: Ø12, Ø8.1, Ø2.5, Ø7 (diameters), 40, 20 (Length in mm).

...a strong paper shell-tube with a ceramic nozzle pressed into it. The 2 mm thickness of the tube provides a sufficient safety margin.

Micro-Motors of the DB-3 and DB-51 types can be used on a wide variety of models. These Motors allow for the creation of flying models of rocket planes of the "Sparrow" and "Swift" classes, as well as scale models of rockets of classes K-0 and K-1. However, for now, due to the lack of domestic micro-Motors, these models exist only in the "FAI Rules".

4. TESTING OF MODEL SOLID ROCKET MOTORS (CHARACTERIZATION)

Testing rocket Motors for models is not only an interesting but also a useful activity. Here, the secrets of rocket Motor fuel combustion are learned practically. Testing makes it possible to check the Motor's operating mode...

Why Test Rocket Motors?

Testing model rocket Motors is not just an interesting activity; it's a vital and useful one. It serves as a practical, hands-on method for understanding the fundamental principles of rocket propulsion and combustion. For hobbyists and students, static firing tests are the primary way to verify an Motor's performance, checking its operating mode and ensuring its reliability before it ever takes flight. This scientific approach bridges the gap between theory and real-world application.

Static Firing Tests for Model Rocket Motors

Testing model rocket Motors, often through *static firing tests,* is the practical method used to verify Motor's performance, reliability, and safety before flight. This hands-on, scientific approach allows enthusiasts to understand the fundamental principles of rocket propulsion and confirm that the motor's thrust profile matches the manufacturer's specifications.

The Testing Setup

In professional and high-level hobbyist settings, a static firing test is performed by securing the rocket motor to *a test stand* (Fernandes et al., 2022). A crucial component of this setup is the *load cell*, a force sensor that measures the instantaneous thrust generated by the motor during its burn (Fernandes et al., 2022).

The important steps in the measurement process:

Securing the Motor: The rocket motor is firmly secured to the test stand, ensuring the force generated is directed solely against the load cell.

Data Acquisition: As the motor ignites and burns, the load cell measures the thrust force (F) at predetermined time intervals Δt This raw data is converted from electrical voltage into Newtons or pounds using a calibrated data acquisition system (Fernandes et al., 2022).

Generating the Thrust Curve: The acquired data is used to plot a graph known as the "thrust versus burn time" curve. This curve is the most essential output of the test, showing how the Motor's power changes over its operating life.

Performance Metric: Total Impulse

The most important single value derived from the static firing test is the *Total* Impulse (I_t).

Definition: Total Impulse is a measure of the Motor's total performance—the overall 'push' the motor provides over its entire burn duration. It incorporates both the magnitude of the thrust and the length of time the thrust is applied (Fernandes et al., 2022).

Calculation: Mathematically, Total Impulse is calculated as the *area under the thrust curve* (Chew et al., 2023). It represents the integral of the thrust force over the total burn time:

$$I_t = \int_{t_0}^{t_1} F \cdot dt$$

A higher total impulse means the Motor can impart more momentum to the rocket, directly influencing how high the rocket can be launched (Fernandes et al., 2022).

Where:

$I_t$is the *Total Impulse* (typically measured in *Newton-seconds (N·s*) or *pound-seconds (lbf·s)).*

$F$is the *instantaneous Thrust force.*

$t_b - t_0$is the *total Burn Time*.

Your notes provide impulse values in both units, which is helpful:

- **D8-3-SM-1.25:** ~0.125 kg·sec *(approx. 1.23 N·s)*
- **D8-51-CM-2.5:** ~0.25 kg·sec *(approx. 2.45 N·s)*

Summary

1. *Micro-Motor Specifications:*

DB-3-SM-1.25: The smallest in the DB-3 family, with a total impulse of ~0.125 kg·sec (1.23 N·s).

DB-51-CM-2.5: A small, composite-propellant Motor with a higher total impulse of ~0.25 kg·sec (2.45 N·s). The cutaway diagram (Fig. 21) is valuable as it clearly labels all key components: the nozzle, propellant grain with its channel, casing, ejection charge, and base.

2. *Construction and Safety:* The micro-Motors use a strong paper tube with a 2 mm wall thickness, deemed sufficient for safety. A pressed-in ceramic nozzle is specified, which is essential for handling the high temperatures.
3. *Application and Historical Context:*

These micro Motors were intended for specific, lightweight model classes like rocket planes ("Sparrow", "Swift") and scale models (K-0, K-1).

The text notes a gap between the regulations (FAI Rules) and availability, stating that a lack of domestically produced micro-Motors limited the practical existence of these model classes at the time, implying they were more theoretical than common.

4. *Introduction to Testing (Chapter IV):*

The manual transitions to the importance of testing rocket motors.

It frames testing not just as a hobbyist activity but as a practical way to understand rocket propulsion principles and verify an Motor's performance and reliability. This emphasises a hands-on, scientific approach to the hobby.

Micro-Engine Specifications

The manual introduces two key micro-engines from the DB-3 family, each with distinct performance characteristics. Total Impulse is the key metric, measuring the total 'push' an engine provides over its entire burn.

DB-3-SM-1.25	DB-51-CM-2.5
1.23 N·s	2.45 N·s
Total Impulse	Total Impulse

Anatomy of a Micro-Engine: DB-51-CM-2.5

The manual highlights a cutaway diagram (Fig. 21) as particularly valuable. This diagram, shows the essential components of the composite-propellant engine, all housed within a strong paper casing.

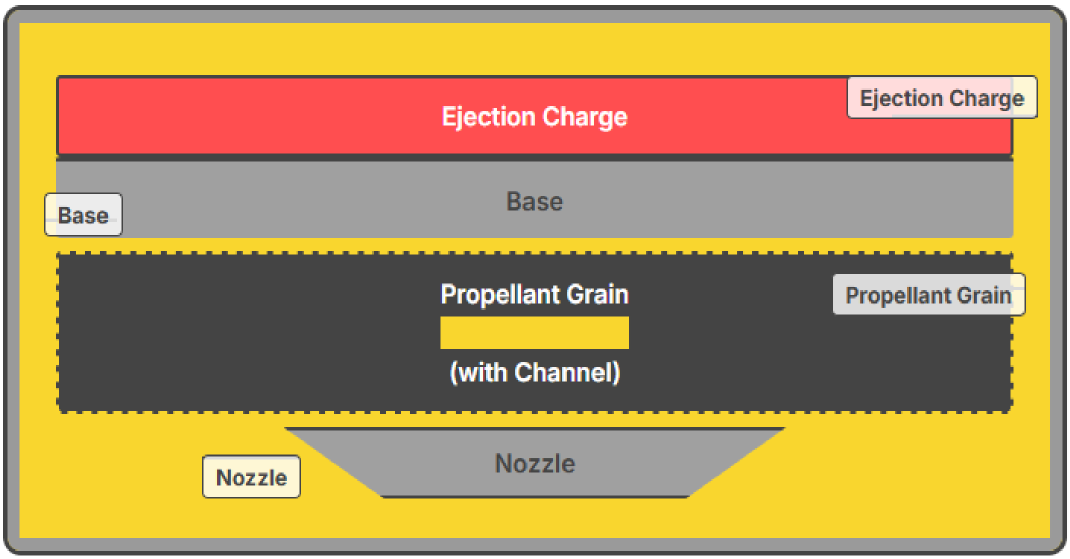
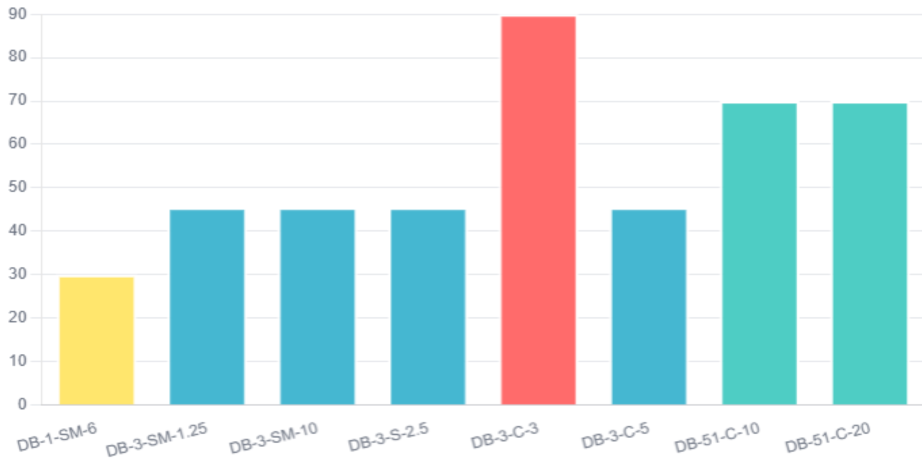


Table 1: Characteristics of DB-Type Motors for Model Rockets

No.	Motor Type	Length L (mm)	Outer Diameter d (mm)	Motor Weight G (g)	Fuel Weight G_t (g)	Total Impulse $I\Sigma$ (N·sec)	Specific Impulse P_{sp} (kg·sec/kg)	Max Thrust P_{max} (kg)	Avg. Thrust P_{av} (kg)	Burn Time t (sec)
1	**DB-1-SM-6**	65	20.5	30	20	6	30	2.3	0.291	2.1
2	**DB-3-SM-1.25**	40	12	5	2.8	1.25	45.5	1.3	0.125	1
3	**DB-3-SM-10**	55	20.5	31	22	10	45.5	0.75	0.25	3.3
4	**DB-3-S-2.5**	25	20.5	13.5	5.5	2.5	45.5	0.72	0.192	1.3
5	**DB-3-C-3**	40	12	5	2.8	3	90*	0.6	0.3	4
6	**DB-3-C-5**	36	20.5	-	-	5	45.5	0.7	0.217	2.3
7	**DB-51-C-10**	40	20.5	23	14.3	10	70	2.2	0.65	2
8	**DB-51-C-20**	-	20.5	28.6	20	20	70	2.3	2	2.6
9	**DB-51-CM-2.5**	40	12	6						

Key Performance: Specific Impulse (Isp)

Specific Impulse (Isp) is the most important metric for engine efficiency, measuring thrust per unit of fuel consumed. The data clearly shows three distinct tiers: the baseline DB-1, the consistent DB-3 black powder series, and the high-performance DB-51 composite family. Note the single DB-3-C-3 outlier, whose 90s Isp is likely a typo in the original data.



**Note*: The specific impulse of 90 sec for the DB-3-C-3 is exceptionally high for a black-powder type Motor and may be a typo or refer to a specialised equationtion. The value 45.5 sec is more consistent with the other DB-3 Motors.*

Summary

This table provides a fantastic overview of the Soviet model rocket Motor lineup, revealing clear design families and performance trends.

1. *Motor Type Designation Decoded:*

The naming convention DB-X-YY-ZZ is consistent:

a) *DB-X:* The fuel type series (e.g., 1, 3, 51).
b) *YY*: The thrust profile.
c) **S:** Booster / Starter high thrust for liftoff.
d) *SM:* Booster Sustainer Motor- Boost-sustain thrust profile.
e) *ZZ:* The total impulse in Newton-seconds (e.g., 10, 2.5).

2. *Performance by Motor Family:*

DB-1 Series:

Represented by the DB-1-SM-6. It has the lowest specific impulse (30 sec), indicating it's a less efficient, likely simple black powder or similar propellant. It's the "baseline" older design.

DB-3 Series (Black Powder Based):

a) This is the workhorse family, using improved black powder ("hunting powder with lacquer").

b) They have a *consistent specific impulse of ~45.5 seconds.*

c) Performance is scaled by changing the number of fuel pellets, which changes fuel mass, total impulse, and physical size (*e.g., DB-3-SM-1.25, DB-3-S-2.5, DB-3-SM-10*).

d) The DB-3-C-3 is an outlier with a listed Isp of 90 sec, which is suspiciously high.

DB-51 Series (Composite Propellant):

a) This is the *high-performance family,* using a potassium nitrate/magnesium/resin composite propellant.

b) They have a *consistent and superior specific impulse of 70 seconds.*

c) They generate significantly *higher maximum thrust* (P_{max}) for a similar total impulse compared to DB-3 Motors (*e.g., compare DB-51-C-10 to DB-3-SM-10*).

3. Physical Scaling:

The table clearly shows how Motors are scaled:

A. *12mm diameter:* Used for the smallest, lowest-impulse "micro" Motors.

B. *20.5mm diameter:* The standard size for a wide range of impulses, from 2.5 N-s to 20 N-s.

4. Thrust Profiles:

S (Starter) Motors: Like the DB-3-S-2.5 and DB-51-C-10, are designed for short, high-thrust burns (short t and high P_{max} relative to P_{av}). They are for lower stages.

SM (Boost-Sustain) Motors: Like the DB-3-SM-10, have longer burn times and a lower max thrust, making them suitable for single-stage rockets or upper stages where a longer burn is more efficient.

A performance analysis of a versatile and well-designed engine lineup, from black powder workhorses to high-performance composites.

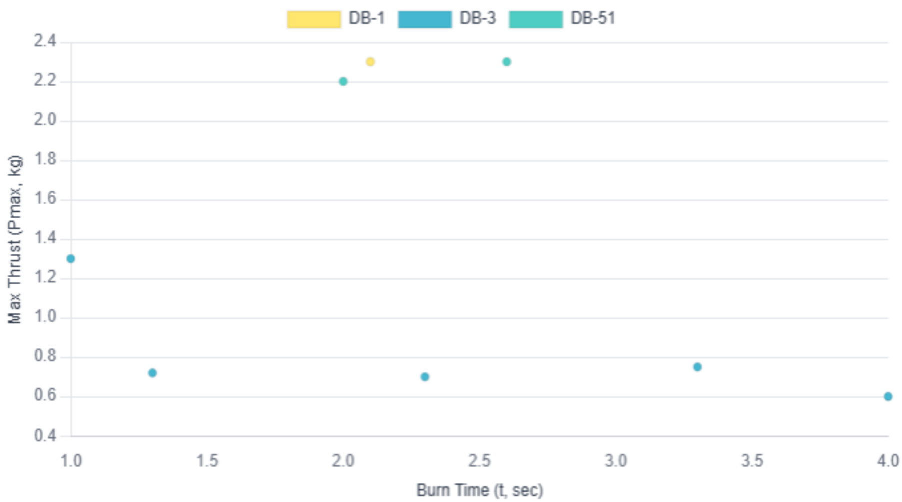
3
Core Engine Families
DB-1 (Baseline), DB-3 (Black Powder), and DB-51 (Composite)

70 sec
Peak Specific Impulse
Achieved by the DB-51 composite propellant family.

+54%
Efficiency Gain
The leap in Isp from the DB-3 (45.5s) to the DB-51 (70s).

Thrust Profiles: Starter vs. Sustain

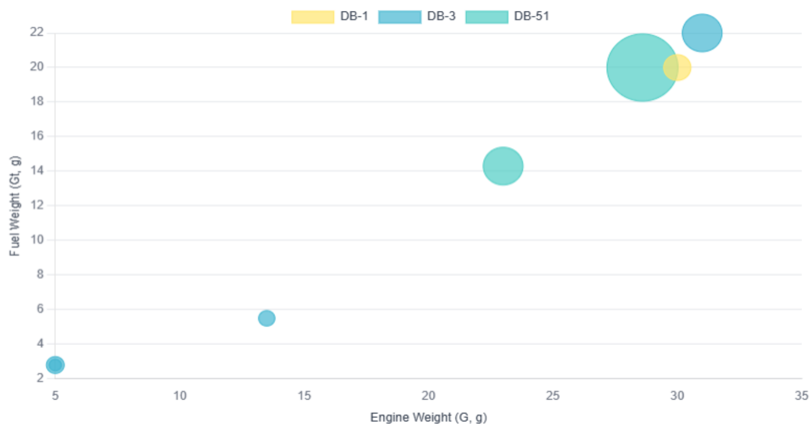
This plot shows the relationship between an engine's maximum thrust and its total burn time. Two clear groups emerge: "Starter" (S) engines, which provide very high thrust for a short duration (bottom right), and "Sustain" (SM/C) engines, which provide lower thrust over a much longer burn (top left), ideal for single-stage flights.



Profile	Thrust Characteristic	Duration	Example Motor
S (Starter)	High initial F_{max}	Short Burn Time (t)	DB-3-S-2.5 (t=1.3sec)
SM / C (Sustain)	Lower, more sustained F_{avg}	Long Burn Time (t)	DB-3-SM-10 (t=3.3 Sec)

Physical Scaling: Mass & Impulse

This bubble chart plots each engine's total weight against its fuel weight, with the size of the bubble representing its total impulse. You can see how impulse scales with mass, and how the different families cluster. The DB-51 engines (teal) provide significant impulse for their mass compared to the less efficient DB-1 (yellow) and DB-3 (blue) engines.



This table encapsulates a mature and well-thought-out model rocket Motor program, offering a range of options for different model performance needs, from small boost-gliders to powerful multi-stage rockets.

The Leap to Composites: Switching from Black Powder (P_{sp} = appr. 45.5 sec to Composite Propellant P_{sp} appr. 70 sec) results in a 54% increase in the amount of thrust generated per unit of fuel mass.

...to approach the evaluation of a particular Motor by comparing their diagrams and calculating characteristics.

Currently, in rocket modeling, the *DB-1-SM-6, DB-3-SM-10, DB-3-SM-5, ARD-2*, and others are widely used. Their casing is a 12-gauge paper hunting cartridge case (Jevelo). These cases are quite strong and can withstand pressures up to 12 kg/cm^2.

Since the operation of a rocket Motor is characterized by thrust force, it is very important for modelers to be able to measure this force. Measurements of the thrust of model SRMs are usually carried out in rocket modeling laboratories under the guidance of rocket modeling instructors.

The thrust force can be measured fairly accurately with a simple, homemade device, similar in design to a spring scale (Fig. 23, 24). The instrument clearly demonstrates the thrust force characteristic and is quite suitable for use during initial training. However, it should be considered that its accuracy is insufficient for recording characteristics according to the requirements of the "FAI Rules".

Its body is made of wood, and the rod passing inside the body is made of an aluminum or wooden tube. The rocket Motor is installed on the upper end of the rod (stem), nozzle up. If you press on the stem from above, it, lowering down, will press on the spring. The scale on the right shows the load experienced by the stem (the spring is selected with appropriate stiffness, calculated for the Motor's maximum thrust). A pencil attached to the stem will draw a curve of thrust force versus time on a rotating drum. The drum is driven by a mechanism, in this case, a gramophone mechanism.

Having such a simplest device, you can test any model Motor, obtain a thrust-time diagram, and then calculate the Motor characteristics necessary for calculating the flight trajectory of a model rocket.

The device automatically draws the thrust curve for any moment of the Motor's operation. The operation of real rocket Motors is studied using such thrust diagrams.

To be confident in the accuracy of the measurements, the device must be carefully calibrated before starting the tests. First of all, the scale is graduated using calibration weights. Place a platform on the stem and gradually load it with weights, each time marking the position of the pointer needle on the scale. Then check the speed and uniformity of the drum's rotation. This is done as follows: the mechanism is started and the number of revolutions per minute is counted using a stopwatch. If there is no difference between the number of revolutions in the first and second minutes, then the mechanism is working satisfactorily. Then, using a stopwatch, the time for a full revolution of the drum is determined. The rotation speed of the drum...

This section describes theoretical performance tables for the *practical testing and validation* of model rocket Motors.

a. <u>*Common Motors:*</u> It lists the most popular Motor types used by Soviet modellers at the time (DB-1-SM-6, DB-3-SM-10, etc.), confirming the widespread use of the 12-gauge paper cartridge case as a standard casing.

B. *The Thrust Stand (Dynamometer):* The core of this passage is the description of a *homemade thrust measuring device*. This is a classic type of test stand used by amateur rocketeers.

a) *Principle:* It works like a spring scale. The Motor's thrust compresses a spring, and the displacement is measured.

b) Data Recording: The ingenious part is the *manual data logging system.* A pencil attached to the moving stem draws directly onto a rotating drum (powered by a gramophone motor), creating a real-time *thrust-time curve.*

c) <u>*Purpose:*</u> This allows modellers to verify the performance of their Motors, generate their own thrust curves (like the ones shown in earlier figures), and calculate the total impulse and average thrust.

<u>*Calibration and Accuracy:*</u> The text importantly emphasises the need for *calibration* (using known weights) and verifying the drum's constant rotation speed. This introduces the concept of measurement integrity. It also honestly states that while this device is excellent for learning, its accuracy does not meet the strict standards required for official FAI record attempts, where more precise electronic equipment would be necessary.

This section highlights the hands-on, practical, and educational spirit of the hobby, encouraging modelers to understand Motor performance through direct experimentation.

.of the drum, although it does not affect the result of the experiment, it is more convenient to select a speed such that the drum makes approximately one revolution during the Motor's operation. This is easy to achieve by approximately knowing the Motor's operating time. If the drum makes more than one revolution during the Motor's operation, the measurement results will be more accurate, but the obtained graph will have to be "unwrapped," i.e., redrawn on a separate sheet of paper.

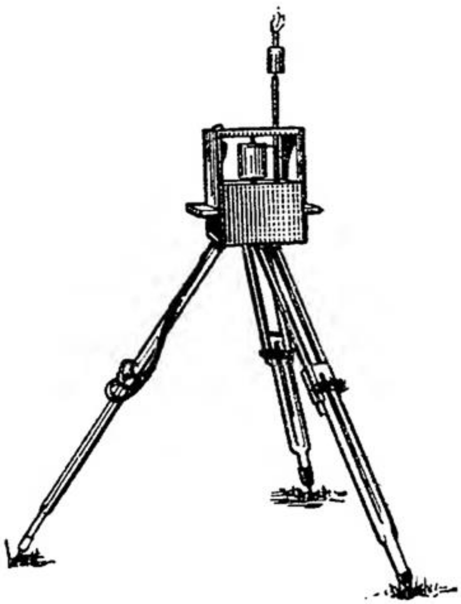


Fig. 22. External view of the device for recording the Model Rocket Motor Parameters

The person conducting the test must ensure that the paper (drawing paper, graph paper) fits tightly against the drum, the pencil tip is reliably pressed against the paper, and the compass-holder washer on the opposite side has a pointer that slides along the marked scale. Before the experiment, a sooted glass plate is placed on the scale. The pointer of the holder, during the movement of the rod, records the Motor's maximum thrust on the glass. The device must be installed strictly horizontally and securely fixed on some convenient stand or tripod (Fig. 22) so that the rod can freely lower with its bottom end without encountering any obstacles.

Having checked the measuring device, the Motor is secured, nozzle up, in a special socket at the end of the rod. An electric igniter or a stopper with an electric igniter is inserted into the nozzle.

When everything is prepared, the test director gives the command for everyone to take cover. Then, he sets the device's mechanism in motion, ensures that the drum has started moving and the pencil is drawing a solid straight line along the top edge of the paper, and then goes to cover. Caution is necessary in all tests, especially of new Motors.

The experiment begins as follows: the test director holds a stopwatch in his hand, with his finger on the start button. On the command "Start," the Motor start button is pressed, and at the moment the Motor begins to operate, the stopwatch is started.

The Motor's operating time is approximately 1 to 5 seconds. The moment the Motor stops operating, the director stops the stopwatch and gives the command "All clear." Then he approaches the device, stops the mechanism, and ensures it is in normal condition...

Explanation of the Testing Process & Procedure

This section details the final preparations and the step-by-step procedure for conducting a static test fire of a model rocket Motor using the described thrust stand.

Drum Speed Optimization: The text offers practical advice: set the drum's rotation speed so the Motor's entire burn fits on roughly one drum revolution. This makes the graph easy to read. A slower speed (multiple revolutions) provides higher time resolution but requires manually "unwrapping" the spiral graph into a straight timeline for analysis.

Pre-Test Checklist: Before firing, a meticulous check is performed:

Paper & Pencil: Ensure the paper is tight and the pencil is sharp and pressing firmly.

Maximum Thrust Indicator: A separate, independent pointer scratches a sooted glass plate to provide a verified, single reading of F_{max}, serving as a crucial check against the drawn graph.

Setup: The entire device must be level and stable so the rod can move without friction or binding, which would distort the thrust measurement.

Safety Protocol: The procedure emphasizes safety, which is paramount when dealing with pyrotechnic devices.

Remote Ignition: The Motor is ignited electrically from a distance.

Taking Cover: Everyone must leave the test area and take cover before the ignition command is given.

Clear Commands:
Standardized commands ("Start", "All clear") are used to coordinate the test.

Test Execution:

The test director synchronizes the start of the stopwatch with the visual confirmation of Motor ignition.

The device records the thrust-time curve automatically.

The test ends when the Motor burns out, marked by stopping the stopwatch.

This process showcases a methodical and safety-conscious approach to empirical data collection, allowing hobbyists to accurately characterize the performance of their homemade rocket Motors.

Device's Operation

This device, a spring dynamometer, is a clever, manual system for measuring and graphing the thrust of a model rocket Motor over time. Here's how it works, based on the numbered components:

The Measuring System (How thrust is captured):

1. The Force Path: The rocket motor is mounted in the cup (5) on top of the stem (11). When the Motor fires, its thrust pushes down on the stem.

2. The Spring (2): This downward force compresses the main pointer spring (2). The stiffness of this spring is calibrated so that its compression is proportional to the thrust.

3. The Recording Scribe (3): Attached to the stem is the scribe (3). As the stem moves down, the scribe moves vertically. Its vertical

position on the paper corresponds to the instantaneous thrust.

4. The Timing System (How time is recorded):

5. The Rotating Drum (7): A sheet of paper is wrapped around this drum. The drum (7) is rotated at a constant speed by a separate mechanism (like a gramophone motor, not shown), which is connected via the drive coupling (9).

6. Creating the Graph: The combined motion of the vertically moving scribe and the horizontally rotating drum causes the scribe to draw a continuous thrust-time curve on the paper.

The Framework:

A. *The Body* (12) holds the entire assembly together.

B. *The axle* (8), *washers* (1, 6, 10), and other components provide structural support and allow the drum and stem to move smoothly.

In essence, this device performs a manual, mechanical version of what a modern digital sensor and data logger would do, providing the crucial thrust-time data needed to calculate the Motor's total impulse and other performance characteristics.

The figure illustrates the individual parts of the homemade thrust stand (dynamometer) described in the previous text. While the exact illustration is not visible, based on the detailed description, the components likely include:

1. *(Body/Housing):* A wooden frame that holds the entire assembly.
2. *(Stem/Rod):* An aluminium or wooden tube that moves vertically. The rocket Motor is mounted on its top end.
3. *(Spring):* The core measuring element. Its stiffness is calibrated for the expected thrust range.
4. *(Scale):* A graduated scale on the side, calibrated with weights, to read the thrust force in kilograms.
5. *Pencil:* Attached to the stem, it traces the thrust curve on the drum.

Drum: A rotating cylinder covered with paper. It is driven by a mechanism (like a gramophone motor) to provide the time axis

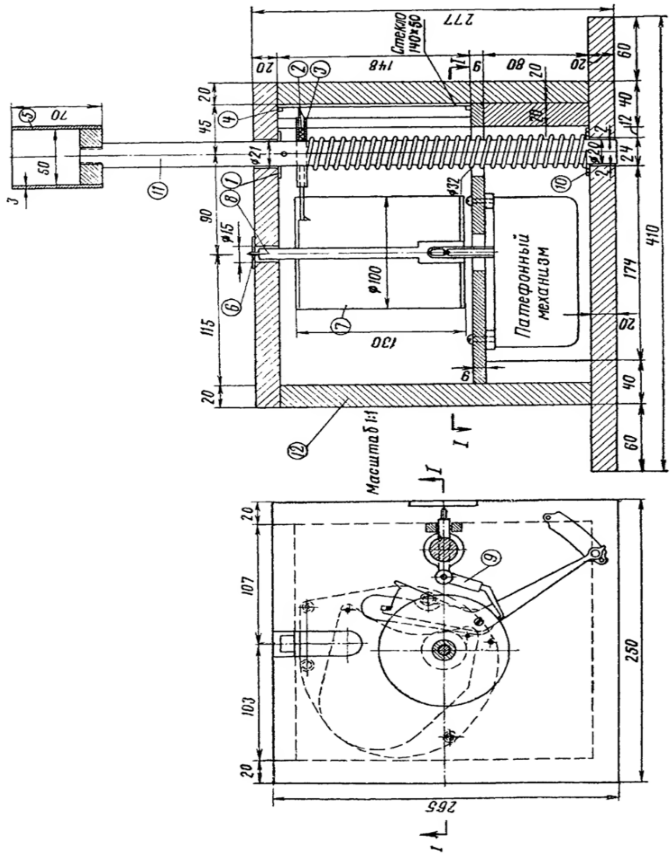


Fig. 23. Data Acquisition System for the Parameters of the Model Solid-Propellant Rocket Motors (SRMs):

Washer

Pointer Spring (the main measuring spring)
Scribe (the pencil or stylus)
Glass Mount / Holder (likely a protective cover or a mount for a transparent scale)
Micro-SRM Mounting Cup (the holder for the rocket motor)
Washer
Drum
Drum Axle
Drive Dog / Coupling (connects the drum to the clockwork motor)
Washer
Stem / Rod (the moving central rod)
Body / Housing

6. .

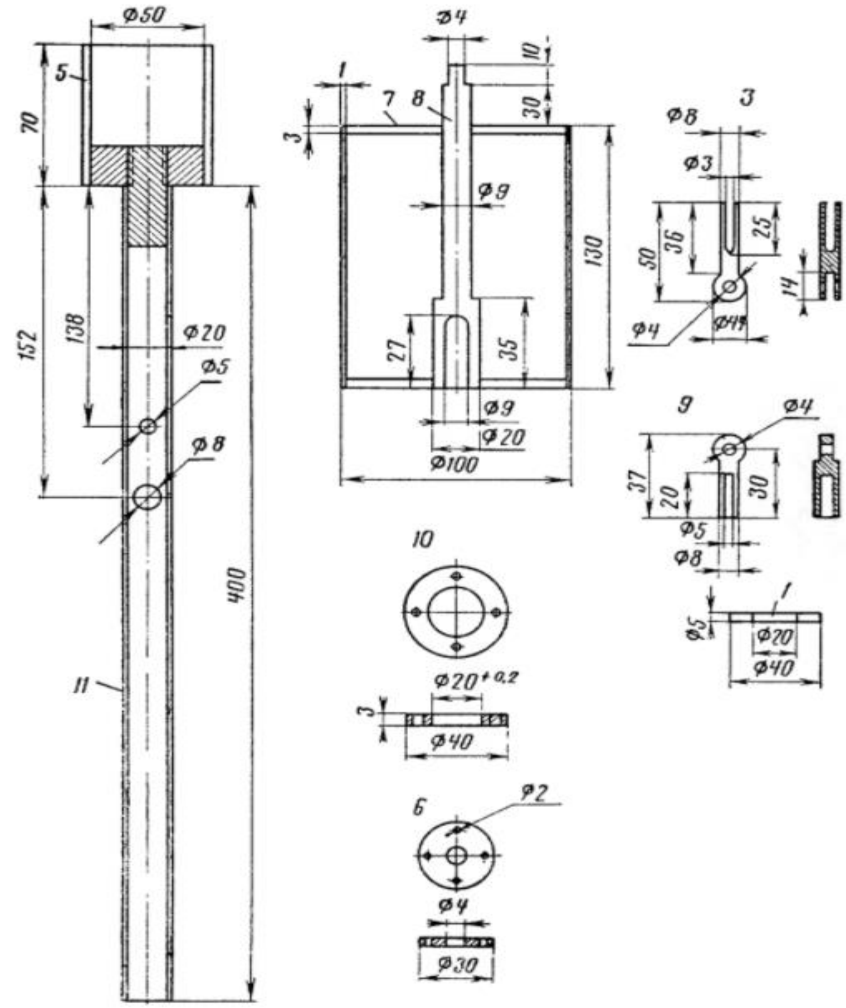


Fig. 24. Components of the instrument for recording the Characteristics of Model Solid-Propellant Rocket Motors.

7. *Rotation Mechanism:* The drive unit (e.g., a spring-powered gramophone motor) that turns the drum at a constant speed.

This device allowed modellers to graphically record the thrust of their rocket Motors over time, enabling them to generate the performance curves and calculate the key parameters (like total impulse and average thrust) discussed in the manual.

For optimal recording of the diagram, and removes the sheet from the drum. He verifies the control measurement of the maximum thrust, as well as the Motor's operating time using a stopwatch. The results of all these measurements are immediately recorded in a notebook.

So, the model Motor test has been conducted. Now it is necessary to process the obtained data. First of all, trace the obtained diagram onto tracing paper. Connect its initial and final points with a straight line, then divide this line into several parts according to the number of seconds that passed during the Motor's operation.

Calculate the time as follows: first, determine the number of full drum revolutions per one second. To do this, lower the pencil onto the drum and count the drum's revolutions. Let's say it made 50 revolutions in 1 minute and 10 seconds, then the time for one revolution is:

$$t_1 = \frac{70\, sec}{50} = 1.4\, sec.$$

In this time, the pencil point covered a distance (with a drum diameter of 100 mm) equal to 314 mm (3.14 × 100), and in one second:

$$L = \frac{314\, mm}{1.4} \approx 224.3\, mm.$$

From the initial point of the Motor operation diagram, set aside 224.3 mm along the straight line to the right. This will be the first second. Mark the second further along the line, and so on, until the new point goes beyond the diagram's limits. Divide the distance between the marked seconds into 10 parts. Each part will be 0.1 sec. This accuracy is quite sufficient. Since the device might not record very small thrusts, stopwatch readings are usually also used for the completeness of the diagram. Therefore, in case of a discrepancy between the device and the stopwatch readings, proceed as follows: suppose the device shows a time of 1 sec, but the stopwatch reading is 1.14 sec. In this case, the stopwatch reading is taken, and the difference of 0.14 sec is distributed equally: 0.07 sec to the left of the diagram's initial point and 0.07 sec to the right of the Motor operation's final point.

Next, proceed to draw the ordinates. From each division point on the straight line, draw a line perpendicular until it meets the curve. Then, on the ordinate drawn from the point starting the diagram, mark the load scale according to the drum's scale in kilograms. The diagram is ready.

The average thrust of the Motor can be determined from the diagram by calculating the average value of the sum of the ordinate magnitudes between the straight line and the curve. To do this, measure the length of each ordinate using a compass, and divide the total sum by the number of ordinates taken.

Explanation of the Data Processing Workflow

It describes the final, crucial step in characterising a model rocket Motor: *manually processing the thrust-time diagram* obtained from the spring-based dynamometer.

1. ***Time Axis Calibration:*** This is the most complex part. Since the drum rotates at a (hopefully) constant speed, the horizontal distance on the paper corresponds to time.

a) They first calculate the exact speed of the drum (e.g., 1.4 seconds per revolution).

b) Using the drum's circumference, they determine how many millimetres of paper travel past the pencil in one second (e.g., 224.3 mm/sec). This becomes the scale for the time axis.

c) They then meticulously mark the timeline on the traced diagram in 1-second and 0.1-second intervals.

2. ***Thrust Axis Calibration***: The vertical deflection, recorded by the pencil, corresponds to thrust. This scale was previously established by calibrating the spring with known weights (P = k * x).

3. ***Handling Instrument Error***: The text acknowledges the instrument's imperfection. If the burn time recorded by the diagram differs from the stopwatch time, they pragmatically split the

difference and adjust the start and end points of the active burn phase on the diagram. This ensures the total impulse calculation remains accurate.

4. ***Calculating Average Thrust (F_{avg}):***

1. The "straight line connecting the initial and final points" represents the *average thrust* if it were constant.
2. The *Coordinates* are vertical lines drawn from this average line down (or up) to the actual thrust curve at regular time intervals.
3. The length of each ordinate represents the *deviation* from the average at that moment.
4. By measuring all these ordinates, summing them, and dividing by the number of ordinates, they find the *average deviation*. This method is essentially a manual integration technique to find the true average thrust, which is necessary for calculating the total impulse ($I_{total} = F_{avg} \times t$).

This entire process demonstrates a robust, low-tech method for extracting precise quantitative data from a simple analogue recording, embodying the practical Motorering spirit of the era.

Let's assume we have a thrust-time diagram for the Motor's operation. The maximum thrust $F_{max} = 1.15\,kg$, the average thrust $F_{avg} = 0.875\,kg$, the Motor operating time $t = 1.14\,sec$, and the fuel weight $M_{pp} = 0.02\,kg$. Let's determine the remaining Motor characteristics.

1. ***Total impulse of the Motor:***

$$I_{Total} = F_{avg} \cdot t = 0.875 \cdot 1.14 \approx 1$$

2. ***Specific impulse of the Motor:***

$$I_{sp} = \frac{I_{Total}}{M_{pp}} = \frac{1}{0.02} = 50$$

Exhaust gas velocity from the Motor nozzle:

$$\boldsymbol{V_e = I_{total} \cdot g = 50 \cdot 9.81 \approx 490\,m/sec}$$

5. PYROTECHNICS IN ROCKET MODELING

The Rocket Motor, being the most important component of every model rocket, as well as its launch means, belongs to pyrotechnic devices.

§1. METHODS OF IGNITING FUEL IN MODEL ROCKET MOTORS

In rocket modelling practice, an ignition means called "stopin" in pyrotechnics is widely used. A stopin is a cotton thread coated with a composition of gunpowder pulp with the addition of glue (e.g., starch, dextrin, etc.). The manufacturing method is very simple.

Cotton threads are twisted into a strand 1–2 mm thick. The resulting cord is soaked for 24 hours in a solution of potassium nitrate (100 g of nitrate per half litre of water).

The soaked and dried cord is immersed for 1–2 hours in a liquid paste made from gunpowder pulp and glue. The gunpowder pulp has the following composition by weight: potassium nitrate - 75 parts, sulfur - 12 parts, pine charcoal - 13 parts. In addition to these 100 parts, 5 parts of glue are added. The glue is added so that the powder does not crumble and the thread does not bend. The threads impregnated with the powder paste are taken out and wound onto a special...

Explanation and Analysis

1. **Performance Calculation Example:**

This section provides a practical example of how to calculate key rocket Motor parameters from test data (thrust-time curve).

a) **Total Impulse (I_{total}):** The area under the thrust-time curve, calculated here as the product of average thrust and burn time. It's a measure of the total momentum imparted.

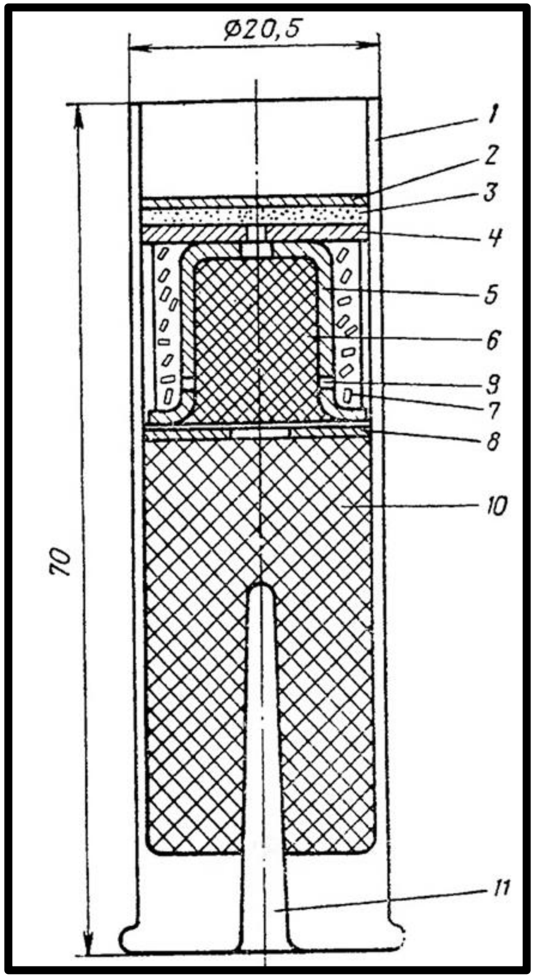
b) **Specific Impulse (I_{sp}):** A crucial efficiency parameter, indicating how much thrust (in kg·sec) is produced per kilogram of fuel. Higher values mean better efficiency.

c) **Exhaust Velocity (V_e):** The speed at which gases exit the nozzle, directly related to specific impulse by the gravity constant g. This determines how effectively the Motor converts fuel into thrust.

2. **Pyrotechnic Ignition (Stopin):**

This highlights the practical, hands-on nature of historical model rocketry, where modellers often prepared their own ignition components.

Stoping acts as a slow-burning fuse. Its composition is similar to black powder but with a binder (glue) to adhere to the cotton thread. The detailed recipe and process (soaking in potassium nitrate solution, then coating with powder paste) ensure consistent and reliable ignition, which is critical for Motor performance and safety.



The text underscores that rocket Motors are classified as pyrotechnic devices, emphasising the need for careful handling and respect for safety protocols.

This chapter bridges the theoretical performance calculations with the practical aspects of Motor construction and ignition, showcasing the comprehensive knowledge required in model rocketry a special rack for drying. While the quick-match is still damp, it is useful to dust it with dry powder pulp. The finished and well-dried quick-match is cut to the required length.

Some Motors, for example, the *DB-51-S-10,* have a fuel grain which is difficult to ignite with ordinary quick-match. In this case, quick-matches prepared with potassium chlorates and perchlorates with aluminum or magnesium are used. The following composition by weight is recommended: potassium chlorate - 70 parts, aluminum 30 parts, and in addition to these 100 parts, 5% dextrin. Such a quick-match provides sufficient heat to ignite the rocket propellant.

The *DB-51-S-10* model Motor has another important element - a smoke grain, which is located at the end of the fuel charge (Fig. 25).

With a smoke grain:

1 - Motor casing; 2 - Motor base; 3 - ejection charge (payload); 4 - delay element diaphragm; 5 - delay element casing; 6 - delay element pyrotechnic composition; 7 - coloured smoke granules; 8 - powder grain diaphragm; 9 - smoke exhaust port; 10 - powder grain; 11 - micro-SRM nozzle

§ 2. PYROTECHNIC CONSIDERATIONS FOR ROCKET MODEL ASSEMBLY

Fuse Cord (Quick Match) Fabrication and Drying

The quick-match must be securely fixed in the Motor nozzle orifice so that it does not fall out during burning at launch and in flight. Particular attention must be paid to the ignition device when equipping multi-stage rocket models, where the cause of failure to transfer flame to the next upper stage is often a quick-match that is loosely placed in the subsequent Motor. In this case, when the spent stage separates, the unsecured quick-match falls out under the influence of acceleration.

Following its braiding, the fuse cord, or "quick match," requires a specialized drying rack. While the cord is still damp, it is beneficial to dust it with dry, finely-ground *Fig. 25. DB-51-S-10 Model Rocket Motor* black powder meal. Once fully prepared and thoroughly dried, the quick match is cut to the required Length.

Certain Motors, such as the *DB-51-S-10,* feature a fuel grain that is difficult to ignite with standard quick match. For these, a more potent equationtion is required, typically based on potassium chlorate or perchlorate mixed with aluminum or magnesium powder. A recommended composition by weight is:

i. ***Potassium Chlorate: 70 parts***
ii. ***Aluminium: 30 parts***

To this 100-part mixture, an additional 5% by weight of dextrin is added as a binder. This type of high-temperature fuse provides sufficient thermal energy to reliably ignite the rocket propellant.

Securing Ignition Trains and a Multi-Stage Warning

A critical rule is that the quick match must be securely fixed within the Motor's nozzle to prevent it from dislodging during the violent ignition sequence and initial flight. This is especially crucial when assembling multi-stage models. A frequent cause of stage-ignition failure is a fuse that is merely placed loosely into the next stage's Motor. In such a case, the separation of the spent stage, combined with the acceleration of the vehicle, can easily cause the unsecured fuse to be pulled out entirely, breaking the ignition chain.

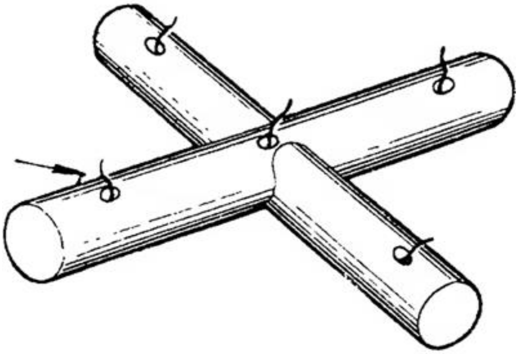


Fig. 26. "Pyrotechnic Cross"

For the simultaneous launch of several motors (for example, in a model-copy of the "Vostok" rocket), a pyrotechnic device called the "Pyrotechnic Cross" is recommended (Fig. 26). This consists of two paper tubes, intersecting at a right angle, with wall thicknesses of 1-2 mm, a diameter of 20-30 mm, and a length of 150-200 mm.

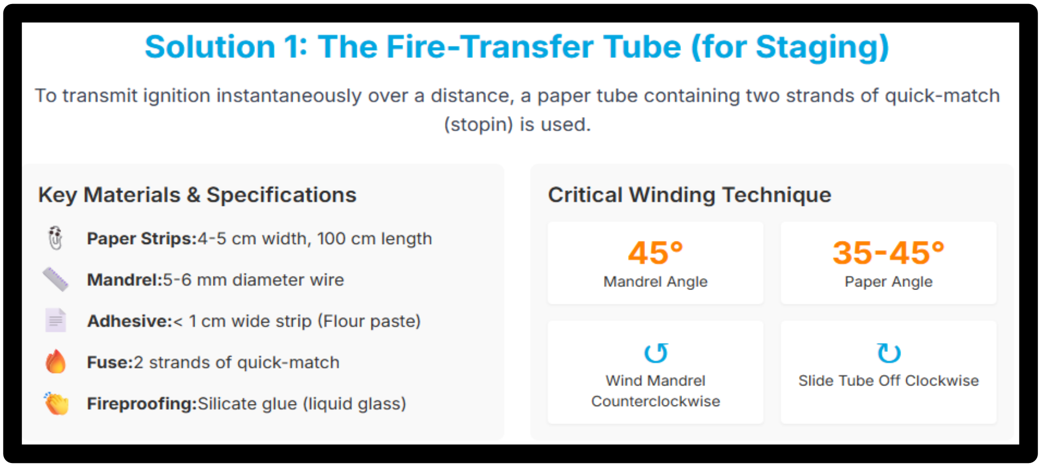
Length of quick-match and 2-3 grams of powder pulp are laid along the tubes. The ends of the tubes are sealed with one layer of writing paper. The locations corresponding to the positions of the motors on the rocket are marked on the surface of the "cross," and holes are then made precisely at these points. The ends of the quick-match from the motor nozzles are inserted into these holes. Ignition can be performed with an electric match at any point on the "cross."

The operating principle of the "cross" is that upon ignition, sufficient pressure is generated inside it; the gases instantly ignite the quick-match leads from the motor nozzles, which are inserted into the "cross," and the motors practically begin to operate simultaneously. The excess pressure in the "cross" ruptures the ends sealed with paper, without damaging the device itself.

§ 3. PYROTECHNIC IGNITION TRANSFER METHODS FOR MULTI-STAGE ROCKETS AND SIMULTANEOUS IGNITION

When equipping multi-stage rocket models with motors, it is necessary to ensure the timely transfer of the thermal impulse to the next motor.

In cases where the motor of one stage is in immediate proximity to the motor of the next stage, instantaneous fire transfer is almost always ensured. But in model copies of "*Vostok*," "*Soyuz*," "*Kosmos*," and others, if their staging is made exactly like the original, the motors are located some distance apart from each other. Because of this, a delay occurs in the transfer of fire to the next stage, and as a result, the model "tips over."



For the instantaneous transfer of fire, there is a reliable method commonly used in theatrical pyrotechnics. Two strands of quick-match of the required length are inserted into a paper tube. The quick-match, ignited from one end, instantly transmits the flame to the other end of the tube.

Paper tubes can be made from writing paper. The paper is cut into strips 45 mm wide and 1000 mm long. The edge of the...

A critical challenge in multi-stage rocketry is ensuring the timely transfer of the ignition impulse to the next stage's motor. While instantaneous ignition is almost guaranteed when motors are in immediate proximity, this is not the case for scale models like the Vostok, Soyuz, or Cosmos, where the stages are separated by a significant distance, just as on the original vehicles. This distance can cause a lag in ignition transmission, resulting in a loss of velocity and stability, often causing the model to "tip over" and fail.

To achieve instantaneous fire transfer over a distance, a reliable method commonly used in professional pyrotechnics is employed. This involves threading two strands of a quick-burning fuse train (stopin) through a sealed paper tube. When ignited at one end, the fuse transmits the flame virtually instantaneously to the opposite end.

Fabrication of Ignition Tubes

These paper tubes can be fabricated from standard writing paper. The paper is cut into strips approximately 45 mm in width and 1000 mm in length. A brush is used to apply adhesive—a flour-based paste or dextrin is traditional—along the strip, ensuring the coated width does not exceed 1 cm. A smooth, straight wire of 5-6 mm in diameter and 50-80 cm in length serves as an effective mandrel.

The glueing and winding process requires precision:

1) The mandrel is held in the right hand at a 45-degree angle.

2) The dry corner of the paper strip is pressed against the top of the mandrel, with the strip itself positioned at a 35–45-degree angle to it.

3) While guiding the paper with the left hand, the mandrel is slowly rotated counterclockwise until the entire strip is wound.

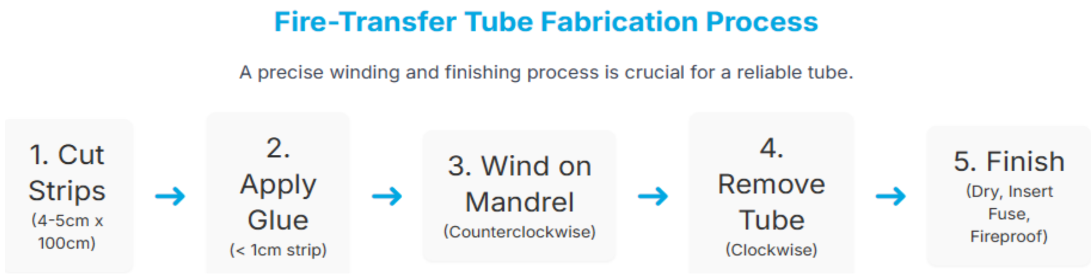
4) The finished tube is then carefully slid off the mandrel by rotating it clockwise while holding the tube steady.

Once dry, the tube is cut to the required length, and the two fuse strands are inserted, leaving a 2-3 cm tail protruding from each end. Short tubes can be joined by splicing them with a narrow, glued paper band. A final coating of silicate glue (liquid glass) fireproofs the tube, preventing post-use smouldering. While thin-walled tubes are often single-use, those with walls 2-3 mm thick can be reused.

The Pyrotechnic Cross for Cluster Ignition

For the simultaneous ignition of multiple Motors, such as those in a Vostok replica, a specialised device known as a "Pyrotechnic Cross" is recommended (see Fig. 26). This apparatus consists of two paper tubes, each with a wall thickness of 1-2 mm, a diameter of 20-30 mm, and a length of 150-200 mm, joined at a perpendicular intersection.

Each tube is pre-loaded with a fuse train and 2-3 grams of finely



ground black powder (powder pulp). The ends of the tubes are sealed with a single layer of writing paper. The surface of the cross is marked, and then holes are pierced in precise correspondence with the positions of the rocket's Motors. The ends of the fuses from the Motor nozzles are inserted into these holes. Ignition can be initiated by an electric match at any point on the cross.

The operating principle relies on contained pressure: upon ignition, the burning powder rapidly pressurises the cross, forcing hot gases and particles instantaneously into all the Motor fuse trains. This ensures all motors in the cluster begin functioning in near-perfect synchrony. The sealed paper ends act as blow-out panels, rupturing safely to vent excess pressure without damaging the integrity of the cross itself.

Materials and Preparation

Paper: Standard writing paper.

Adhesive: Flour-based paste or dextrin.

Mandrel: A smooth, straight wire of 5–6 mm in diameter and 50–80 cm in length.

Strips: Paper cut into strips approximately 4–5 cm in width and 100 cm in length.

Glue Application: Apply adhesive along the paper strip, ensuring the coated width does not exceed 1 cm.

Glueing and Winding Process

The glueing and winding process requires precision to ensure a tight, even tube:

1. Hold the mandrel in the right hand at a 45-degree angle.

2. Press the dry corner of the paper strip against the top of the mandrel.

3. Position the strip itself at a 35^0–45^0 angle to the mandrel.

4. While guiding the paper with the left hand, slowly rotate the mandrel counterclockwise until the entire strip is wound.

5. Carefully slide the finished tube off the mandrel by rotating it clockwise while holding the tube steady.

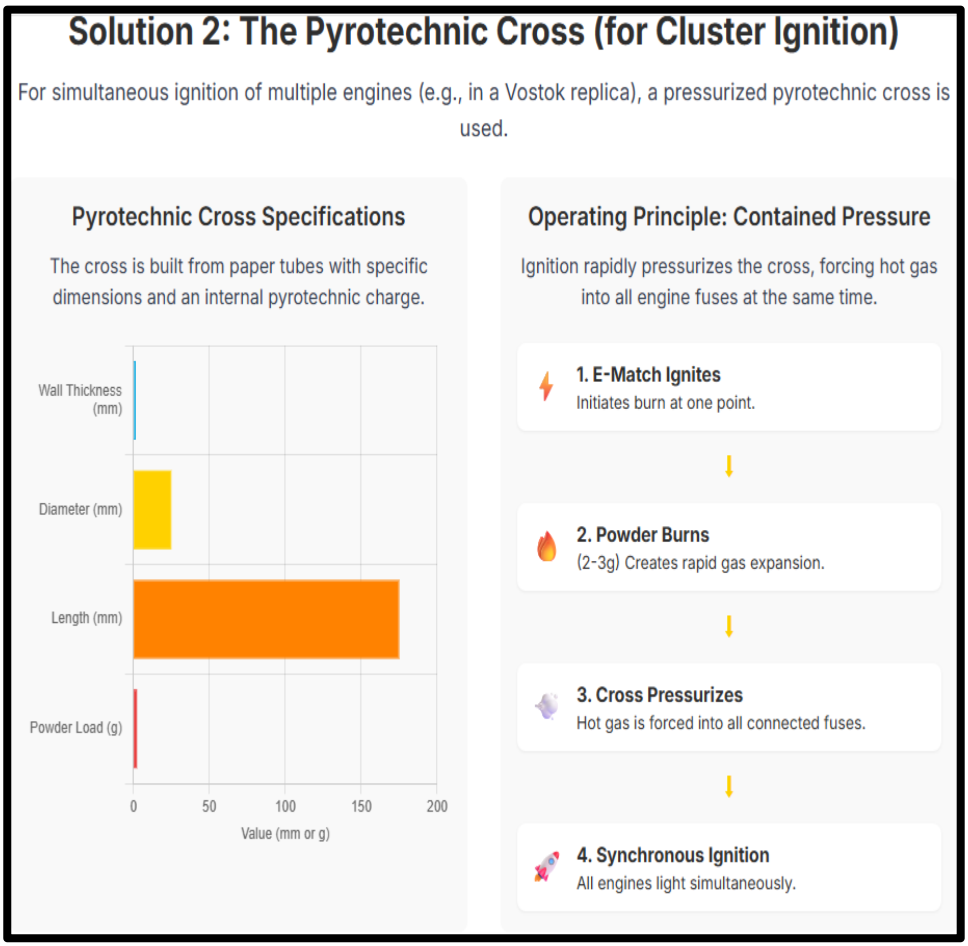
Finishing the Tube

1. Once dry, the tube is cut to the required length.

2. Insert the two fuse strands (quick-match), leaving a *20 – 30 mm tail* protruding from each end.

3. Short tubes can be joined by splicing them with a narrow, glued paper band.

4. A final coating *of* *silicon glue (liquid glass)* fireproofs the tube, preventing post-use smouldering.



Note: Thin-walled tubes are often single-use, but those with walls 2–3 mm thick can be reused.

The spools are coated with glue using a brush. The width of the glue application should be no more than 1 cm. Pyrotechnicians usually use flour-based cooked glue or dextrin for this purpose. A mandrel can be a straight, smooth wire with a diameter of 5-6 mm and a length of 50-80 cm. The strip coated with glue is immediately wound onto the mandrel; otherwise, the glue may dry.

In practice, this is done as follows. The mandrel is held in the right hand at an angle to the horizon, approximately 45°. The corner of the paper strip that has no glue is pressed against its top end. The relative position of the paper strip and the mandrel is usually 35-45°. While holding the strip with the fingers of the left hand, the mandrel is slowly rotated counterclockwise until the entire strip is wound onto the mandrel. Then, holding the finished tube with the left hand, the mandrel is turned clockwise with the right hand, carefully removing the tube from it. Once the tube has dried, it is marked to the required length and two pieces of quick-match are inserted, long enough to protrude from the ends of the tube by 2-3 cm.

Short tubes are made on short mandrels in the usual way. The required paper format, coated with glue, is wound in 2-3 turns. Short tube pieces can be joined by pasting over the joints with a narrow strip of paper.

Tubes ready for loading are coated with silicate glue (liquid glass), which prevents them from smoldering after use on the model. Thin, single-use tubes are disposable, while tubes with wall thicknesses of 2-3 mm CAN be used multiple times.

Delay tubes are called retarders. They are used to fully utilise the passive section of the trajectory for gaining altitude. Retarders are produced industrially with action times from 1 to 10 seconds. The modeller selects the retarders himself, depending on the launch weight and class of the model.

§ 4. ASSEMBLY OF THE PYROTECHNIC PART OF A MODEL "VOSTOK" ROCKET

The assembly of the pyrotechnic part of the model must be done carefully and with strict adherence to safety regulations. This step is a critical phase that demands meticulous attention to detail and *strict adherence to all applicable safety regulations.* This process involves the installation of fuse trains and rocket motors, which must be handled with care to ensure a successful and safe launch sequence.

4.1.1 Central Core Assembly

The primary pyrotechnic sequence is housed within the central core tube. The assembly is as follows:

1. *Install Fuse Trains*: Two fuse trains (quick-match cords) are inserted into the central load-bearing tube.
2. *Upper Charge Connection:* One end of each fuse train is securely fixed into a socket containing a *0.5–0.7 gm charge of black powder*. This charge is responsible for the parachute ejection event at apogee.
3. *Lower Ignition Connection:* The opposite end of each fuse train is positioned and fixed in the lower section of the model, adjacent to the central second-stage motor. This configuration ensures the ignition sequence propagates from the first-stage motors to the ejection charge after a timed delay.

Figure 8, Item 4: Detail of the central load-bearing tube and fuse train installation

4.1.2 Booster Motor Installation

The four outer booster Motors are installed in the blocks of the side boosters. The installation must balance security with safety:

1. The motors should be inserted securely enough that they will not detach or fall out under normal handling and launch forces.
2. *Crucially, these motors must not be permanently fixed with adhesive*. This allows for safe pre-launch handling and ensures that spent

motors can be safely removed and replaced post-flight.

**Note:* *The terms "fuse trains" and "quick-match cords" are used interchangeably within this manual to describe the same components.*

It is necessary to provide for one important detail. When the fuel in the second-stage motor burns out, the thermal impulse is transferred to the quick-match enclosed in the central tube. When the quick-match burns, gases are produced for which an exit must be provided; otherwise, they will rupture the second-stage casing. For this purpose, two or more vent holes, 6-7 mm in diameter, are made strictly opposite each other. For the simultaneous ignition of the four booster units of the second-stage motor (they are all started at once), it is recommended to use a "pyrotechnic cross".

During motor start-up, ignition failures can occur for various reasons. For example, with the electrical ignition method, this happens when there is no contact on the terminals, a wire is broken, the current Strength is insufficient, or the electric match filament does not reach the required glow. Finally, it is quite often the fault of the pyrotechnic part of the igniter: the igniter compound has become damp, the quick-match is of poor quality (it contains too much moisture or binder), etc.

In all cases of ignition failure, one must remember the mandatory rule: if instantaneous ignition does not occur, one must wait 3-4 minutes and then repeat the start-up. There are often cases when the motor does not start immediately, but after 1-2 minutes after start-up. The cause may be damp, crushed, or simply poor-quality quick-match, which does not burn properly but smoulders, slowing the transmission of the flame to the rocket motor grain, and sometimes not igniting it at all.

6. RECOVERY SYSTEMS & PRINCIPLES

The launch is only half the mission. A successful flight is defined by the safe and undamaged return of the rocket to Earth. The recovery system is a critical, non-negotiable component that transforms a ballistic projectile into a reusable model. This chapter covers the physics, design, and deployment methods that ensure your rocket flies again.

§ 1. The Physics of Recovery

Understanding the forces at play is essential for designing an effective recovery system.

§ 1.1. The Role of Drag in Recovery

Principle: the parachute recovery systems work by dramatically increasing the rocket's aerodynamic drag, which counteracts the force of gravity.

Terminal Velocity: This is the constant speed achieved when the drag Force equals the Gravity force. The objective of recovery system design is to achieve a low terminal velocity, typically 3.5 to 4.5 meters per second ensuring a soft landing.

The Drag Equation: Drag Force = ½ * $D_f = \frac{1}{2} \times \rho \times V^2 \times A$, where:

- ρ (rho) = air density
- v = velocity
- Cd = coefficient of drag (a measure of the shape's effectiveness)

- A = cross-sectional area
- By maximizing *A* (area) and *Cd*, we maximize drag and minimize descent velocity.

§ 1.2. Calculating Descent Rate and Impact Force

Descent Rate Calculation: A simple field measurement can be used: Descent Rate = Altitude / Time. For a more predictive approach, use the drag equation to solve for terminal velocity.

Impact Force: The energy upon impact is proportional to the square of the velocity. Halving the descent rate reduces the impact force by a factor of four. A low descent rate is the primary factor in preventing damage.

§ 2. Design Calculation of Model Rocket Parachute Recovery Systems

The recovery system ejection mechanism consists of two parts: the command to eject the parachute (recovery system) and the energy source for ejecting the parachute (recovery system).

The command to eject the recovery system on model rockets can be given by following methods:

i. The Motor or its system (pyrotechnic command);

ii. The magnitude of the incoming airflow (aerodynamic command);

iii. The magnitude of the g-load (ballistic command).

iv. The energy source for ejecting the recovery system is burning a pyro (pyrotechnic ejection system), a rubber cord, or a spring.

v. The command source and the type of ejection energy are combined in a variety of ways, resulting in nine options.

Axial parachute ejection

Ejection by black powder gases and labyrinth seal. The most common parachute ejection system is one that receives the command from the Motor, most often through a pyrotechnic delay system to a powder charge, which ejects the recovery system (parachute) using the energy of the powder gases. This is an onboard ejection system (Fig. 42).

Advantages of the system: simplicity, lightness, reliability.

Disadvantages:

- The possibility of powder gas breakthrough through the wadding, which leads to burning of the parachute if it is made of paper, silk, or other natural materials, and to melting of the parachute if it is made of synthetic materials: nylon fabric, PET film, etc.

This system becomes reliable only if there is a reliable protection system against a breakthrough. Different rockets require different recovery methods. Choosing a right Recovery system is a trade-off balanced design of *weight, volume,* and *required descent rate.*

Fig. 42. Single-stage model rocket for the parachuting duration of the first USSR champion in rocket modelling, M. Panteleev:

1 - nose cone; 2 - body; 3 - parachute; 4 - wadding; 5 - labyrinth seal; 6 - ejection charge; 7 - delay element; 8 - micro-solid rocket Motor; 9 - stabilizer.

of powder gases. Such a system was developed and successfully applied. It consists of a labyrinth seal, wadding plugs, and a cover for the parachute made of tracing paper (see Fig. 42).

Labyrinth Seal. The process in the labyrinth resembles throttling. In each chamber of the labyrinth, the axial velocity of the gas drops to zero due to vortex formation and wall impacts. Moving from chamber to chamber, the gas expands adiabatically, and its pressure drops. Since the pressure drop in the labyrinth between two adjacent chambers is small, the Bernoulli equation, written for the cross-section in chamber i and the slot following it, takes the form:

$$P_i = P_{(i+i)} + \frac{\gamma \times C^2}{2g}$$

where c is the velocity in the chamber.

Here, hydraulic resistance and compressibility effects are not accounted for.

For each ratio of the gap δ between the model wall and the labyrinth to the labyrinth height h, there is an optimal number of slots Z_{opt} at which the gas flow is minimal:

$$Z_{opt} = 1 + 0.06 \times \left(\frac{h}{\delta}\right)$$

From this equation one can determine the structural height of the labyrinth:

$$h = \delta \times \left(\frac{Z - 1}{0.06}\right)$$

The most successful shape for the labyrinth comb ridges is shown in Fig. 43. Labyrinths are manufactured by turning on a lathe from linden wood, or are assembled from cardboard discs with foam spacers. The par-a

DIRECTIONS OF MOVEMENT FROM POWDER GASES

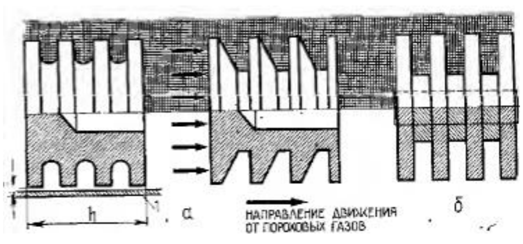


Fig. 43. Shapes of labyrinth seal combs: a - turned from wood; b - assembled from cardboard; 1 - model body parachute is sewn on. The discs have some freedom of movement in parallel planes, which compensates for assembly inaccuracies.

Ejection by "Slingshot" (Rubber Cord). To avoid ejecting the parachute using the energy of powder gases, a system is used which consists of a command from the Motor (pyro-command) and an energy source from rubber cords, a "slingshot".

The delay element in some cases is a powder strand, which holds the "slingshot" in the cocked position.

The "slingshot" is a piston, made with grooves from linden wood, as in the labyrinth seal. A rod made of pine slat is screwed into the piston from above, onto which the parachute is packed. The rod has a nose cone made of balsa or foam plastic at the top. A shackle, made of steel or an alloy, is attached to the bottom of the piston, which engages with a groove in the frame.

* Zak. 349

of copper. Additionally, two rubber cords (of circular cross-section) are attached to the piston, serving as the energy source for parachute ejection. The opposite ends of the rubber cords are attached to the upper part of the model rocket's body.

The presence of a frame

A design feature of the model rocket with this chosen parachute ejection system is the frame (Fig. 44). This frame separates the instrument compartment with the pyrotechnic element from the payload compartment containing the parachute (parachute container). The pyro-check is cut from a micro-solid rocket Motor grain; the composition

Fig. 44. Parachute ejection by "slingshot":

1 - pyro-check; 2 - frame; 3 - piston; 4 - rubber cords; 5 - rod; 6 - nose cone; 7 - body; 8 - shackle; 9 - micro-solid rocket Motor must have a relatively low combustion temperature and, most importantly, be sufficiently strong. From this point of view, micro-solid rocket Motors, whose propellant grain composition includes resin, have proven effective.

The instrument compartment must have two holes for the symmetrical outflow of gases from it. The axis of these holes is perpendicular to the plane of the shackle and is aligned with the hole in the shackle, into which the pyro-check is inserted using tweezers.

Advantages of the system: the possibility of powder gases reaching the parachute is almost eliminated, its lightness, simplicity of manufacture. Disadvantages: relative complexity of assembly, and most importantly, the possibility of the parachute lines getting tangled with the cords of the ejection system, which leads to failure.

For ease of installing the pyro-check, it is advisable to make the instrument compartment from organic glass (plexiglass), which allows visual inspection of the assembly (installation of the pyro-check) and partially eliminates one of the system's disadvantages - inconvenient assembly.

Ejection by Spring.

To prevent the parachute lines from getting tangled with the elements of the ejection system, a spring ejection system was developed. The spring is attached to the frame at one end, and at the other, free end, the parachute bag is attached via a piston-labyrinth. In this case, the spring serves not only as a source of energy for parachute ejection but also as a shock absorber at the moment of canopy opening and the aerodynamic jerk.

The system for ejecting the parachute using springs has disadvantages:

i. complexity of calculation and technological manufacture of the spring;
ii. a somewhat overweight system.
iii. However, the chapter on the aerodynamics of model rockets mentions the most advantageous model weight, which is not equal to the minimum (see Fig. 10, 6).

Non-Axial Parachute Ejection

The schemes considered above implied a cylindrical, unslit body-parachute ejection inside a tube.

In practice, a scheme for ejecting the parachute sideways through an opening flap is also used. As a rule, the model rocket body is cut lengthwise along its generators (into two halves). Such a scheme creates a softer release of the parachute than ejection. To implement it, hinges and sufficiently rigid body flaps are necessary. It is better if they are made from fibreglass (glass-epoxy laminate) by winding or moulded from polystyrene.

Two schemes for body opening are possible: with longitudinal and transverse hinges (more often with one). The command to open the body is given by the same systems as in other schemes.

Opening the model rocket body with a longitudinal hinge. The energy source for opening the body is a rubber cord, mounted on a bracket. The longitudinal bracket is a rod with movable elements - "antennae". The hold *locking element* is a lock-rod with a set of longitudinal locks, which disengage after the movement of the motor compartment relative to the body, which has one degree of freedom, and even that is limited (Fig. 45). The motor compartment can move relative to the model rocket's body under the energy source of the powder gases from the ejection charge.

To introduce the parachute into the airflow (without relying on the element of chance – whether it will fall out on its own or not), a push-out mechanism is used. The energy source for the push-out mechanism is rubber cords or springs.

Rubber cords are installed at the ends of the parachute container, while springs can be recessed into a set of niches. The push-out surface is made in the form of a half-cylinder or a rail.

Disadvantages of the scheme:

i. complexity of manufacturing hinges and the push-out mechanism;
ii. the slit body, which is an open profile, has insufficient torsional stiffness when the lock is open.

Opening model rocket body with a transverse hinge. Since the body in this scheme opens on a transverse hinge, its semi-cylinder has a large lever arm. The parachute is attached to the flaps at the end opposite the hinge. This eliminates the need for a push-out mechanism. The command to open can be given in the same way as for the model

(Page 14, 25, 15 - likely figure/photo references)

Fig. 46. Opening model rocket body with a transverse hinge (manufactured from polystyrene on a wooden mandrel):

1 - nose cone (celluloid); 2 - cord (rubber); 3 - post (plywood); 4 - lever (plywood); 5 - frame (plywood); 6 - ring (celluloid); 7 - hinged part of the body (polystyrene); 8 - frame (plywood); 9 - hinge (steel); 10 - frame (plywood); 11 - cone (paper); 12 -

tie (thread No. 10); 13 - bracket (beech); 14 - pyrotechnic system: 15 - micro-solid rocket Motor

with a longitudinal hinge. The rubber cord is attached to a bracket. The bracket is best made from the same material as the body, and if it is plastic, it can be welded on (Fig. 46).

Compared to the scheme with a longitudinal hinge, in this scheme the parachute container represents an open profile during all flight stages. This requires a more rigid structure (up to the installation of frames), which increases the weight and labor intensity of manufacturing the rocket model. These are the disadvantages of the scheme. The advantages of both considered schemes are:

1. *Prevents the breakthrough of pyro-charge gases* into the parachute container;
2. Eliminates the incomplete exit of the parachute from the rocket model's body;
3. The influence of friction force on the parachute's deployment is almost absent, and consequently, its effect when the parachute material absorbs moisture from the atmosphere is also minimized.

Rocket models of the latter schemes, with high manufacturing quality, are more reliable than schemes for the pyrotechnic ejection of the parachute by the energy of powder gases.

MANUFACTURING ROCKET MODEL HALF-BODIES FOR NON-AXIAL PARACHUTE EJECTION

The structures of the deployable half-bodies for rocket models must be of increased rigidity, therefore it is advisable to make them from plastics by moulding, for example, from polystyrene. The body halves, frames, nose cone, brackets, and other parts made from polystyrene are best joined by welding.

Moulding and Welding Polystyrene. Styrene Polymers. Polystyrene is a high-molecular-weight, carbon-chain polymer of styrene (vinylbenzene $C_6H_5\text{-}CH{=}CH_2$). The elementary unit of the polymer chain of polystyrene is the styrene monomer with a phenyl group substituent: $-C_6H_5-CH-CH_2-$.

Polystyrene is a thermoplastic material, almost completely water-resistant, and possesses exceptionally good dielectric properties. It is resistant to the effects of weak acids and alkalis, but is destroyed by the action of strong acids, and in gasoline and petroleum products. Its disadvantage is high brittleness and low Strength; it is susceptible to aging.

From polystyrene, parts for rocket model bodies and the same parts are made as from vinyl plastic and organic glass. Polystyrene is in an amorphous state at room temperature. The technology for manufacturing the body is the same as for other plastics.

The flow temperature corresponds to 150°C, and the thermal degradation temperature is 220°C. Hence, the heating temperature of the thermal oven for stamping polystyrene parts should be 150°C, the matrix and punch at 100°C, and the workpieces at 125±3°C. In all other respects, the technological process for stamping parts from polystyrene is the same as for vinyl plastic.

Welding of polystyrene is carried out using esters, ketones (acetone, methyl ethyl ketone, cyclohexanone), aromatic hydrocarbons (benzene, toluene, xylene), and chlorinated hydrocarbons as solvents.

In industry, polystyrene parts are joined using dichloroethane, sometimes dissolving 1-5% polystyrene in it. In many cases, dichloroethane, which is a toxic solvent, is replaced. An example of such compositions, which can be used when working in clubs for joining polystyrene, is butyl acetate, into which about 4% toluene is introduced. For joining parts of complex shape, a solution of polystyrene in a mixture of the indicated solvents is used, introducing 6% bulk polystyrene into a mixture of 4% toluene and 90% butyl acetate. The pressing time at room temperature is up to 20 minutes.

BALLISTIC AND AERODYNAMIC COMMANDS FOR EJECTING THE RECOVERY SYSTEM

All the considered schemes receive commands to eject the recovery system from the Motor through a delay system or ***"directly". A variation of the delay system...***

is a pyrotechnic delay element. However, commands can be issued not only by a pyrotechnic system but also by systems triggered by aerodynamic and ballistic parameters: by dynamic pressure q or by the magnitude of the overload n. In the general case, the ratio of the force of interaction with a support to the force of interaction under normal conditions is called the overload n = P / G.

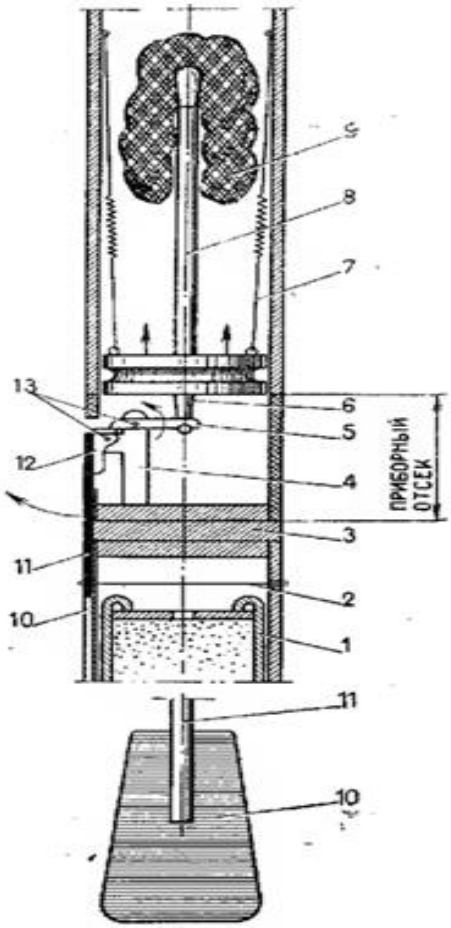
Aerodynamic Commands. In the practice of domestic rocket and space modeling, the command based on dynamic pressure is received by an aerodynamic vane. During flight, the vane is held flush against the rocket model's body by the dynamic pressure. When the dynamic pressure becomes equal to 0 or close to 0, the vane is thrown back by the action of a rubber cord. The command is transmitted to a lever system, which, in turn, releases a hook, and the parachute ejection system is activated. The ejection system itself can be in the form of a "catapult" or a spring. A scheme is possible where the lever closes contacts and triggers a pyrotechnic parachute ejection system, but this happens if the rocket model is equipped with an on-board source of electrical energy. In terms of weight parameters, this scheme is suitable for high-altitude rocket models of class S-4 and copies of class K-4.

A safety lock must be installed on the vane to prevent accidental activation at launch, when $q \neq 0$. The lock is a capron or silk thread (capron melts faster than cotton thread burns), which either passes over the upper part of the micro-SRM and melts at the end of its operation, or is looped over its metal part, if present, near its nozzle and melts during the initial stage of the micro-SRM's operation.

If you gently blow on the aerodynamic vane and it is held down by this dynamic pressure, and then, when you stop blowing, the vane activates, this means the parachute ejection system will activate at the highest point of the trajectory (apogee).

One possible design solution for the scheme is shown in Fig. 47; the micro-SRM, upon burnout, severs the thread 2, which was holding the aerodynamic vane. Under the action of the rubber cord 7, the vane 10 strives to be thrown back, which will occur at q=0. The vane 10 on the rack 11 will rotate around the axis 13 of the bracket, and the vane bracket 12 will cease to obstruct the rotation of the lever 5 around its axis. The hook 6 will disengage, and the rack 8 will eject the parachute 9.

In this mechanism, it is necessary to select the ratio of the lever arms so that the vane activates with almost zero force. The assembly of the system is complex. To simplify it, the instrument compartment of the rocket model is made from organic glass.



Deployable body of a rocket model upon command from dynamic pressure.

One possible design solution: on the fixed part of the body, an aerodynamic vane 1 is mounted on a hinge, which engages with a catch on the deployable part of the body with its tooth. The tooth enters a hole in the traverse and locks the half-body. If the vane's tooth disengages and releases the traverse, then the rubber...

Instrument Compartment

1 - micro-SRM; 2 - thread; 3 - frame; 4 - fixed bracket; 5 - lever; 6 - hook; 7 - cord; 8 - rack; 9 - parachute; 10 - vane; 11 - vane rack; 12 - vane bracket; 13 - bracket axis cord will open the body. The parachute will be exposed to the airflow and deploy.

Fig. 47. Aerodynamic command issued to the recovery system using levers:

The remaining elements of the rocket model are the same as in the previous one: the safety lock, the design of the vane and the parachute (Fig. 48).

Command issued for ejecting the recovery system based on the magnitude of overload. The magnitude of overload in flight was first measured by Professor V. P. Vetchinkin in 1918 using ordinary spring scales. Under normal conditions, the overload is equal to one $n = P / G = 1$, since the force acting on the support is equal to the weight. If the force of interaction with the support is absent, then the overload equals 0. This state is called weightlessness. Weightlessness appears at the apogee of the rocket model's flight. The mechanism for issuing a command based on the magnitude of overload is based on this principle. The mechanism itself is a simplest accelerometer.

Such an accelerometer can cut the thread that prevents the deployable body, the "catapult" or the spring, from activating (Fig. 49). The main parts in the instrument compartment are: a spring, a weight, and a razor blade that cuts the thread. Capron thread is more sensitive to nicks than cotton thread, therefore it is better to use it. The thread passes through two holes in the instrument compartment.

It is desirable to make the instrument compartment itself transparent, and since it is located far from the powder gases, it can be made not only from organic glass but also from celluloid.

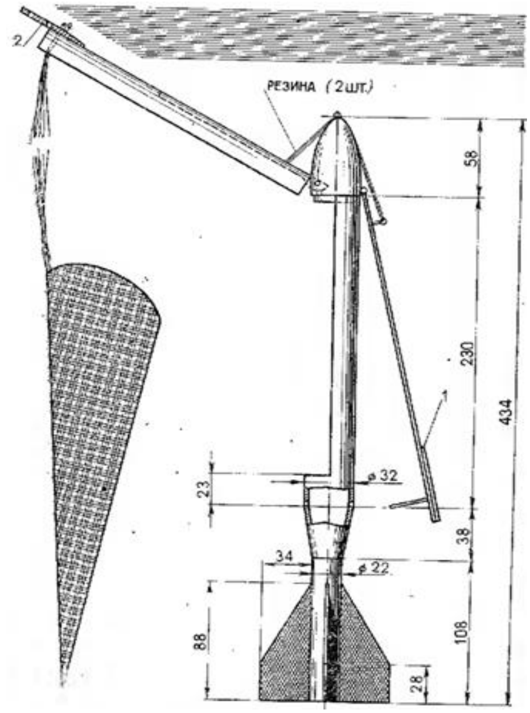


Fig. 48. Deployable body of a rocket model upon command from dynamic pressure:

1 - vane; 2 - bracket, holding the body

1 - nut (ebonite); 2 - spring (internal diameter 20 mm); 3 - rod (steel); 4 - body (organic glass); 5 - razor blade; 6 - thread (is cut at n=0)

SECURING THE MICRO-SRM IN THE ROCKET MODEL'S BODY

One of the characteristic failures during a rocket model's flight is the ejection of the Motor. This typically occurs on models that use the energy of the powder gases to eject the recovery system. If the friction forces of the parachute and the nose cone against the rocket model's body are greater than the friction force of the micro-SRM body against the model's body, then the Motor will be ejected, not the recovery system.

The rocket model must be reusable; therefore, it is not permissible to glue the Motor in place.

There are two ways to prevent Motor ejection: increase the coefficient of friction (we will assume the normal pressure force is constant - the Motor fits tightly) and secure it mechanically.

To increase the coefficient of friction, four strips of sandpaper are glued along the Motor body. To mechanically secure the Motor, an easily removable bracket is installed to limit axial movement (Fig. 50), or two pins passing through the swept stabilisers are used. Practice has shown that these are simple and reliable methods for securing Motors in rocket models.

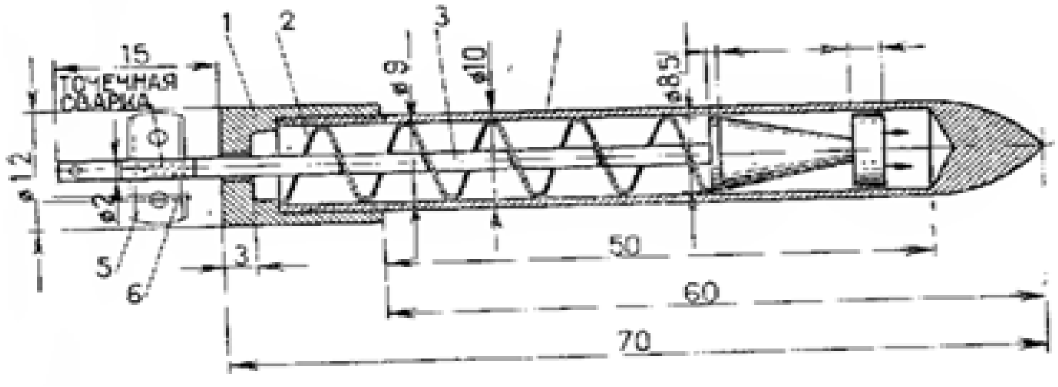


Fig. 49. Accelerometer for axial overloads:

7. MANUFACTURING DURATION-FLIGHT MODEL-COPIES

MODEL COPIES OF SOVIET EXPERIMENTAL, GEOPHYSICAL, AND RESEARCH ROCKETS

The history of Soviet rocket building begins with GIRD, founded in April 1932 in Moscow. Similar groups were created in Leningrad (LenGIRD and GDL), Kharkov, and other cities.

In these small scientific and technical cells, almost all future directions of rocket building and cosmonautics were concentrated. Motorers worked on rocket designs, liquid Motors and component feed systems, ramjet air-breathing Motors, developed testing methodologies, created ground support complexes, devised systems for observing and monitoring the rocket in flight, and methods for returning its payload to earth. They dealt with gas dynamics, heat transfer, materials science, combustion chemistry, automation, supersonic flight aerodynamics, and even what would later be called space medicine. In 1933, GIRD and GDL were merged into the RNII.

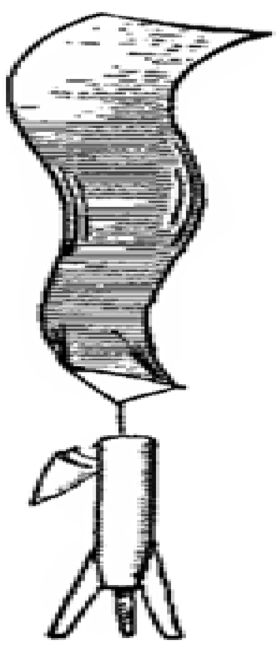
Model copy of the Soviet experimental rocket GIRD-09

GIRD-09 was the first Soviet experimental liquid-propellant rocket, created in GIRD based on the design of *M. K. Tikhonravov* and manufactured under the leadership of S. P. Korolev. Its launch weight was 19 kg, fuel weight 15 kg, length 2405 mm, diameter 180 mm, and stabilizer span 650 mm.

The Motor, with a thrust of 25-33 kg, ran on liquid oxygen, fed into the chamber by the pressure of its own vapours, and on solidified gasoline, which was placed in the combustion chamber. Launch was performed from vertical guides. During its first flight on August 17, 1933, it reached

§ 2.1. Streamer Design and Calculation

Streamers are the recovery device, the best selection for lightweight rockets (typically under 50 grams), low-altitude flights, or models with very limited body tube volume for packing a parachute. This design consists of a long, thin strip of brightly coloured, lightweight material like Mylar, plastic tape, or rip-stop nylon, which ensures high visibility during descent. A good starting ratio,



Effective sizing includes a practical ratio: the streamer's length should be *10 to 15* times the body tube's diameter, while its width should be roughly *1/3rd to ½* of the body tube's length. This specific geometry creates a large surface area that generates significant aerodynamic drag to slow the rocket's fall, while the elongated, narrow form prevents the rapid spinning that can occur with shorter, wider strips, resulting in a stable and controlled return to earth.

§ 2.2. Parachute Design and Calculation

The parachute is the most effective device for achieving a slow, controlled, and predictable descent. Its design is a deliberate exercise in balancing physics, material science, and practical geometry to ensure the rocket returns to Earth safely and is ready to fly again.

Application and Purpose

Parachutes are best suited for heavier rockets and all models where a slow, stable descent is critical to prevent damage upon landing. Unlike a streamer, which primarily prevents a high-speed tumble, a parachute actively decelerates the rocket by creating a large, sustained drag area, dramatically lowering its terminal velocity.

Canopy Geometry: A Balance of Stability and Efficiency

The shape of the parachute canopy, known as its planform, directly influences its drag coefficient (Cd), stability, and ease of construction.

1) *Hexagonal/Octagonal Planform:* This is the most common and highly recommended shape for model rocketry. The polygonal design, with its six or eight sides, creates stable air vortices as it descends. This vortex stability significantly reduces oscillation (the rocking or "swinging" motion), leading to a smoother descent and less strain on the shroud lines. It offers an optimal balance of high drag, inherent stability, and straightforward construction from flat sheets of material.

2) *Circular Planform*: While the circle is a naturally efficient shape, a simple flat circular parachute is prone to instability in descent. The air can "slosh" unevenly under the canopy, causing it to oscillate or even collapse in a phenomenon known as "canopy breathing." While slightly easier to cut from a single piece of material, this instability makes it a less desirable choice than a hexagonal shape for most applications.

Sizing the Parachute: From Physics to Practicality

Selecting the correct parachute size is fundamental. An undersized chute leads to a hard landing; an oversized one risks the rocket being carried far downwind. We can approach this through precise calculation or a reliable rule of thumb.

1. *The Physics-Based Calculation:*

To achieve a specific, target descent rate, use the following equation derived from the drag equation at terminal velocity:

$$Area = \frac{(2 \times Rocket\ Mass \times g)}{\rho \times V^2 \times C_d}$$

<u>*Area:*</u> The required surface area of the parachute canopy (in square meters, m^2).

<u>*Mass of Rocket:*</u> The total mass of the descending rocket, *including* the spent motor (in kilograms, kg).

g: Acceleration due to gravity (9.8 m/s^2).

ρ: Density of air (approximately 1.22 kg/m^3 at sea level).

v: Your desired descent velocity (in meters per second, m/s). A safe target is *3.5 to 4.5 m/s.*

C_d: Drag Coefficient. For a flat sheet plastic or nylon parachute, a value of *0.75* is a standard and reliable estimate.

Example Calculation:

For a rocket with a mass of 0.5 kg (500g), targeting a descent rate of 4.0 m/s:

$$Area = \left(\frac{(2.05\ kg \times 9.8 \frac{m}{s^2})}{1.22\ kg/m^3 \times 4^2 m/s^2 \times 0.75} \right)$$

Area = (9.8) / (1.22 × 16 × 0.75)
= 9.8 / 14.64 ≈ *0.67 m^2*

To convert this to a practical diameter for a *circular* equivalent:

$$Diameter = 2 \times \sqrt{\left(\frac{Area}{\pi}\right)};$$

$$\text{Diameter} = 22 \times \sqrt{\left(\frac{0.67}{3.14}\right)} = 0.92\ \text{m}$$

For a hexagonal chute, you would design one with a similar total area.

2. The Simplified Rule of Thumb:

For quick estimates and low-power rockets, a reliable guideline is to provide *100 to 150 square centimetres of parachute area for every 100 grams of rocket mass.* For a heavier 500g rocket, this suggests a parachute area of 500 to 750 cm^2 (or 0.05 to 0.075 m^2). This simpler method errs on the side of a slightly faster descent but is very practical for beginner and mid-power projects.

The Stabilising Role of the Spill Hole

A key feature of a well-designed model rocket parachute is the *spill hole*—a circular hole cut in the apex (top centre) of the canopy. Its functions are critical:

a) *Oscillation Damping:* As the parachute descends, air must flow around the sides of the canopy. Without a spill hole, this airflow can become irregular, causing the parachute to rock or swing violently. The spill hole provides a controlled, central exit for air, stabilising the descent by preventing the asymmetric shedding of air that causes oscillation.

b) *Canopy Integrity*: During the initial inflation or in turbulent air, a parachute without a spill hole can "breathe," where the canopy partially collapses and re-inflates. This inconsistent inflation can lead to a higher average descent rate. The spill hole maintains a steady internal pressure, promoting consistent and full inflation.

c) *Sizing:* A spill hole typically constitutes *10% to 20%* of the total canopy area. A hole in this range provides excellent stability without significantly reducing the overall drag. The area of the spill hole itself is *not* included in the calculated canopy area used for your sizing equations.

§ 2.3. Shroud Line and Attachment

i. *Length:* Shroud lines should be 1 to 1.5 times the parachute's diameter.
ii. *Material:* Strong, lightweight string like nylon or Kevlar thread. Kevlar is highly recommended for its heat resistance.
iii. *Attachment:* Securely tie or loop shroud lines through reinforced holes at the canopy's periphery. Distribute them evenly for a stable descent.

§ 3. Deployment Methods

How and when the recovery system is deployed is as important as the device itself.

§ 3.1. Ejection Charge Deployment (Black Powder)

Principle: The rocket motor's delay element burns through after powered flight, igniting a small black powder charge at apogee (the highest point of the flight).

Mechanism: The rapid pressure build-up from this charge blows off the nose cone, pushing out the recovery system.

Operational Requirements:

Recovery Wadding: Cellulose or paper-based wadding must be packed between the motor and the recovery system to protect the parachute from the hot ejection gases.

Flame-Resistant Blanket: A reusable alternative to wadding, made of Nomex or other high-temperature fabric.

§ 3.2. Tumbling Recovery

Principle: For very small, lightweight rockets, the simplest recovery is to have no dedicated device. The ejection charge is used to destabilise the rocket, causing it to tumble back to Earth.

Method: The shock cord is attached to the inside of the body tube, just behind the nose cone. When the charge fires, the nose cone and parachute are not released, but the sudden shift in mass distribution induces a tumble.

§ 3.3. Redundant Systems:

Introduction to Dual Deployment

Principle: A two-stage deployment system for high-altitude flights. A small drogue parachute is deployed at apogee to stabilise and slow the descent. Then, a larger main parachute is deployed at a low altitude (e.g., 200 meters) for a soft landing.

Advantages:

1. Prevents the rocket from drifting miles downwind under a large chute at high altitude.
2. Provides greater control and precision for recovery location.
3. Reduces the risk of landing under a fully inflated chute in high winds.

§ 4. Electronic Deployment Systems

For advanced rocketry, electronic altimeters provide precise control and redundancy.

§ 4.1. The Role of the Altimeter

The main Function of an electronic altimeter is to measure barometric pressure to determine altitude. It can be programmed to trigger ejection charges at specific events: at apogee, at a specific altitude, or after a specific time delay.

This is the most reliable deployment method. The altimeter detects the moment the rocket's ascent stops by sensing the apogee and its velocity when it becomes zero at the apogee, firing the charge precisely at the optimal moment.

§ 4.2. Wiring an Avionics B

An avionics bay is a sealed section within the rocket containing the following main components:

1. The altimeter.
2. A 9V battery or LiPo pack.
3. An on/off switch accessible from the outside.
4. Output terminals for e-matches (electronic igniters) connected to ejection charges.

Isolation: The av-bay must be airtight to prevent ejection gases from falsely triggering the altimeter or damaging it.

Redundancy: Advanced systems often use two independent altimeters for critical safety.

§ 4.3. Testing and Safety Procedures

1. **Ground Testing:** *Always test your ejection system* without the rocket motor, using a fresh battery and a dummy load (e.g., an LED in place of the e-match) to verify the altimeter fires as programmed.
2. **Continuity Checks:** Use a multimeter to check the resistance of your e-matches immediately before installation. Never check continuity with the altimeter powered on.
3. **Physical Security:** Ensure all components in the av-bay are securely mounted with foam or zip-ties to survive the forces of launch.

§ 5. Troubleshooting Common Recovery Failures

1. *Problem: "The 'Chute Didn't Deploy" (Lawn Dart)*

Causes: Forgotten recovery wadding; recovery system packed too tightly; failed ejection charge; nose cone stuck due to friction or paint.

2. *Problem: "The Shock Cord Burned Through" (Zippering)*

Cause: The ejection charge fires while the rocket is still under high-speed, coasting ascent. The sudden deployment snaps the cord taut, and the body tube's sharp edge cuts through it. The solution is to use a longer, elastic shock cord or Kevlar and ensure deployment at or near apogee.

3. *Problem: "The Parachute Melted"*

Cause: Insufficient or forgotten recovery wadding/flame blanket. The hot ejection gases directly contacted the nylon canopy.

4. *Problem: "The Rocket Came Down Ballistically, but the Ejection Charge Fired on the Ground"*

Cause: The motor's delay element was too long, causing the rocket to hit the ground before the charge ignited. Use a motor with a shorter delay.

A Note on Safety: The recovery system is your rocket's primary safety system. Always double-check its packing, connections, and deployment mechanism before every flight. A successful recovery is a safe recovery.

8. AERODYNAMICS AND STABILITY OF ROCKET MODELS

§ 1. AERODYNAMIC FORCE AND ITS COMPONENTS

When a rocket model moves in the air, a force arises that resists its motion. This force appears as a result of the interaction of the air with the surface of the moving rocket model. This cumulative effect is known as the *total aerodynamic force*. This concept implies the resultant of all friction and pressure forces that act on the model Rocket during its flight. This force, acting directly opposite the direction of motion, is the total aerodynamic force in its simplest form.

This fundamental force can be easily visualised by considering a flat plate positioned perpendicular to an airflow. For example, a total aerodynamic force arises when an airflow strikes a plate positioned perpendicular to the direction of the flow. The air exerts a force upon the plate, pushing it back if the plate is moving through still air, or holding it in place if the air is flowing onto a stationary plate. This force hinders the movement of the plate (if the plate is moving in a stationary...

Critical Considerations for Staging and Ignition

A crucial detail must be addressed for multi-stage rockets. Upon burnout of the second-stage motor, the thermal impulse is transferred to a fuse train (stopin) housed within a central tube. The combustion of this fuse generates gases, and a vent path for these gases is absolutely mandatory; failure to provide one will result in the over-pressurisation and rupture of the second-stage airframe. To prevent this, two or more drain holes, precisely aligned opposite one another and with a diameter of 6–7 mm, must be drilled into the casing.

To ensure the simultaneous ignition of all four booster modules for the second-stage Motor—which must fire at once—the use of a "pyrotechnic cross" is highly recommended. This device ensures the flame front is distributed uniformly and instantaneously to all four units.

Motor ignition failures can occur for a variety of reasons. In electrical ignition systems, common issues include poor contact at the terminals, broken wires, insufficient current, a failed igniter filament, or a faulty pyrotechnic element. The latter is a frequent culprit, often due to a dampened igniter charge, or a low-quality fuse that may contain excess moisture or binder.

In any case of an ignition failure, a mandatory safety rule must be observed: if instantaneous ignition does not occur, one must wait for a period of three to four minutes before attempting to approach or restart. It is not uncommon for an Motor to exhibit a significant delay, igniting one to two minutes after the initial start command. This hazardous situation is typically caused by a dampened, damaged, or substandard fuse that does not burn cleanly but instead smoulders, slowly propagating the flame to the main rocket motor grain, or sometimes failing to ignite it at all.

The Components of Aerodynamic Force

When an object is placed within a flowing fluid, such as air, it experiences a resultant force known as the *total aerodynamic force*. To understand its effects, it is useful to resolve this single force into components relative to the direction of the oncoming flow.

Consider a simple flat plate. If it is held perfectly perpendicular to the airflow, the air simply pushes against it. The aerodynamic force generated acts directly opposite to the direction of the flow, pushing the plate backwards if it is moving, or holding it steady if the air is moving past a stationary plate. This force, acting directly "head-on" against the motion, is termed the *Drag Force (X),* as illustrated in Figure 27.

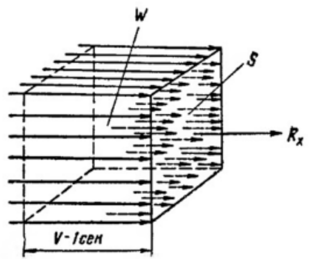


Fig. 27 Application of Aerodynamic Forces

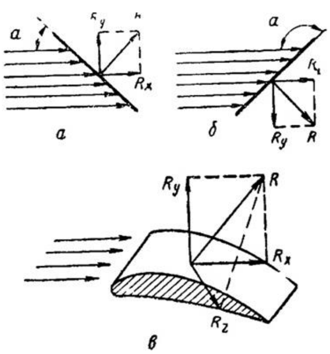


Fig. 28. Acting Aerodynamic Forces

The situation becomes more nuanced when the plate is inclined at an angle to the flow, as shown in Figure 28a. The total aerodynamic force can now be resolved into two distinct components. The component perpendicular to the direction of the oncoming flow is called the *Lift Force (Y).* This is the force that lifts a rocket from the launchpad or sustains an aircraft in level flight. It is crucial to note that lift is not always directed upward; its direction is defined by the orientation of the object. A plate at a positive angle of attack generates lift upward, while the same plate at a negative angle, as in Figure 28b, produces a downward lift force.

This principle of force resolution extends directly to more complex shapes like an airfoil or wing (and, by extension, to the largest cross-section of a rocket body). As flow passes over a wing, we again observe the generation of both drag (X) and lift (Y). If the wing is then rotated about its longitudinal x-axis—a motion known as yaw—a third component emerges: the ***Lateral Force (Z)***. This side force acts to the right or left, depending on the direction of the wing's rotation relative to the wind.

It is vital to remember that these three forces—drag, lift, and lateral force—are a conceptual convenience. In physical reality, there exists only one resultant aerodynamic force acting upon the body. We decompose it into these orthogonal components for practical necessity. This approach allows Motorers to experimentally determine the magnitude and direction of each component independently. Once known, they can be recombined using the parallelogram rule of vector addition to accurately reconstruct the full, three-dimensional aerodynamic force acting on the vehicle.

Air Resistance (Drag)

When you inflate the balloon and then let it fly, it spins around, and you have no idea where it is going. This is because air resistance is a major force that prevents balloons from flying. This force is proportional to the shape of the object and the density of the air, and also increases in proportion to the square of the speed. This is expressed by the equation:

D=1/2CpV2A

As shown in the figure on the right, try swinging your arm with your palm up or down. If you swing it slowly, you will not feel much difference, but if you swing quickly, you will notice the magnitude of resistance changes depending on your hand shape. This is because the resistance is proportional to the reference area (projected area) of the object and also proportional to the square of the velocity.

The drag coefficient (C) varies depending on the shape and surface of the object, and the coefficients for 4 types of shapes are shown below.

Drag Coefficient

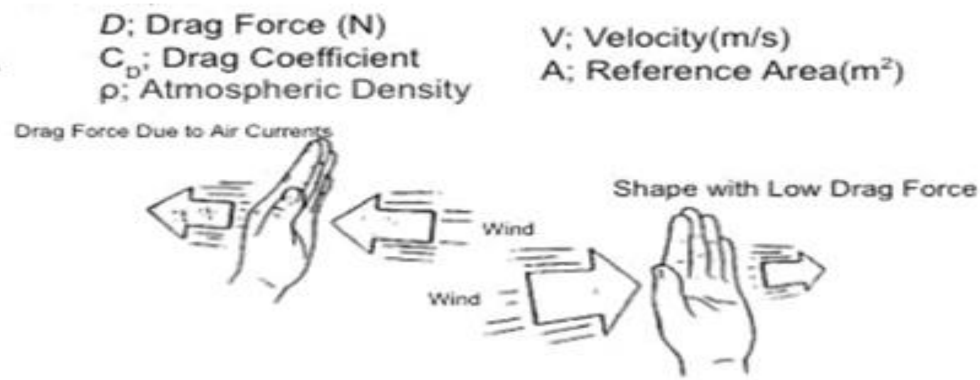
D; Drag Force (N)

C.; Drag Coefficient p: Atmospheric Density Drag Force Due to Air Current

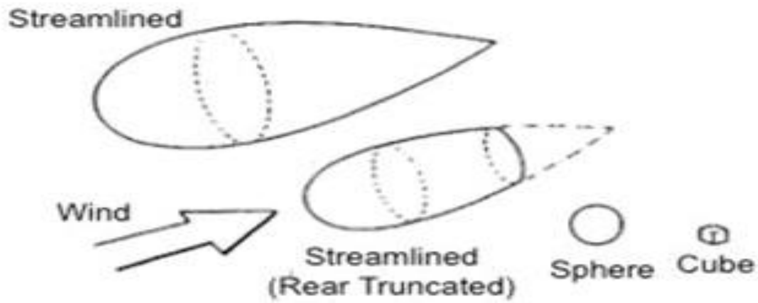
Wind

V; Velocity(m/s)

A; Reference Area(m2)



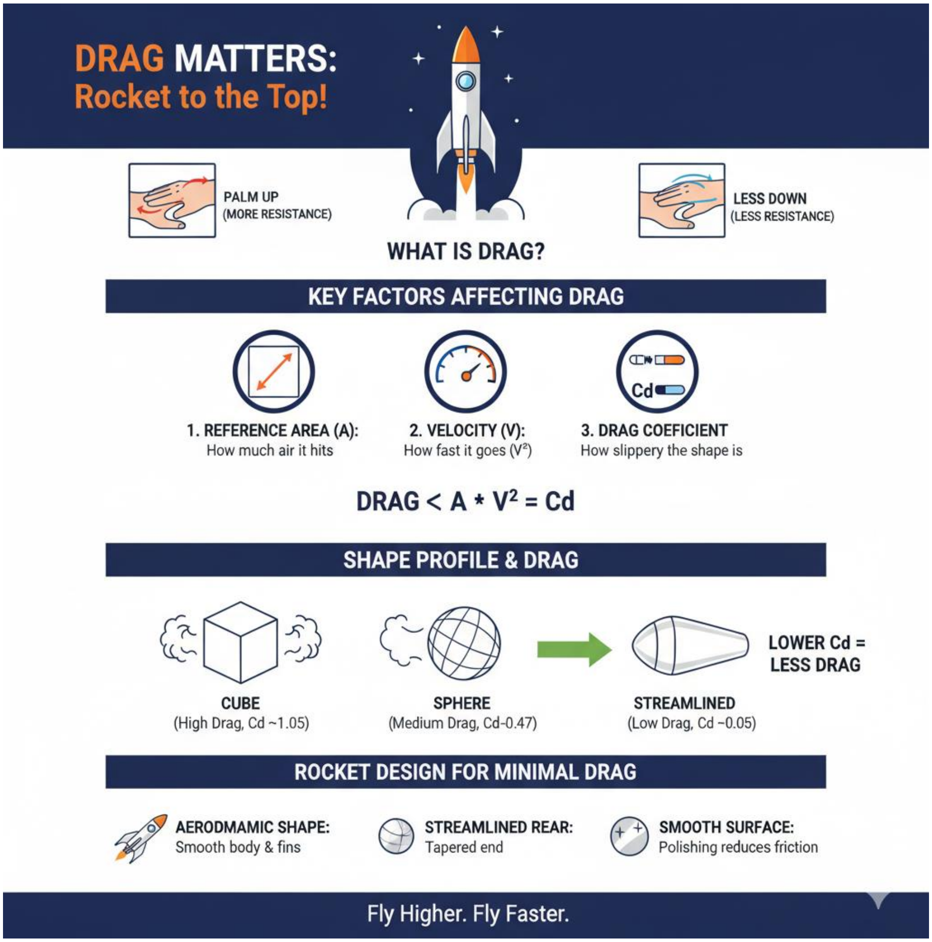
Drag force will differ based on the shape of the object.



Comparison of object sizes when drag is equal

Shape	**Drag Coefficient (C)**	**Relative Drag (Comparison)**
Cube/Square	1.05	Very High Drag
Sphere	0.47	Medium Drag
Streamlined (Rear Truncated)	0.1	Low Drag
Streamlined (Full)	0.05	Very Low Drag (Best Aerodynamics)

To make a model rocket fly high, it is necessary to reduce as much air resistance(drag) as possible. This drag is divided into four types depending on how it is generated: skin friction drag, form drag, induced drag, and interference drag. To reduce drag, the shape of the rocket body and fins (tail fins) should be made smooth and aerodynamic, and if possible, the rear of the rocket should be streamlined. Painting or polishing the surface is also effective.



The drag force is equal to:

$$X = C_x \times \left(\frac{\rho v^2}{2}\right) \times S$$

Similarly, the equations for the lift force and the lateral force are:

$$Y = C_y \times \left(\frac{\rho v^2}{2}\right) \times S$$

$$Z = C_z \times \left(\frac{\rho v^2}{2}\right) \times S$$

where:

$\left(\frac{\rho v^2}{2}\right)$is the dynamic pressure;

V is the velocity (m/sec);

ρ is the air density ($kg \cdot sec^2/m^4$), near the ground $\rho \approx 0.125\ kg \cdot sec^2/m^4$;

Cy is the lift coefficient;

Cz is the lateral force coefficient;

S is the area of the largest cross-section of the model rocket, perpendicular to the incoming airflow (m^2);

Cx is the drag coefficient.

The drag coefficient Cx, lift coefficient Cy, and lateral force coefficient Cz are analogous in nature. Calculating these coefficients is a difficult task; they are determined approximately and then refined based on wind tunnel test results.

The model rocket is placed in a wind tunnel, through which an airflow of a certain speed passes, and the forces acting on it are measured. Afterwards, the aerodynamic coefficients, including the value of Cx, are calculated.

There are other methods for determining the value of Cx, for example, by comparison with existing model rocket designs. Therefore, it is necessary to maintain the same shape for the model rocket that was tested in the wind tunnel.

The drag coefficient C_x is a dimensionless quantity that depends mainly on the rocket's shape and flight speed. Since the drag coefficient remains approximately constant for subsonic speeds, and in rocket modelling we deal with precisely such speeds, we will not consider the influence of velocity on Cx. The value of the coefficient also depends on the angle of attack, the surface condition of the model rocket, and a number of other factors, which we also will not consider.

The shape of the model rocket has a significant influence on the value of Cx. From an aerodynamic standpoint, the best shape is the one that minimises the value of Cx. Therefore, with the goal .to achieve the minimum possible drag for a given speed range, one must strive for the optimal shape of the model rocket.

The fineness ratios (length-to-diameter) of model rockets, $\lambda = l/d$, can range from 8 to 30, with an average diameter of 25 mm. The value of the drag coefficient C_x for this geometry can be taken from 0.25 to 0.4, with the lower C_x value corresponding to the optimal fineness ratio of the model rocket: $\lambda \approx 22$. The cross-sectional area S of the rocket is calculated based on the maximum body diameter D: cases where,

$$S = \frac{\pi \times D^2}{4} \qquad (19)$$

§ 2. FLIGHT STABILITY OF MODEL ROCKETS

Stability is one of the most important factors to consider when designing your own rocket. Manufactured kits are pre-tested for stability. Since you are not building a manufactured kit for this project, you must show your rocket is stable before launch. At launch, one can sometimes observe a model rocket, upon leaving the launch rail, instead of vertical (directed) flight, starts to tumble. The frustrated designer often does not understand the reason for the unstable flight. However, the stability is explained simply: the CENTER OF PRESSURE and the CENTER OF GRAVITY of the model rocket are incorrectly positioned.

Never launch a rocket until after its stability has been proven.

For stable flight of a model rocket, the CENTER OF GRAVITY (C.G.) of the model rocket must be ahead of the CENTER OF PRESSURE (C.P.). Practically, in rocketry modelling, the distance between them should be at least one diameter of the model rocket (Fig. 29).

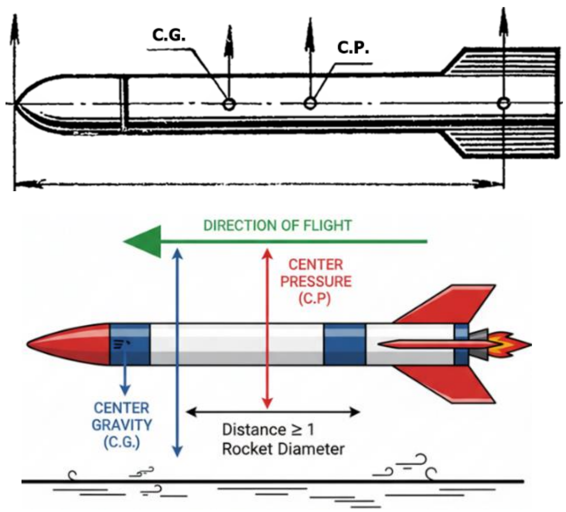


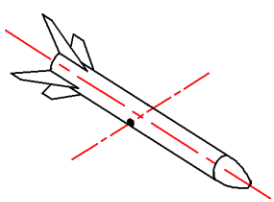
Fig. 29. Location of the C.G. relative to the C.P. on a model rocket

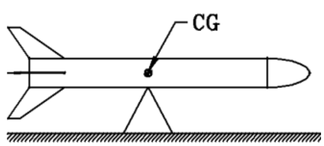
Proving your rocket is stable involves determining the center of gravity (CG) and center of pressure (CP), also known as the point of pressure. If you have a multistage rocket, you must find all of the CG and CP locations and show that each stage is stable. Also, don't forget to test your rocket for stability after you have painted it and applied any decals. Both can change a rocket's stability.

Centre of Gravity

The centre of gravity is found by finding the balancing point of the prepared rocket. A prepared rocket is "ready for launch." This means your rocket is finished and painted, the recovery system is properly prepared for flight, and an Motor is loaded in your rocket. The Motor is not to be armed while finding the CG location of your rocket. Mark the CG location on your rocket.

The centre of gravity is found by finding the balancing point of the prepared rocket. A prepared rocket is "ready for launch." This means your rocket is finished and painted, the recovery system is properly prepared for flight, and an Motor is loaded in your rocket. The Motor is not to be armed while finding the CG location of your rocket. Mark the CG location on your rocket.





Centre of Pressure (CP) or Point of Pressure

You can find the point of pressure using one of these three methods:

The Barrowman Method, which is not explained here, involves mathematical calculations. If you choose to use this method, you are expected to show your work.

Model rocket software programs, which are not explained here, are readily available. If you use this method, you are expected to show a printout of this information.

The cardboard cutout method, described below, works fine for most rockets. This method is the simplest, but it has its limitations with complex designs relying on base drag or other more complex methods to increase stability. (It can show "false" stability issues.) If you use this method, you are expected to bring your cutout with the C.P. location marked.

Cardboard Cutout Method)

a) Start by drawing your rocket "full size" on a piece of cardboard or foam poster board. Start with the length and width of the body tube, and then trace the fins and nose cone. Ensure that the cardboard or foam poster is strong enough to keep from bending. For long models, thin wood may be required.

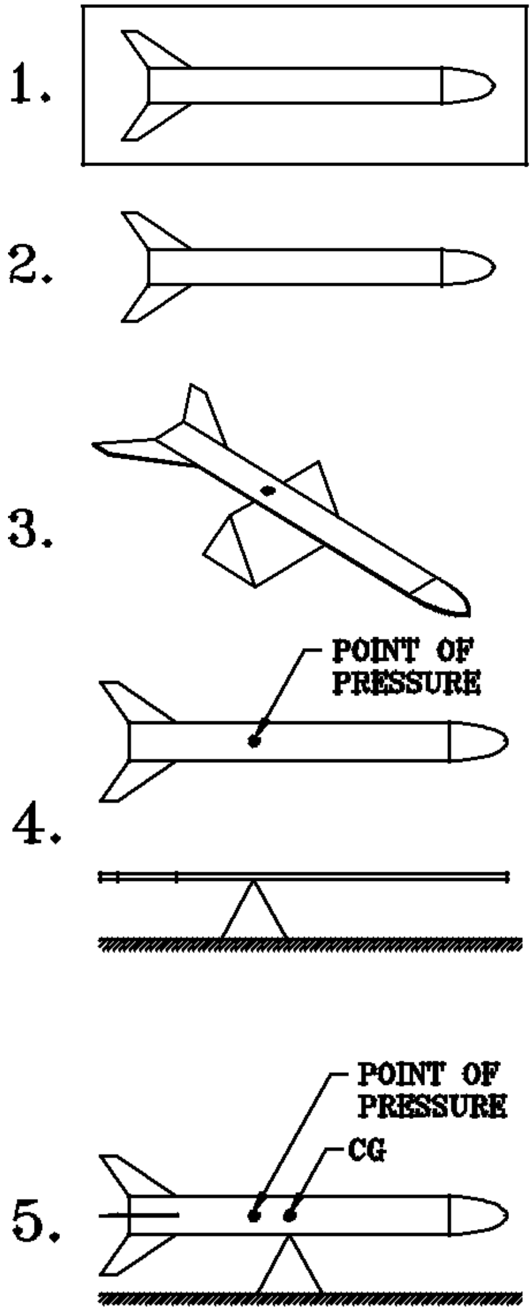
b) Carefully cut out the drawing.

c) Find the balancing point of the cutout. This is the CP, or point of pressure.

d) Mark the point of pressure on the cutout.

e) Measure the point of pressure from the base of the cutout and transfer it to your rocket.

Divide the largest diameter of your rocket in half. Compare the half-diameter length to the length between the CG and CP locations you found on your rocket. If the GG is at least this half-diameter length in front of the CP, your rocket is stable.



More precisely, you can numerically find the C.P. of a model rocket after the C.G. of the Planform of the model rocket is determined. Let's describe one of the simplest methods for finding the C.P. On the drawing of the model rocket (Fig. 30), the dimensions of the model rocket are given, as well as the distances from the nose of the model to the centres of gravity of individual flat shapes. For example, the nose section of the model rocket on the plane represents a triangle. The body is a rectangle; the stabiliser fins consist of a triangle and a rectangle. The centres of gravity of the shapes are found geometrically; the distances to them from the nose of the model are measured.

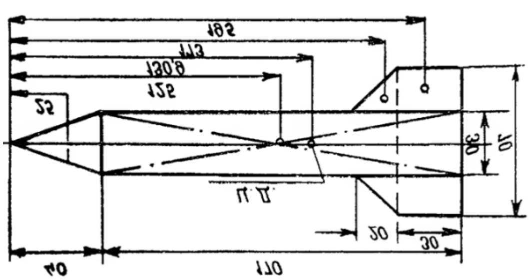


Fig. 30. Flat Silhouette of the Model Rocket

The sum of all moments from the nose of the rocket's projection, divided by the total area of the model's flat silhouette, gives the distance from the nose of the projection to its C.G., and consequently, to its C.P. In the given example, the total area of the model rocket's flat silhouette is: $F = F_{nose} + F_{body} + F_{stabilizers} = 600 + 5100 + 1200 + 400 = 7300\ mm^2$.

The sum of the moments is composed of the moments of all the flat shapes (the moment is equal to the product of the area of the flat shape and the distance from the model rocket's nose to its C.G.):

a) $600\ mm^2 \times 25\ mm = 15000\ mm^3$;

b) $5100\ mm^2 \times 125\ mm = 637500\ mm^3$;

c) $1200\ mm^2 \times 195\ mm = 234000\ mm^3$;

d) $400\ mm^2 \times 173\ mm = 69200\ mm^3$.

Sum of moments: $955700\ mm^3$.

The distance from the nose of the model rocket's projection to the C.G. of the flat silhouette, i.e., to the model's C.P., is:

$L = 955700\ mm^3 / 7300\ mm^2$

L = 130.9 mm.

The calculated C.P. is marked on the drawing and on the model rocket. By measuring a distance equal to the diameter of the model rocket from the C.P. towards its nose, we obtain the lowest permissible position for the C.G.

When the model rocket is fully assembled, it is necessary to check the position of the C.G. For this, the model is placed horizontally balanced on the point of a knife or on the edge of a ruler (Fig. 31). If the model's actual C.G. is below the marked limit, it is necessary to add weight to the nose section of the model rocket (e.g., with modeling clay) or to increase the area of the stabilizers. In the first case, the C.G. will move forward, and in the second, the C.P. will move backwards.

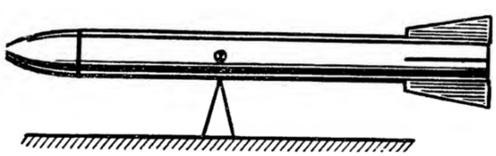


Fig. 31. Checking the correct position of the C.G. on the model rocket

As a rule, it is recommended to position the C.P. as low as possible. If the model is not carrying a payload, it is better to lower the C.P. by increasing the area of the stabilisers rather than by loading the model with useless weight. Furthermore, by increasing the stabiliser area to optimal dimensions instead of adding weight, we achieve the lowest possible starting weight, $M_{initial}$ for the model rocket.

For younger schoolchildren, it is recommended to determine the C.P. using the method shown in Fig. 32. The C.P. is found by balancing a flat cutout of the model rocket, made according to the drawing, on the edge of a ruler.

The stability of a model rocket in flight, and especially at the moment it leaves the launch rail, depends on its speed at launch and the wind speed. During strong winds, the model rocket will inevitably deviate from its intended trajectory. In windy conditions, one should not launch unguided scale models, which have a large lateral surface area, and model rockets with low acceleration a = (1 – 2)g. Moreover, the lower...

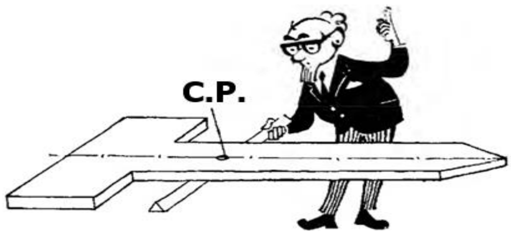


Fig. 32. A practical method for determining the C.P. of a flat silhouette of the model rocket

the acceleration of the rocket model will be, the more it will deviate from the intended trajectory.

The correct attachment of stabilisers is of great importance for stable flight. Even one stabiliser, not aligned with the axis of the model rocket, will cause it to veer off the intended trajectory. Another reason for the instability of a model rocket in flight is the presence of asymmetrical objects on its body. For example, launch lugs or tubes for the launch rod are often attached to one side of the model. These rings or tubes are sometimes of such size that they clearly interfere with flight in the intended direction. In such cases, a part of equal aerodynamic resistance should be attached to the opposite side.

Swing Test for Stability

One of the best ways to test the stability of a model rocket is with a "swing test." The steps for conducting a swing test are below, but remember, when you swing the rocket, make sure you are in an open area away from any people or objects.

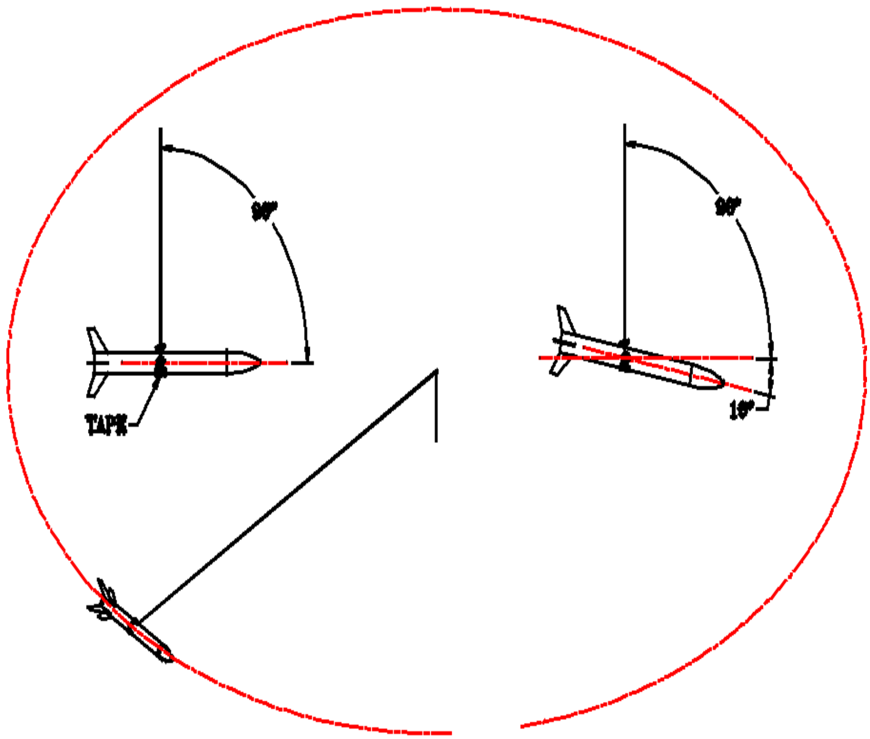
a) *Prepare the rocket by packing the recovery system,* including recovery wadding, in your rocket. Then place the heaviest rocket motor that will fit in your rocket. (For example, place a C6-5 instead of an A8-3.) No igniter is inserted in the motor for this test.

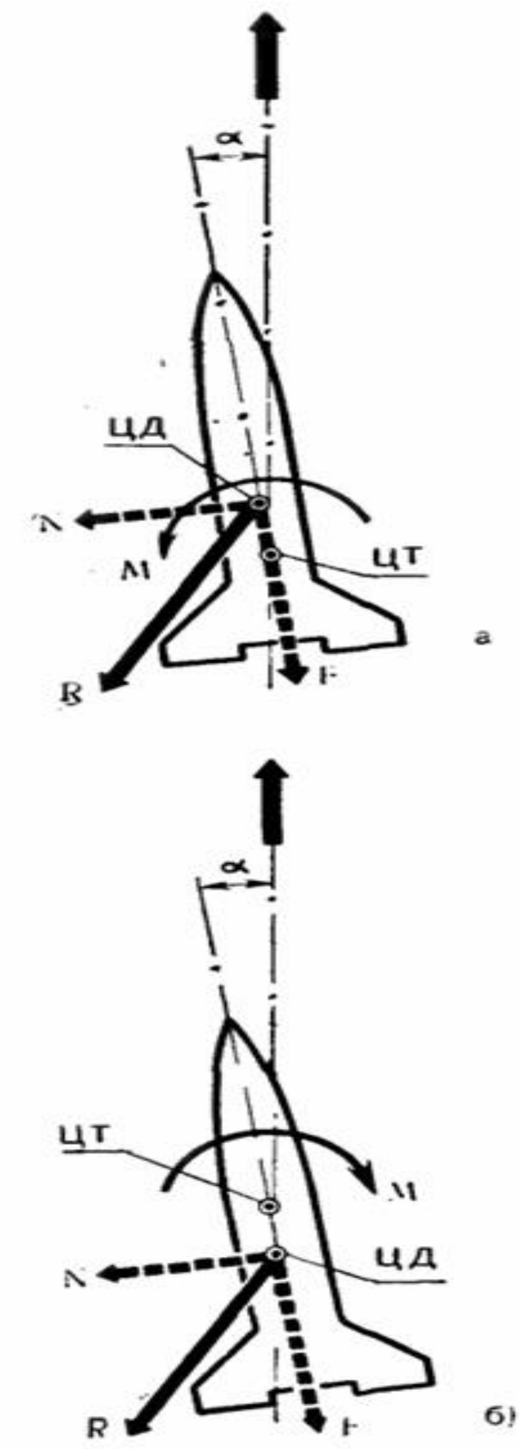
b) *Tie a loop* in one end of 6-10-foot piece of string. Tie it around the body tube where the rocket balances horizontally (90° from the string). Place a piece of tape to keep the string from sliding off the CG.

c) *Start swinging the rocket overhead* with the nose cone facing forward. It may take several attempts to get the rocket to start this way. If the rocket continues to face forward, continue to step 4. If the rocket tries to turn around backwards, stop the test, and add weight to the nose. This usually can be done by packing some clay into the nose cone. Then repeat steps 1-3.

I. Loosen the tape and move the string towards the back of the rocket until the nose points down 10° from horizontal then re-tape the string.

II. Start swinging the rocket overhead with the nose cone facing forward, just like before. If the rocket continues to face forward, you have a stable rocket. If the rocket tries to turn around backwards, stop the test, and add weight to the nose. Then repeat steps 4 and 5.

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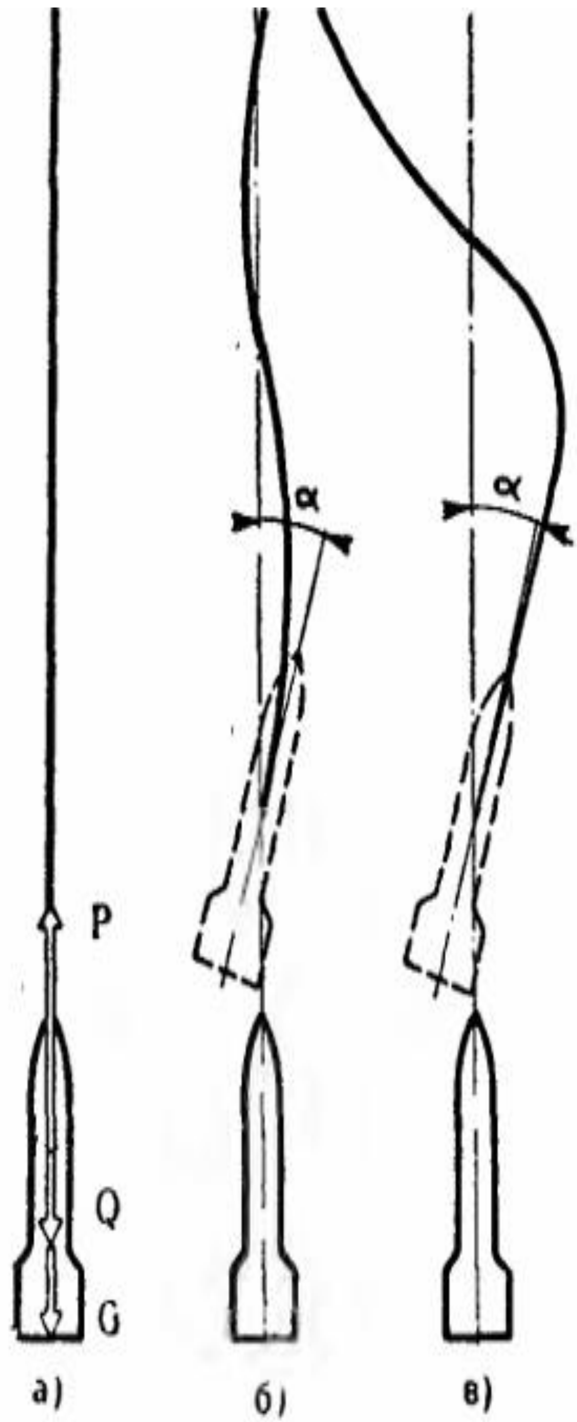
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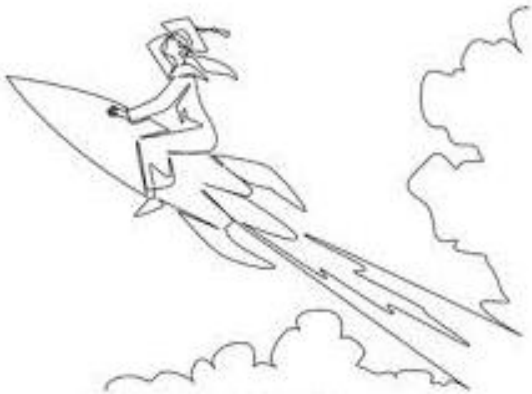
9. FLIGHT PARAMETERS OF MODEL ROCKETS



Designing, building, and launching model rockets is not easy. Especially when the designer strives to achieve the highest results in competitions.

An athlete's success largely depends on the correct choice of Motor for the model. Another step towards achieving a record is knowledge of the laws of motion of the model.

In this chapter, we will familiarise ourselves with concepts related to motion: Velocity, acceleration, and other factors affecting flight altitude.

The flight qualities of model rockets mainly depend on the following factors:

$M_{intiali}$ - starting weight of the model rocket (kg);

M_{prop} - weight of the fuel (kg);

I_{total} - total impulse of the Motor(s) (kg·sec);

$I_{specific}$ - specific impulse of the Motor(s) (kg·sec/kg);

V - velocity of the model rocket (m/sec);

F - thrust of the Motor (kg);

a - acceleration of the model rocket (m/sec^2);

t - operating time of the Motor(s) (sec);

i - number of stages of the model rocket.

§ 1. IDEAL VELOCITY OF A MODEL ROCKET

The flight altitude of a model rocket depends primarily on the speed it achieves at the end of the Motor's operation. First, let's consider how to find the final velocity of the model without taking into account the air resistance and Earth's gravity. This velocity will be called the ideal velocity of the model rocket.

To determine the velocity of the model rocket, we use the following law of mechanics: the change in the momentum of a body is equal to the impulse of the force applied to it. Momentum is the product of the body's mass (m) and its velocity (V), and the impulse of a force is the product of the force (F) applied to the body and the time (t) of its action.

$m \times V = F \times t.$

In our case, this law is expressed by the equation:

$m\ (V_{final}-V_{initial})=P \times t,$

where:

m - mass of the model rocket;

V_{final} - velocity of the model rocket at the end of the Motor's operation;

$V_{initial}$ - velocity of the model rocket at the start of movement (in this case $V_{Initial}=0$);

P - Motor thrust;

t - Motor operating time.

Since $V_{initial} = 0$ at the moment of launch, we get:

$$m \times V_{final} = P \times t. \qquad (20)$$

The mass of the model rocket changes during Motor operation as fuel burns away. We will assume that the fuel consumption is constant and that during the Motor's operation, the fuel weight decreases uniformly from M_{Prop} to 0. To simplify calculations, let's assume the average fuel weight is $\left(\frac{M_{Prop}}{2}\right)$then the average mass of the model rocket will be:

$$m_{Avg} = m_0 + \frac{m_f}{2} = \frac{G_0}{g} + \frac{G_{final} - m_{pp}}{2g}$$

Considering that P * t = I_{total} = P_specific * G_fuel, and based on the average fuel weight, we rewrite equation (20):

$$\left(\frac{M_{0Art}}{g} - \frac{M_{Prop}}{2g}\right) \times V_{final} = F_{Spec} \times M_{prop}$$

$$\left(\frac{\left(M_{0Art} - \frac{M_{prop}}{2}\right) \times V_{final}}{g}\right) = F_{spec} \times M_{Prop}$$

From which:

$$V_f = 2 \times g \times F_{spe} \times \left(\frac{M_{pro}}{2 \times M_0 - M_{pro}}\right) \quad (21)$$

Or

$$V_f = \frac{2 \times g \times F_{sp}}{2 \times \frac{M_0}{M_{pro}} - 1} \quad (22)$$

This equation is an approximate expression of the well-known K. E. Tsiolkovsky equation. It can also be written in another form, more convenient for calculation. To do this, multiply the numerator and denominator of the right side of the equation by g:

$$V_f = \frac{F_{Spec} \times g \times M_{Pro}}{M_0 - \frac{M_{Pro}}{2}} \quad (23)$$

Calculating Model Rocket Velocity

To design and predict the flight of a model rocket, it is essential to calculate its speed. We will explore three key concepts: a simple ideal speed, a more accurate ideal speed, and the final real-world speed.

1. A Simplified equation for Ideal Velocity

We can first estimate the rocket's ideal speed using a simplified equation. This "ideal" speed ignores air resistance and gravity to give us a basic theoretical value.

The equation is:

$$V_f = \frac{I_{sp} \times g \times M_{pro}}{M_0 - \frac{M_{Pro}}{2}}$$

Where: V_f is the ideal final velocity (in m/s); *Isp* is the specific impulse of the motor (sec).

g is the acceleration due to gravity (9.81 m/s^2).

M_{Pro} is the weight of the propellant (in kg).

M_0 is the rocket's initial launch weight (in kg).

Problem Example 4:

Calculate the ideal speed of a single-stage model rocket with the following data: Initial Launch Weight (M_0) = 0.1 kg; Specific Impulse (Isp) = 30 s; Propellant Weight (M_0) = 0.018 kg;

Solution:

Using the equations above:

V_f = (30 × 9.81 × 0.018) / (0.1 - (0.018 / 2))

V_f = (5.2974) / (0.1 - 0.009)

V_f = 5.2974 / 0.091

V_f **≈ 58.2 m/s**

§ 2. The Tsiolkovsky Rocket Equation

A more precise method for calculating the ideal speed is to use the fundamental rocket equation, derived by Konstantin Tsiolkovsky. This equation uses the logarithm of the mass ratio.

The equations are:

$$V_f = V_e \times ln\, ln\left(\frac{M_0}{M_f}\right)$$

or, equals to

$$V_f = I_{sp} \times g \times 2.3026 \times \left(\frac{M_0}{M_f}\right)$$

Or $V_f = I_{sp} \times g \times 2.3026 \times (Z)$ (24)

Where:

1) *Ve* is the exhaust velocity (Ve = Isp * g).
2) *ln* is the natural logarithm.
3) log_{10} is the base-10 logarithm.
4) M_0 is the initial total mass of the rocket (kg).
5) M_f is the final mass of the rocket after the propellant is burned (kg).
6) $\frac{M_0}{M_f}$ is known as the "mass ratio Z."

Example Problem 5:

Calculate the ideal speed using the Tsiolkovsky rocket equation. Use the same data as in Problem 1.

Solution:

1. First, find the final mass (Mk):

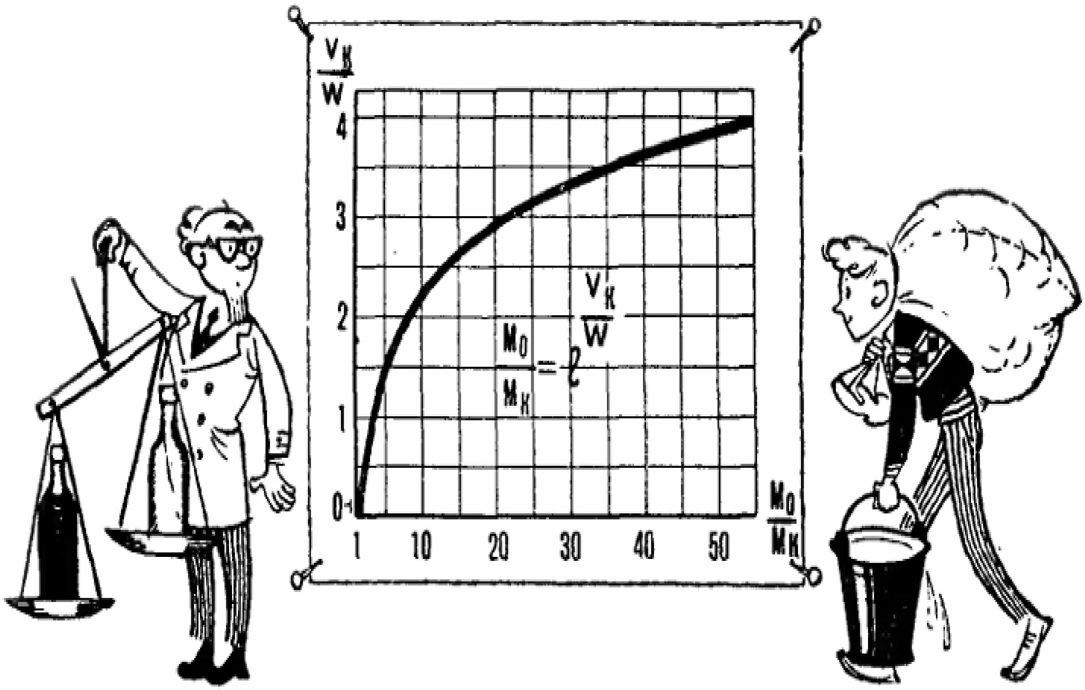
2. M_f = M_0 - M_{pro} = 0.1 kg - 0.018 kg = 0.082 kg
3. Now, apply Tsiolkovsky's equation:
4. V_f = Isp × g ×2.3026 ×$\log_{10}(\frac{M_0}{M_f})$
5. V_f =0×9.81×2.3026× $\log_{10}$(0.1 / 0.082)

V_f = 30×9.81×2.3026× $\log_{10}$(1.22)

V_f = 30 × 9.81 ×2.3026× 0.0864

$V_f \approx$ *58.5 m/s*

As we can see, the results from both methods are very close (58.2 m/s vs. 58.5 m/s).



§3. The Actual Velocity of a Model Rocket

The flight of a rocket model is influenced by air resistance and the presence of Earth's gravity. Therefore, it is necessary to introduce a correction for these factors into our calculations. Only then will we obtain the actual velocity of the rocket model at the end of the Motor's operation, based on which we can calculate the flight trajectory of the model.

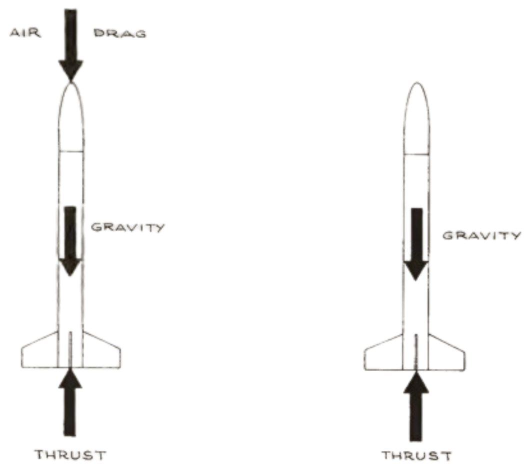
The actual final velocity of the rocket model can be calculated using the equation:

The calculations above give us the *ideal* speed in a vacuum without gravity. However, in a real flight, two main forces work against the rocket:

1. *Air Resistance (Drag):* The force of the air pushing against the rocket.

2. *Gravity:* The Earth's gravitational pull.

Therefore, the actual speed of the rocket at the moment the Motor stops burning (the burnout speed) is lower than the ideal speed. To accurately predict the rocket's flight path and maximum altitude, we must use this lower, *actual velocity* in our calculations. This value can be estimated using more complex equations that account for drag and gravity losses.



**The actual final velocity of the rocket model can be calculated using the equation: 5 Cl. 117*

$$V_{effective} = V_f - g \times t - \left(\frac{D^2}{F_{avg}}\right)$$

(25)

...where:

V_{ideal} is the ideal velocity of the model rocket;

F_{avg} is the average thrust of the Motor;

g is the gravitational acceleration;

t is the time;

D is the diameter of the cross-section;

A is a coefficient.

In this equation, the term $g \times t$ accounts for Earth's gravity, and the term $\left(\frac{D^2 \times A}{F_{avg}}\right)$ accounts for the effect of air resistance. The coefficient A depends on the ideal velocity and the flight altitude of the model rocket. The values of coefficient A for various ideal velocities and flight altitudes are given in Table 2.

Table 2

Average Value of Coefficient "A" for Various Flight Altitudes

Ideal Velocity (m/s)	Up to 500 m	Up to 1000 m	Up to 2000 m	Up to 5000 m
30	0.01	0.01	0.01	0.01
40	0.03	0.03	0.03	0.03
50	0.05	0.05	0.05	0.04
60	0.09	0.09	0.09	0.07
70	0.15	0.14	0.14	0.12
80	0.22	0.22	0.20	0.18
90	0.32	0.31	0.29	0.25
100	0.43	0.42	0.40	0.34
120	0.75	0.73	0.70	0.60
140	1.19	1.17	1.11	0.95
160	1.78	1.74	1.66	1.42
180	2.53	2.48	2.36	2.03
200	3.48	3.40	3.23	2.79
250	6.79	6.64	6.32	5.44
300	11.78	11.52	10.97	9.45
350	22.20	21.71	20.68	17.80
400	40.07	39.19	37.32	32.13
450	62.55	61.18	58.27	50.16

Problem 6. Determine the actual velocity of the model rocket at the end of the active phase of the flight trajectory, if: I_{sp} = 30 kg·sec/kg; M_{prop}= 0.018 kg; M_o= 0.1 kg; t = 0.6 sec: F_{avg} = 0.9 kg; D = 3 cm.

Solution.

First, we determine the ideal velocity of the model rocket using one of the variants of K. E. Tsiolkovsky's equation given earlier:

$$V_{ideal} = \left(\frac{I_{sp} \times g \times M_{Pro}}{M_0 - \frac{M_{Prop}}{2}} \right) = \left(\frac{30 \times 9.81 \times 0.018}{\frac{0.1 - 0.018}{2}} \right) = 58.2\ m/sec$$

Calculating the Actual Velocity of a Model Rocket

The actual velocity of a model rocket at the end of its powered flight is calculated using Equation (25):

$$V_{effective} = V_{ideal} - gt - \left(\frac{D^2 - F_{avg}}{M_{empty}} \right) A$$

For the given flight altitude, the coefficient *A* is *0.083*.

Sample Calculation:

$$V_{effective} = 58.2 - (9.8 \times 1.06) - \left(\frac{3^2 - 0.9}{0.9} \right) \times 0.083$$

= 58.2 - 10.4 - (9 × 1 × 0.083)

= 47.8 - 0.747

= *47.05 m/sec* (Approximately 47.1 m/sec)

Sample Problem 7

Determine the actual velocity of a model rocket at the end of its powered flight, given the following data:

Specific Impulse, I_{sp} *= 25 kg·sec/kg*

Final Mass (without fuel), G_{final} = 0.1 kg

Motor Burn Time, *t = 4 sec*

Motor Diameter, *D = 3 cm*

Propellant Mass, M_{prop} = 0.1 kg

Solution:

Step 1: Calculate the Launch Mass ($M_{initial}$**)**

The launch mass is the final mass plus the propellant mass.

$M_0 = M_f + M_{pro} =$ 0.1 kg + 0.1 kg = *0.2 kg*

Step 2: Calculate the Ideal Velocity (V_{ideal})

$$V_{ideal} = \left(\frac{I_{sp} \times g \times M_{pro}}{\frac{M_0 - M_{pro}}{2}} \right)$$

= (25 × 9.81 × 0.1) / (0.2 - 0.05)

= 24.525 / 0.15 = 163.5 m/sec

Step 3: *Calculate the Average Thrust (F_{avg})*

$\boldsymbol{F_{avg}} = \left(\frac{\boldsymbol{I_{sp} \times M_{pro}}}{\boldsymbol{t}} \right)$ = (25 × 0.1) / 4 = 2.5 / 4 = 0.625 kg

Step 4: Calculate the Actual Velocity *($V_{effective}$)*

$$V_{eff} = V_{ide} - g \times t - \left(\frac{D^2 \times F_{avg}}{M_{empt}} \right) A$$

= 163.5 - (9.81 × 4) - ((3^2 × 0.625) / 0.1) × 1.79

= 163.5 - 39.24 - (5.625 / 0.1) × 1.79

= 124.26 - (56.25 × 1.79)

= 124.26 - 100.69

= *23.57 m/sec*

Note on Practical Calculation:

Since the total impulse and burn time are the primary parameters of a rocket Motor, the equation for practical use is more conveniently written by substituting F_{avg} with (I_{sp} $I_{sp} \times \frac{M_{prop}}{t}$):

$$V_{eff} = V_{ide} - g \times t - \left(\frac{D^2 \times F_{avg}}{M_{empt}} \right) A$$

§ 4. Maximum Altitude of a Model Rocket

Now we will determine how to find the maximum altitude of a model rocket based on its velocity. We will consider a perfectly vertical flight path. The rocket's flight trajectory can be divided into two phases:

1. *Powered Flight (Active Phase):* The period when the rocket's Motor is thrusting.

2. *Coasting Flight (Passive Phase):* The period after Motor burnout when the rocket coasts upward due to inertia.

Therefore, the total maximum altitude, *H*, of the model rocket is the sum of the altitudes gained during these two phases. The total altitude, *H,* of a model rocket is the sum of the altitudes achieved during its powered and unpowered flight phases.

$H = h_1 + h_2$ (26)

where:

h_1 is the altitude gained during the *powered flight phase* (active segment).
h_2 is the altitude gained during the *unpowered, coasting phase* (passive segment).

1. *Calculate the Powered Flight Altitude (h_1)*

The altitude h_1 can be calculated by assuming the rocket's velocity increases uniformly from 0 to its effective velocity, $V_{effective}$, at the point of Motor burnout. The average velocity during this phase is therefore:

$$V_{avg} = \left(\frac{0 + V_{eff}}{2}\right) = \frac{V_{eff}}{2}$$

Thus, the altitude h_1 is given by:

$$h_1 = \left(\frac{V_{effe}}{2}\right) \times t$$

$$V_{avg} = \frac{V_{effective}}{2} \quad (27)$$

where "t" is the duration of the powered flight. Please note that the calculation in equation (27) already accounts for the effect of air resistance.

2. *Calculating the Coasting Flight Altitude (h_2)*

The calculation for h_2 is different. In the absence of air resistance, a body coasting upwards with an initial velocity, $V_{initial}$, would gain a height given by the equation of mechanics:

$h = \frac{V^2{}_0}{2g}$. In this case, the initial velocity for the coasting phase is $V_{effective}$. Without air resistance, the height would be:

$h_2 = \frac{V^2{}_{effe}}{2g}$. However, to account for the significant effect of air resistance, an empirical coefficient must be introduced. Experimental data shows that this coefficient is approximately 0.8. Therefore, the equation for the coasting altitude, accounting for air resistance, becomes:

$$h_2 = 0.8 \times \left(\frac{V^2{}_{effe}}{2g}\right) \quad (28)$$

3. Total Altitude Equation

By combining equations (26), (27), and (28), the final equation for the total altitude is:

$$H = \left(\frac{V_{effe}}{2}\right) \times t + 0.8 \times \left(\frac{V^2{}_{effe}}{2g}\right) \quad (29)$$

Sample Problem 8

Calculate the maximum altitude and acceleration of a model rocket based on the following data:

Empty Mass of Rocket, M_{empt} = 0.08 kg; Motor Diameter, D=2.3 cm; Specific Impulse, I_{sp}= 45.5 sec; Average Thrust, F_{avg}= 0.25 kg; Motor Burn Time, t= 4 sec; Propellant Mass, M_{prop}= 0.022 kg; Motor Model: DB-3-SM-10

Solution

Step 1: *Calculate the Ideal Velocity (V_{ideal})*

$$V_{ideal} = I_{sp} \times g \times ln\, ln\left(\frac{M_0}{M_f}\right)$$

$= 45.5 \times 9.8 \times \ln(\frac{(0.08 + 0.022)}{0.08})$

$= 45.5 \times 9.8 \times \ln(\frac{0.102}{0.08})$

$= 45.5 \times 9.8 \times \ln(1.275)$

≈ *142.3 m/sec*

Step 2: *Calculate the Effective Velocity ($V_{effective}$)*

To find the effective velocity, we adjust the ideal velocity for drag and gravity losses. A simplified correction is used:

$$V_{effective} = V_{ideal} - (g \times t) \times A$$

Where A is a drag factor. For this rocket, A is calculated as:

$$A = \left[\frac{\left(\frac{G_{empty}}{2}\right)}{(\frac{\pi \times D^4}{4} \times F_{avg}}\right]$$

$$= \left[\left(\frac{\left(\frac{0.08}{2}\right)}{\frac{(\pi \times 2.3^2)}{4} \times 0.25}\right)\right]$$

$$= 1.26$$

Therefore,

$V_{effective}$ = 142.3 - (9.8 × 4) × 1.26

= 142.3 - 65.9 ≈ 76.4 m/sec

Step 3: Calculate the Powered Flight Altitude (h_1)

$h_1 = (\frac{V\_effective \times t}{2}) = (\frac{76.4 \times 4}{2})$ = *152.8 m*

Step 4: Calculate the Coasting Flight Altitude (h_2)

$$h_1 = 0.8 \times \left(\frac{V_{effectiv}{}^2}{2g}\right) = 0.8 \times \left(\frac{76.4^2}{2 \times 9.8}\right)$$

$$= 0.8 \times \frac{5837}{19.6} = 238\, m$$

Step 5: ***Calculate the Total Maximum Altitude (H)***

$H = h_1 + h_2 = 152.8 + 238 = 390.8$ m

(End of Calculation)

Total Flight Altitude of the Model Rocket:

$H = h_1 + h_2 = 152.8 + 238 = 390.8$ m

§ 5. CHANGE IN THE FLIGHT TRAJECTORY PARAMETERS OF A MODEL ROCKET DEPENDING ON MOTOR OPERATION TIME

It can be seen from equation (29) that the flight altitude of the model rocket depends mainly on the magnitude of the velocity reached by the model rocket at the end of Motor operation. The greater this velocity, the higher the model will fly. Let's look at the ways this velocity can be increased. Let's return to equation (25):

$$V_{Actual} = V_f - g \times t - \frac{D^2}{F_{avg}} \times A$$

We see that the smaller the value of g×t and $\frac{D^2}{F_{avg}} \times A$, the higher the velocity of the model rocket, and therefore the greater the flight altitude.

Table 3 shows the change in the flight trajectory parameters of the rocket depending on the Motor operation time. The table is given for model rockets with a launch weight of M_0 = 0.08 kg and a *DB-3-SM-10* Motor. Motor characteristics: J_s = 1.0 kg·sec; I_{sp}= 45.5 kg·sec/kg; M_{Prop}= 0.022 kg. The total impulse remains constant throughout the flight.

Table 3

t (sec)	P (kg)	V_{actual} (m/sec)	h_1 (m)	h_2 (m)	H (m)
4	0.25	76.4	152.8	238	390.8
2	0.5	110.8	110.8	500	620.8
1	1	125.8	62.9	645	707.9

0.8	1.25	189.6	51.6	682	733.6
0.5	2	134.1	33.6	733	766.6
0.4	2.5	136.7	27.2	755	782.2
0.25	4	138.2	17.2	780	797.2
0.2	5	138.5	13.9	785	798.9
0.1	10	140.6	7.03	806	813

It can be seen from the table that with a Motor operation time of 0.1 seconds, the theoretical flight altitude of the model is 813 meters. It would seem, "Let's make Motors with such an operating time and records are guaranteed." However, with such an Motor operating time, the model must accelerate from 0 to 140.6 m/sec. If there were living creatures on board a rocket with such acceleration, not one of them could withstand such an *overload.*

Thus, we have approached another important concept in rocketry: the *rate of velocity gain, or acceleration.* The *overloads* associated with excessive acceleration of the model rocket can destroy the model. In order to make the structure stronger, its weight need to be increased. Furthermore, flights with high accelerations are hazardous and not safe for spectators.

§ 6. ACCELERATION OF A MODEL ROCKET

The following forces act on a model rocket in flight: the *thrust force* of the Motor, directed upwards, and the *force of Earth's gravity (the model's weight)* and *air resistance,* directed downwards.

Let us assume that air resistance is absent. To determine the acceleration of our model, we use the second law of mechanics: the product of a body's mass and its acceleration is equal to the force acting on the body ($F = m \times a$).

$$F - M_0 = \frac{M_0}{g} \times a$$

In our case, this law takes the form:

from which

This is the expression for acceleration at the *beginning of the flight.*

Due to the burning of fuel, the mass of the model rocket constantly changes. Consequently, its acceleration also changes. To find the acceleration at the *end of the active phase* (a_f), we will assume that all the fuel in the Motor has burned, but the Motor is still operating in the last moment before shutdown. Then the acceleration at the end of the active phase can be calculated by the equation:

$$a_f = \left(\frac{F-(M_0-M_{prop})}{M_0-M_{prop}}\right) \times g$$

(31)

If we introduce the average weight of the model rocket on the active

Noting that $I_{sp} \times g = V_e$ and $M_{Pro} - \frac{M_{prop}}{2} = M_{avg}$

we get:

$$a_{avg} = \left(\frac{V_e \times G_t}{G_{avg} \times t}\right) \qquad (33)$$

$$a = \left(\frac{(F-M_0)}{M_0}\right) \times g \qquad (30)$$

$$a = \left(\frac{F - M_0}{M_0}\right) \times g$$

phase $M_{avg} = M_0 - \left(\frac{M_f}{2}\right)$, we get the equation for the **average acceleration**:

$$a_{avg} = \left(\frac{F-M_{avg}}{M_{avg}}\right) \times g$$

(32) The acceleration of the model rocket can also be determined from the approximate Tsiolkovsky equation (23). Knowing that from the well-known equation of mechanics $M_f = a_{avg} \times t$(where t in our case is the Motor operating time), we substitute this value for V_k into equation (23):

$$a_{avg} \times t = \left(\frac{I_{sp} \times g \times M_{prop}}{M_{prop} - \frac{M_{Prop}}{2}}\right)$$

Explanation of Concepts and Equations

This section applies *Newton's Second Law* ($F_{net} = m \times a$) to a model rocket, whose mass is constantly decreasing.

1. **Initial Acceleration (Equation 30):**

a) **Net Force (F_{net}):** At launch, this is the Motor's Thrust (F) minus the rocket's full Weight (M_0).

b) **Mass (m):** The initial mass, calculated as M_0 / g.

c) **Equation**: $a = \left(\frac{F-M_0}{\frac{M_0}{g}}\right) = \left(\frac{(F-M_0}{M_0}\right) \times g)$

d) If F is less than M_0, the acceleration is negative (the rocket doesn't lift off). If P is much greater than M_0, the acceleration is high.

2. **Final Acceleration (Equation 31):**

i. By the end of the burn, the rocket's mass has decreased. The fuel mass $M_{prop}$is gone, so the final weight is $M_0 - M_{Prop}$

ii. The net force is now $F - (M_0 - M_{prop})$

Mass (m): The final mass,$\left(\frac{M_0 - M_{prop}}{g}\right)$

iii. **Equation**: a_k = [P - (M_0 - G_t)] / [(M_0 - G_t) / g] = (P / (M_0 - G_t)) · g

iv. This shows why acceleration *increases* during the flight: the thrust P remains fairly constant, but the mass $(M_0 - M_{prop})$ decreases.

3. **Average Acceleration (equation 32):**

i. This is a practical equation for calculations over the entire burn time.

ii. It uses the **average weight** M_{avg} of the rocket during the burn, which is the average of the initial weight (M_0) and the final weight $(M_{final}) = (M_0 - M_{prop})$, hence $M_{avg} = M_0 - \frac{M_0}{2}$.

iii. The net force is approximated as $F - a_{avg}$

iv. **Equation**:

$$a_{avg} = \left(\frac{(F - M_{avg}}{M_{avg} \times 9.8}\right)$$

4. **Average Acceleration from Exhaust Velocity (Equation 33):**

i. This derives average acceleration from fundamental rocket parameters.

ii. It starts with the basic kinematic equation

$$V_{final} = a_{avg} \times t$$

iii. It equates this to the ideal rocket velocity from a previous equation, which is $= \left(\frac{V_e \times M_{prop}}{a_{avg}}\right)$ where V_e is the exhaust velocity.

iv. Solving for A_{avg} gives:

v. $A_{avg} = \left(\frac{V_e \times M_{prop}}{M_{avg} \times t}\right)$

This is a useful equation because it connects acceleration directly to the Motor's efficiency (V_e) and fuel consumption rate $\left(\frac{M_{prop}}{t}\right)$.

The approximate Tsiolkovsky equation does not take into account the effect of Earth's gravity, which is directed downward and imparts an acceleration equal to g to all bodies. With a correction for Earth's gravity, the equation for the average acceleration on the active phase of the flight becomes:

$$a_{avg} = \left(\frac{V_e \times M_{prop}}{M_{avg} \times t}\right) - g \quad (33)$$

It should be emphasized once again that equations (32) and (33) do not account for air resistance.

Problem 9. Determine, without considering air resistance, the average acceleration of a model rocket if M_0 = 0.08 kg; G_t = 0.022 kg; F_{avg}= 0.25 kg; t = 4 sec; F_{avg}= 45.5 kg·sec/kg; $V_e = I_{sp} \times g$ = 446 m/sec.

Solution. Let's find the average acceleration of the model rocket using equations (32) and (33):

$$M_{avg} = M_0 - \frac{M_f}{2} = 0.08 - \frac{0.022}{2} = 0.069\ kg$$

$$a_{avg} = \left[\frac{(F - M_{avg})}{M_{avg}}\right] \times g = \left[\frac{(0.25 - 0.069)}{0.069}\right] \times 9.8 = 25.7\ m/Sec^2$$

Or

$$a_{avg} = \left[\frac{(V_e \times M_0)}{M_{avg} \times t}\right] - g = \left[\frac{(446.0 - 0.022)}{0.069 \times 4}\right] - 9.8 = 25.7\ m/Sec^2$$

As you can see, the results are identical. However, since these equations do not account for air resistance, the value of the actual velocity calculated by the equation $V_{actu.} = a_{avg} \times t$ will be overestimated.

Problem 10. Determine, without considering air resistance, the velocity of the model rocket at the end of the active phase and the flight altitude, based on the results of Problem 9. Compare the results with the results of Problem 8.

Solution.

$V_{actu.} = a_{avg} \times t = 25.7 \times 4 = 102.8$ m/sec. The actual velocity of the model rocket in Problem 8, solved *considering* air resistance, was 76.4 m/sec. Therefore, neglecting air resistance gives an absolute error of:

ΔV = 102.8 - 76.4 = 26.4 m/sec

and a relative error of:

$$\Delta V = \frac{26.4 \times 100}{102.8} \approx 25.7\%$$

Without considering air resistance, the flight altitude of the model rocket is:

In the active phase:

$$h_1 = \left(\frac{V_{effe} \times t}{2}\right) = \frac{102.8 \times 4}{2} = 205.6\,m$$

On the passive (coasting) phase:

h2 = V_actual² / (2 * g) = (102.8²) / (2 * 9.8) ≈ 538 m

$$h_2 = \left(\frac{V^2{}_{eff}}{2 \times 9.8}\right) = \frac{102.8^2}{2 \times 9.8} = 538\,m$$

Total altitude:

H = h1 + h2 = 205.6 + 538 = 743.6 m

Important Concepts

This section highlights a critical step in moving from ideal theory to practical reality: accounting for significant real-world losses.

1. *Gravity Loss (Equation 33):* The corrected equation $\boldsymbol{a_{avg}} = \left[\left(\frac{\boldsymbol{V_e \times M_{prop}}}{\boldsymbol{M_{avg} \times t}}\right)\right] - \boldsymbol{g}$ explicitly subtracts the acceleration due to gravity (g). This represents the constant drain on the rocket's performance as it fights against Earth's pull. Even in a vacuum, a rocket would not achieve the ideal Tsiolkovsky velocity because of this gravity loss.

2. *Drag Loss (The Main Point of Problems 9 & 10):* This is the central lesson. The calculations show a dramatic difference:

i. *Ideal World (No Drag):* Velocity = 102.8 m/s, Altitude ≈ 744 m

ii. *Real World (With Drag):* Velocity = 76.4 m/s, Altitude ≈ 391 m (from earlier problems)

3. *The "K-Factor" in Practice:* The 25.7% error in velocity and the halving of the achievable altitude demonstrate why the empirical drag coefficient K (introduced earlier, typically between 0.66 and 0.8) is so essential in model rocketry. It's a simplified but effective way to account for the complex physics of aerodynamic drag, which is too complicated for simple calculations.

In summary, while fundamental equations help understand the physics, accurate performance prediction for model rockets *must* incorporate corrections for both gravity and, most importantly, aerodynamic drag. Ignoring drag leads to highly optimistic and unrealistic results.

Comparison with Problem 8

Comparing these results with those from Problem 8, where the model's altitude was calculated taking into account air resistance and was equal to 390.8 m, we obtain:

Δh = 743.6 - 390.8 = 352.8 m;

Δh% = (352.8 / 743.6) * 100 ≈ 47.5%.

§ 7. TRUE ACCELERATION OF A MODEL ROCKET

$$a_{avg} = \left(\frac{a_{initial} + a_{final}}{2}\right)$$

To determine the true acceleration of a model rocket, the following equation is often used:

(34)

In the derivation of equation (34), two positions of the model rocket during flight are considered: at launch, when its mass is $\frac{M_0}{g}$, and at the end of the powered phase, when its mass is

$\frac{M_0}{g}$. The acceleration of the model is calculated for these two positions, and its average value is taken. However, this method does not account for the fact that propellant consumption during flight leads not to a constant (linear) change in acceleration, but to an uneven one.

Example Calculation

As an example, let us consider the flight of a model rocket with a launch weight of M_0= 0.08 kg and a DB-3-SM-10 Motor with the following data: F_{avg}= 0.25 kg; t = 4 sec; M_{Prop} = 0.022 kg; $V_e = \frac{M_{prop}}{t} = 0.0055\ kg/sec$

$\frac{M_{Prop}}{t} = 0.0055 kg/sec$;

$I_{sp} = 45.5. kg.sec/kg.$

Using equation (30), which does not account for air resistance, we will calculate the acceleration every 0.5 seconds, assuming a constant propellant mass flow rate (V_e = const).

At launch:

$$\boldsymbol{a_o = \left(\frac{F - M_o}{M_o}\right) \times g = \left(\frac{0.25 - 0.08}{0.08}\right) \times 9.8 = 20.8\ m/s^2}$$

After 0.5 sec:

$$\boldsymbol{a_{0.5} = \left(\frac{F - M_{prop\ 1}}{M_{prop\ 1}}\right) \times g = \left(\frac{0.25 - 0.07725}{0.07725}\right) \times 9.8 = 21.9\ m/s^2}$$

After 1.0 sec:

$$\boldsymbol{a_1 = \left(\frac{F - M_{prop\ 2}}{M_{prop\ 2}}\right) \times g = \left(\frac{0.25 - 0.0745}{0.0745}\right) \times 9.8 = 23.1\ m/s^2}$$

After 1.5 sec:

$$\boldsymbol{a_{1.5} = \left(\frac{F - M_{prop\ 3}}{M_{prop\ 3}}\right) \times g = \left(\frac{0.25 - 0.07175}{0.07175}\right) \times 9.8 = 24.4\ m/s^2}$$

After 2.0 sec:

$$\boldsymbol{a_2 = \left(\frac{F - M_{prop\ 4}}{M_{prop\ 4}}\right) \times g = \left(\frac{0.25 - 0.069}{0.069}\right) \times 9.8 = 25.7 m/s^2}$$

After 2.5 sec:

$$\boldsymbol{a_{2.5} = \left(\frac{F - M_{prop\ 2.5}}{M_{prop\ 2.5}}\right) \times g = \left(\frac{0.25 - 0.06625}{0.06625}\right) \times 9.8 = 27.2\ m/s^2}$$

After 3.0 sec:

$$M_3 = M_o - V_e \times 3 = 0.08 - 0.0165 = 0.0635\ kg$$

$$a_3 = \left(\frac{F - M_{prop\ 3}}{M_{prop\ 3}}\right) \times g = \left(\frac{0.25 - 0.06075}{0.06075}\right) \times 9.8 = 28.8 m/s^2$$

After 3.5 sec:

$$M_{3.5} = M_o - V_e \times 3.5 = 0.08 - 0.01925 = 0.06075\ kg$$

$$a_{3.5} = \left(\frac{F - M_{prop\ 3.5}}{M_{prop\ 3.5}}\right) \times g = \left(\frac{0.25 - 0.06075}{0.06075}\right) \times 9.8 = 30.6 m/s^2$$

After 4.0 sec

$$M_4 = M_o - V_e \times 4.0 = 0.08 - 0.022 = 0.058\ kg$$

$$a_4 = \left(\frac{F - M_{prop\ 4}}{M_{prop\ 4}}\right) \times g = \left(\frac{0.25 - 0.058}{0.058}\right) \times 9.8 = 32.4 m/s^2$$

*If a graph of the acceleration change a_{avg}over time t were plotted based on these calculations, this change would be represented not by a straight line, but by a curved line.

Let's calculate the average acceleration using equation (34):

$a_{avg} = \frac{a_{avg} + a_{final}}{2} = \frac{20.8+32.4}{2} = 26.6$ m/s^2

Now, let's determine the average acceleration using equations (32) and (33), which also do not account for air resistance:

$$a_{avg} = \left(\frac{F - M_{avg}}{M_{avg}}\right) \times g = \left(\frac{0.25 - 0.069}{0.069}\right) \times 9.8 = 25.7 m/s^2$$

$$A_{avg} = \left(\frac{V_e \times M_{prop}}{M_{avg} \times t}\right) - g = \frac{45.5 \times 9.8 \times 0.022}{0.069 \times 4} - 9.8\ 25.7 m/s^2$$

The difference between the obtained results is now clearly visible. Equation (34) for calculating the average acceleration of a model rocket is unsuitable, as it does not apply to bodies with variable mass. One must use equations (32) and (33), which provide sufficient accuracy at any point on the model rocket's flight trajectory. However, as the results of model rocket flights and their tests in wind tunnels have shown, it is necessary to introduce a coefficient K, which accounts for air resistance, into equations (32) and (33). This coefficient varies within the range of 0.66 to 0.8.

Thus, the equations for the true acceleration of a model rocket take the form:

text

$$a_{avg} = k \times \left(\frac{F - M_{avg}}{M_{avg}}\right) \times g \quad (35)$$

$$a_{avg} = k \times \left(\frac{V_e \times M_{avg}}{M_{vg} \times t} - g\right) \quad (36)$$

Let's conclude the above example.

Let us determine the true acceleration of the model rocket and its actual velocity (let's take the average value of the coefficient K = 0.743):

$M_{avg} = 0.743 \times 25.7 = 19.1\ m/s^2$

Actual Velocity Calculation:

$$V_{actual} = m_{avg} \times t = 19.1 \times 4 = 76.4\ m/sec$$

Selection of Coefficient K:

The value of coefficient K must be chosen depending on the model rocket's *cross-sectional area*. The larger the cross-sectional area, the smaller the value of K one should take from its range of variation, *0.66 to 0.8.*

The calculation method presented for the model rocket's actual velocity is the simplest and sufficiently accurate. It eliminates the need to use tables.

§ 8. VELOCITY OF MULTI-STAGE MODEL ROCKETS

The idea of multi-stage rockets belongs to a Russian pioneer, a school mathematics teacher, but a remarkable scientist K. E. Tsiolkovsky. A multi-stage model rocket, with the same fuel reserve as a single-stage one, achieves a greater final velocity, range, and flight altitude because the Motors of each stage operate sequentially, one after another. When the lower stage's Motor burns out, it separates, and the next stage's Motor starts working, and so on. As each subsequent stage separates, the mass of the model rocket decreases. This repeats until the last stage. Due to prolonged acceleration and decreasing mass, the model attains a significantly higher velocity than if all Motors were fired simultaneously.

The weight ratios of the stages are of great importance. These ratios are even more critical than the choice of fuel for the Motors.

Let us assume that each stage of the model rocket uses Motors with the same *specific impulse*, i.e., the same exhaust gas velocity from the Motor nozzle.

The ideal velocity of the model rocket's final stage can be calculated using Tsiolkovsky's equation (24), but instead of the mass ratio $\frac{M_0}{m_f}$, we use the quantity M. Equation (24) takes the form:

$$V_1 = V_e \times ln\, ln\, M$$
$$(where\ M = m_1 \times m_2 \times \dots)$$

where:

V_e is the exhaust gas velocity;

ln is the sign of the natural logarithm; M is the *reduced mass ratio* $m_1 \times m_2 \times \dots$;

m_1 is the ratio of the model rocket's mass at the start of the first stage's operation to the mass at the end of the first stage's operation, i.e., $\frac{M_{01}}{M_{prop1}}$.

Summary

Multi-Stage Advantage: The core principle explained is *staging*: jettisoning empty mass (spent stages) during flight. This allows the remaining stages to accelerate more effectively, leading to higher final speeds than a single-stage rocket with the same total fuel mass.

1) *Tsiolkovsky's Rocket Equation for Multiple Stages:* The text introduces the application of the fundamental rocket equation to multi-stage rockets. The key variable becomes the *reduced mass ratio (M),* which is the *product* of the individual mass ratios of each stage ($m_1 \cdot m_2 \cdot \dots$).
2) *Mass Ratio is Paramount:* The text strongly emphasizes that the *weight/mass distribution between stages* is more critical for performance than the specific type of fuel used. This highlights the importance of structural design and staging optimization in rocketry.
3) *Simplified Velocity Calculation*: The initial part mentions a simplified method for calculating a model rocket's velocity ($V = a_{avg} \times t$),

noting that a correction factor (K) is needed to account for aerodynamic drag, which is more significant for rockets with a larger cross-sectional area.

m_2 is the ratio of the model rocket's mass at the start of the *second* stage's operation to its mass at the end of the *second* stage's operation, i.e.,$\left(\frac{M_{02}}{M_{prop2}}\right)$

M_n is the ratio of the *last* stage's initial mass to its final mass, i.e., $\left(\frac{M_0}{M_{prop}n}\right)$

Where:

M_0 is the initial mass of the entire rocket;

M_01 is the initial mass of the first stage;

M_on is the initial mass of the last stage;

$m_{prop}1$ is the mass of the first stage's fuel;

m_P2 is the mass of the second stage's propellant;

m_pn is the mass of the last stage's propellant.

Calculation Note:

For calculations in the absence of natural logarithm tables, one can use common (base-10) logarithm tables, considering that: ln M = 2.3026 * log M

Note also that instead of the mass ratio, one can use the weight ratio, since: $\left(\frac{m_0}{m_f}\right) = \left(\frac{\frac{m_0}{g}}{\frac{m_f}{g}}\right)$

It should be remembered that this equation does not account for the influence of air resistance and Earth's gravity.

Problem 11. Calculate the ideal flight velocity of single-stage, two-stage, and three-stage model rockets if the rockets are equipped with DB-3-SM-10 Motors with a specific impulse of 45.5 kg·sec/kg. The mass ratios for each stage are $m_1 = m_2 = m_3 = 2$.

Solution.

Exhaust gas velocity:

$V_e = F_{sp} \times g =$ 45.5 * 9.8 ≈ 446 m/sec

Ideal velocity of a single-stage model rocket:

$V_1 = V_e \times \ln(2) = 446 \times 0.6931 \approx 315$ m/sec

Ideal velocity of a two-stage model rocket:

$V_2 = w \times \ln(2 \times 2) = W * \ln(4) = 446 \times 1.3863 \approx 617$ m/sec

Ideal velocity of a three-stage model rocket:

$$V_3 = w \times ln\, ln\, (2 \times 2 \times 2) = (8) = 446 \times 2.079 \approx 930\, m/sec$$

Problem 12. Calculate the flight altitude of a three-stage model rocket if its launch weight is $M_0 =$ 0.12 kg; the weight of the first stage is $M0_1 = 0.03$ kg; the weight of the second stage is $G_2 = 0.03$ kg; the weight of the third stage is $G_3 =$ 0.06 kg. Each stage is equipped with a DB-28-SM-10 Motor with the following data: $F_{sp} =$ 70 kg·sec/kg; t = 3 sec, G_t = 0.0143 kg (fuel weight per stage).

*(The solution for Problem 12 would involve calculating the mass ratios for each stage based on the given weights and then applying the multi-stage rocket equation, followed by a calculation to convert the final ideal velocity into an altitude, assuming ballistic flight and neglecting drag and varying gravity.

Summary

1) *Multi-Stage Mass Ratios:* The core concept is that the total mass ratio (M) for a multi-stage rocket is the *product* of the individual mass ratios of each stage ($m_1 * m_2 * ... * m_n$). This dramatically increases the argument of the logarithm in Tsiolkovsky's equation compared to a single-stage rocket.
2) *The Power of Staging: Problem* 11 perfectly illustrates the immense benefit of staging. Using the same Motors and the same per-stage mass ratio of 2:
    1) Single-Stage: V ≈ 315 m/s
    2) Two-Stage: V ≈ 617 m/s
    3) Three-Stage: V ≈ 930 m/s The final velocity nearly triples by adding two more stages, demonstrating why staging is fundamental to achieving high speeds in rocketry.
3) *Practical Calculations:* The text provides practical tips for calculations, such as using

common logarithms (log) to find natural logarithms (ln), and confirming that weight ratios can be used directly since the acceleration due to gravity (g) cancels out.

4) *Ideal vs. Real Velocity:* It's consistently emphasized that these equations calculate the *ideal* velocity in a vacuum, without accounting for losses due to atmospheric drag and gravity. Real flight velocities and altitudes will be lower. Problem 12 sets up a more complex, real-world scenario where the stages have different masses, requiring careful calculation of each stage's individual mass ratio before applying the overall equation.

Solution for Problem 12

Solution.

Mass ratio of the first stage:

$$m_1 = \left[\frac{M_{01}}{M_{f1}}\right] = \frac{0.01225}{0.0108} \approx 1.132$$

where:

$M_{01} = \frac{M_0}{g} = \frac{0.12}{9.8} \approx 0.01225$ kg·sec²/m

$M_{f1} = \frac{M_{01}}{g} = \frac{0.1057}{9.8} \approx 0.0108$ kg·sec²/m

Mass ratio of the second stage: $m_2 = \left[\frac{M_{02}}{M_{f2}}\right] = \frac{0.0092}{0.00773} \approx 1.19$

where:

$M_{02} = \frac{M_{02}}{g} = \frac{0.09}{9.8} \approx 0.0092$ kg·sec²/m

$M_{f2} = \frac{M_{f2}}{g} = \frac{0.0757}{9.8} \approx 0.00773$ kg·sec²/m

Mass ratio of the third stage:

$m_3 = \frac{M_{03}}{M_{f3}} = \frac{0.00612}{0.00467} \approx 1.305$

where:

$M_{o3} = \frac{M_{03}}{g} = \frac{0.006}{9.8} = 0.00612\ kg.Sec^2/m$

$$M_{f3} = \frac{M_{o3}}{g} = \frac{0.0457}{9.8} = 0.00467\ kg.sec^2/m$$

We determine the ideal velocity of each stage using Tsiolkovsky's Equation:

$V_e = I_{so} \times g = 70 \times 9.8 = 686\ m/sec$

$V_1 = W \cdot \ln m_1 = 686 \cdot \ln(1.132) = 686 \cdot 0.1239 \approx 85$ m/sec

$V_2 = W \cdot \ln(m_1 \cdot m_2) = 686 \cdot \ln(1.132 \cdot 1.19) = 686 \cdot \ln(1.347) \approx 686 \cdot 0.2976 \approx 204.2$ m/sec

$V_3 = W \cdot \ln(m_1 \cdot m_2 \cdot m_3) = 686 \cdot \ln(1.132 \cdot 1.19 \cdot 1.305) = 686 \cdot$

$\ln(1.758) \approx 686 \cdot 0.564 \approx 387$ m/sec

(Note: There are slight discrepancies in the logarithmic values (e.g., $\ln(1.347) \approx 0.2976$ vs. text's implied 0.3; $\ln(1.758) \approx 0.564$ vs. text's 0.5653) and final results ($V_2 \approx 204$ m/s vs. text's 206 m/s; $V_3 \approx 387$ m/s vs. text's 388 m/s) due to rounding differences in intermediate steps. The method remains consistent.)

Determine the flight altitude of the model rocket on the first trajectory segment:

Ideal acceleration: $a_1 = V_1 / t = 85 / 3 \approx 28.3$ m/sec²
True acceleration: $a\_actual = (28.3 - 9.8) \cdot 0.66 \approx 12.2$ m/sec² (accounts for gravity and drag)
True velocity: $V\_actual = a\_actual \cdot t = 12.2 \cdot 3 = 36.6$ m/sec
Flight altitude: $H_1 = (V\_actual \cdot t) / 2 = (36.6 \cdot 3) / 2 \approx 55$ m

Determine the flight altitude of the model on the second trajectory segment:

Ideal acceleration: $a_2 = V_2 / t = 206 / (3+3) = 206 / 6 \approx 34.5$ m/sec² (assuming 3s burn for stage 1 and 3s for stage 2)

Problem-Solving Approach

This problem demonstrates a practical application of calculating the performance of a multi-stage model rocket, moving from ideal theory to estimated real-world performance.

1) *Stage Mass Ratios:* The initial mass for each stage is the total weight of the rocket *at the ignition of that stage*. The final mass is the mass *after that stage's fuel is expended*. The mass ratio (m) for each stage is calculated precisely by converting weights (kg-force) to masses (kg-mass) using g.

2) *Ideal Velocity per Stage Segment:* The velocity increase for each segment of the flight (corresponding to each stage's burn) is calculated using Tsiolkovsky's rocket equation, but applied cumulatively:

a) *After Stage-1:* $V_1 = W \cdot \ln(m_1)$

b) *After Stage-2:* $V_2 = W \cdot \ln(m_1 \cdot m_2)$ (This is the total ideal velocity after stage 2, not just the increase from stage 2).

c) *After Stage-3:* $V_3 = V_e \times \ln(m_1 \times m_2 \times m_3)$ (Total ideal velocity after all stages).

1) *Real-World Flight Simulation (Altitude Calculation):* The solution then attempts to estimate the actual altitude gained during each stage's burn, acknowledging that the ideal vacuum velocity is not achieved due to gravity and drag losses.

- *Ideal Acceleration:* Found by dividing the ideal velocity increment for that segment by the burn time.
- True Acceleration: An empirical correction is applied: (Ideal Acc-Gravity) · Drag Factor. Here, gravity (9.8 m/s²) is subtracted, and the result is multiplied by a drag factor K=0.66 (from the range 0.66-0.8 mentioned earlier, chosen based on the rocket's cross-section).
- *Altitude*: The altitude gained during the burn is calculated using the simplified equation for motion with constant acceleration: $H = \left(\frac{V_{effe} \times 2}{2}\right)$

This method provides a structured, step-by-step approach to predicting the performance of a complex multi-stage rocket, bridging the gap between ideal theory and practical, observable results like altitude.

Actual acceleration:

$$a_{actual} = (34.5 - 9.8) \cdot 0.66 = 16.3\, m/sec^2$$

Actual velocity:

$$V_{actual} = a \cdot t = 16.3 \cdot 6 = 98\, m/sec$$

Flight altitude:

$$\boldsymbol{h_2 = \frac{V_2 + V_1}{2} \cdot t = \frac{98 + 36.6}{2} \cdot 3 = 202\, m}$$

Determine the flight altitude of the model on the third trajectory segment:

Ideal acceleration:

$$a_3 = \frac{388}{9} = 43.2\, m/sec^2$$

True acceleration:

$$a_{actual} = (43.2 - 9.8) \cdot 0.66 = 22.2\, m/sec^2$$

True velocity:

$$V_{actual} = a \cdot t = 22.2 \cdot 9 = 200\, m/sec$$

Flight altitude:

$$h_3 = \frac{V_3 + V_2}{2} \cdot t = \frac{200 + 98}{2} \cdot 3 = 446\, m$$

Determine the flight altitude on the passive (coasting) segment:

$$h_4 = K \cdot \frac{V^2}{2g} = 0.66 \cdot \frac{200^2}{2 \cdot 9.8} = 1200\, m$$

<u>Total flight altitude of the three-stage model rocket:</u>

$$H = h_1 + h_2 + h_3 + h_4 = 55 + 202 + 446 + 1200 = 1903\, m$$

§ 9. CALCULATION OF THE FLIGHT ALTITUDE FOR A SCALE MODEL OF THE *"VOSTOK" SPACECRAFT LAUNCH VEHICLE*

Problem 13. Calculate the flight altitude of a scale model of the "Vostok" rocket, based on the following data:

$M_0 = 0.5\, kg$; $M_1 = 0.09\, kg$; $\dot{m} = 0.0225\, kg/sec$ $t = 4\, sec$; $D = 11.3\, cm$; $W = 686.7\, m/sec$

Note: For scale models of the "Vostok" type, considering their diameter and consequently larger drag area, a coefficient of $K = 0.7$ should be used. This will make the calculated flight altitude approximately the practical values The true average acceleration of the model rocket, accounting for air resistance and Earth's gravity, is found by equation (37):

$$a_{cp} = K(\frac{W \cdot G_{sec}}{G_{cp}} - g) = 0.7(\frac{686.7 \cdot 0.0225}{0.455 \cdot 4} - 9.8) = 17\, m/sec^2$$

Actual velocity of the model rocket:

$$V_{actual} = a \cdot t = 17 \cdot 4 = 68\, m/sec$$

Concepts & Calculations

1. *Multi-Stage Altitude Calculation:*

The total altitude is the sum of the altitudes gained during the thrusting phase of each stage (h1, h2, h3) and the coasting phase after burnout (h4).

Thrusting Phase Altitude: For each stage, the altitude is calculated assuming constant acceleration, using the distance equation covered under constant acceleration, starting from an initial velocity: $h = \left(\frac{V_{initial}+V_{final}}{2}\right) \times t$

<u>*Coasting Phase Altitude*</u>: After the last Motor burns out, the rocket continues to coast upwards until its kinetic energy is converted to potential energy. The calculation $h = \frac{K \times V^2}{2g}$ h is a modified version of this energy principle, where the factor K (0.66) empirically accounts for aerodynamic drag losses during the coast.

2. "Vostok" Scale Model Calculation:

This problem applies the same fundamental principles to a single-stage scale model.

Key Parameter - Mass Flow Rate: The value $\dot{m}$= 0.0225 kg/sec is calculated from the given fuel mass m_{prop}= 0.09 kg and burn time t = 4 sec (0.09 kg / 4 sec = 0.0225 kg/sec).

<u>*Average Acceleration Equation:*</u>

The core equation $a_{avg} = K \times \left(\frac{V_e \times \dot{m}}{M_{avg} \times t}\right) - g$is derived from the thrust equation and Newton's second law. $V_e \times \dot{m}$ is the thrust force.

- $\left(\frac{V_e \times \dot{m}}{M_{avg} \times g}\right)$ is the ideal acceleration in gs`.
- Subtracting g accounts for gravity.
- Multiplying by the drag factor K (here 0.7 for a larger, less aerodynamic model) accounts for air resistance.

Average Mass: M_{avg}= 0.455 kg is the average mass of the rocket during the burn, typically calculated as (Initial Mass + Final Mass) / 2 = (0.5 kg + (0.5 - 0.09) kg) / 2.

Flight altitude of the model rocket on the active (powered) segment:

$$h_1 = \frac{V_{actual} \cdot t}{2} = \frac{68 \cdot 4}{2} = 136\, m.$$

Flight altitude on the passive (coasting) segment:

$$h_2 = K \cdot \frac{V_{actual}^2}{2g} = 0.7 \cdot \frac{68^2}{2 \cdot 9.81} \approx 164\, m.$$

Total flight altitude of the model:

$$H = h_1 + h_2 = 136 + 164 = 300\, m.$$

The road to space began just like this - with simple, small rockets.

Explanation of Concepts & Final Summary

This concludes the detailed calculation for the scale model of the "Vostok" rocket.

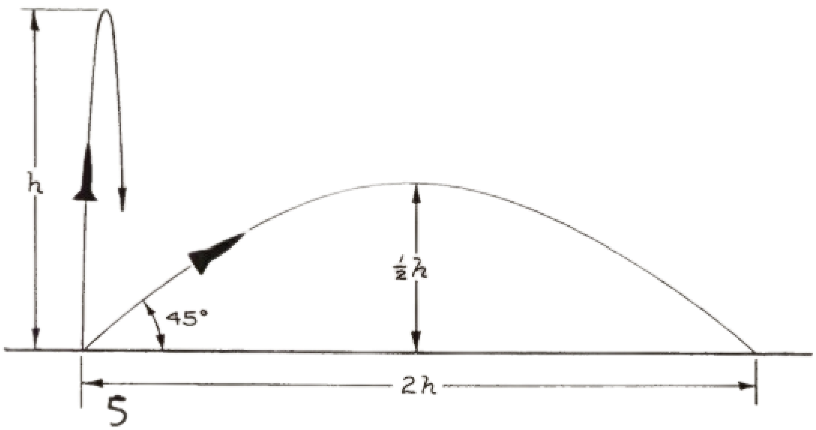
3. *Powered Ascent Altitude (h1*): This calculation assumes constant acceleration during the Motor burn. The equation $\boldsymbol{h = \frac{V \times t}{2}}$ is derived from the equations of motion for constant acceleration starting from rest. With an average velocity of $\boldsymbol{\frac{V_{actual}}{2}}$ over the burn time t, the distance covered is 136 meters.

4. *Coasting Altitude (h2):* After Motor burnout, the rocket coasts upwards, slowed by gravity and air resistance. The calculation is based on converting kinetic energy at burnout $\boldsymbol{\frac{1}{2} \times m \times V^2{}_{actual}}$ into potential energy (m * g * h). The empirical drag factor K = 0.7 is applied to account for energy lost to aerodynamic drag, resulting in a coasting gain of 164 meters.

5. *Total Estimated Altitude:* The model is predicted to reach 300 meters.

This entire section, from the multi-stage rocket to the "Vostok" scale model, demonstrates a practical and applied methodology for predicting model rocket performance. It effectively bridges fundamental rocket theory with real-world constraints like gravity and drag using empirical factors to achieve realistic results.

This section demonstrates how the theoretical rocket equations are adapted with empirical factors (K) to make practical predictions for model rocket performance, even for complex multi-stage vehicles or scale replicas.



A graphic depiction of Tartaglia's Law. This is why the tilt of a launch rod is limited to 30 degrees from the vertical.

"The road to space began just like this - with simple, small rockets,"

It’s not rocket science

No matter what the size or power, most hobby rockets are constructed using the same simple components. What matters is the thrust of the engine. Any rocket more than about 3 ½ pounds, regardless of power, is considered a high-power rocket, but even small rockets, given the right combination of thrust and fuel-burn time, can be considered high power.

Model rockets:

Are made of paper, wood or breakable plastic (no metal parts), weigh no more than 53 ounces and hold up to 4.4 ounces of slow-burning propellant.

High-power rockets:

Can be made of any material, any weight, have a high thrust and some can reach suborbital altitudes. Usually they reach 5,000 to 6,000 feet and go a few hundred miles per hour.

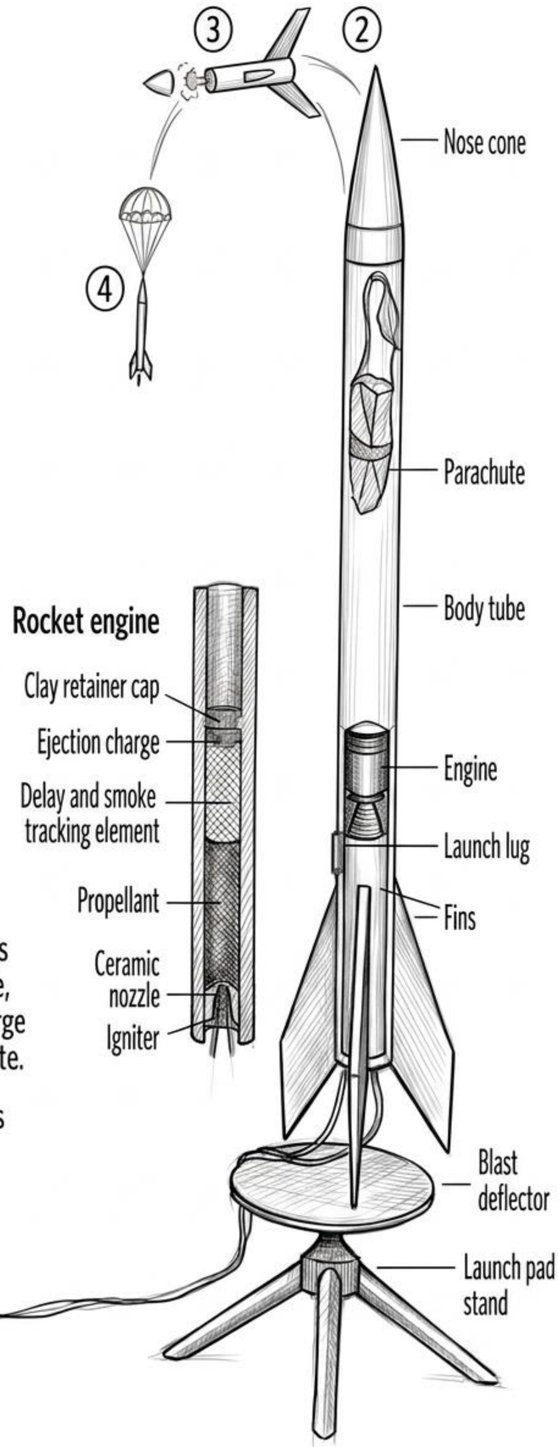
Launching

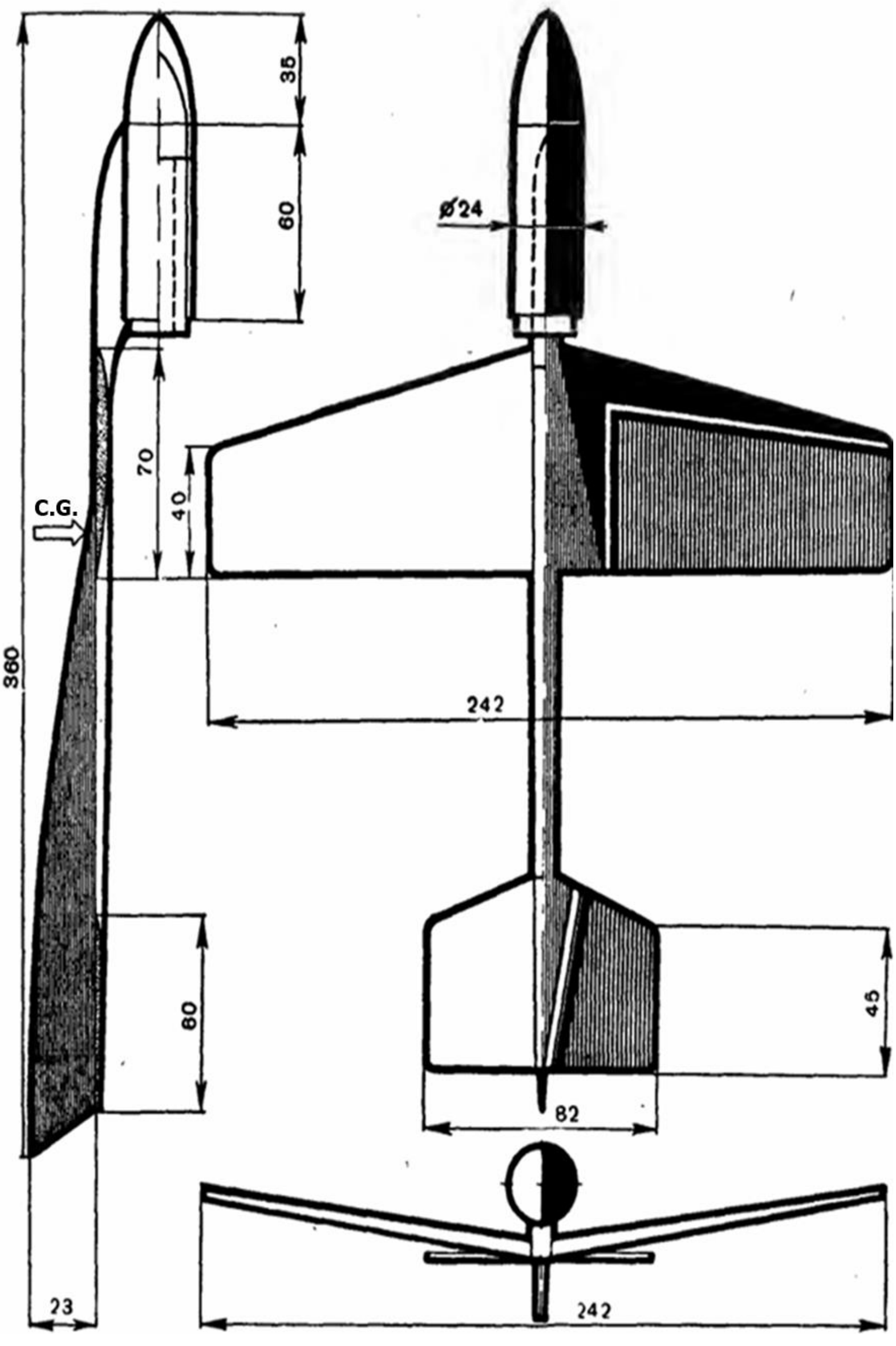
1. To launch, the controller sends electric current through wires to ignite the propellant in the engine.

2. The engine burns through the fuel, gaining altitude.

3. The rocket reaches its maximum altitude, and the ejection charge releases the parachute.

4. The rocket returns to the ground.





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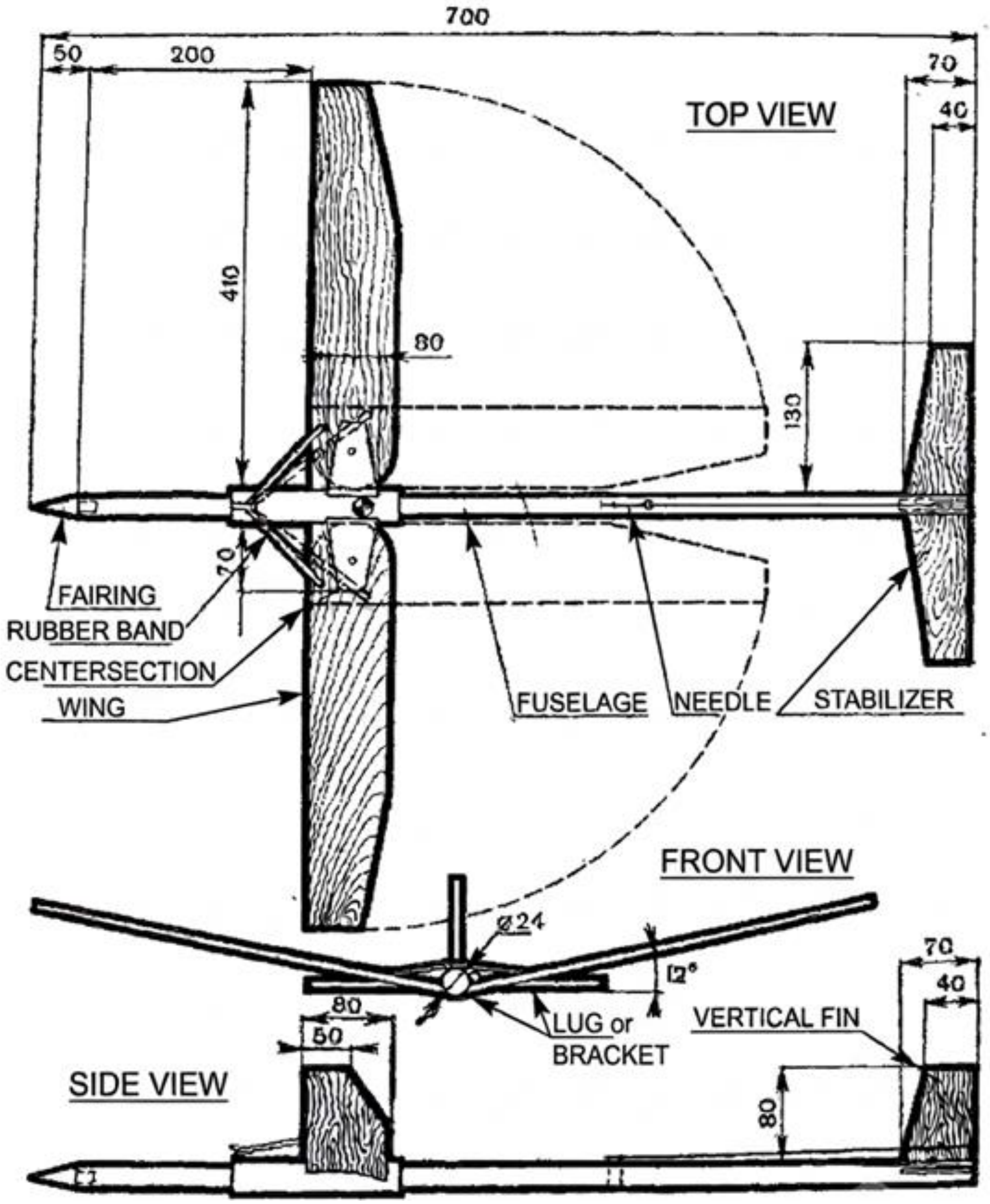


Model Rocket Plane with Foldable Wings

10. THE MODELER'S WORKSHOP: TOOLS AND MATERIALS

A well-prepared workspace is the foundation of successful model rocketry. The right tools and materials not only make construction easier and more precise but also ensure the safety of the builder and the reliability of the finished rocket. This chapter details everything you need to establish your own basic rocketry workshop.

§ 1. The Essential Workstation: Safety and Setup

Before acquiring a single tool, one must establish a safe and organised space for building.

§ 1.1. Choosing Your Workspace: Bench, Lighting, and Ventilation

1. *Workspace Requirements*

Element	Key Requirement	Purpose
Work Surface	Sturdy table or desk protected by a self-healing cutting mat.	Provides a stable base, an ideal cutting surface, and protects tools and the desk itself.
Lighting	Good, bright light, preferably an adjustable desk lamp.	Non-negotiable for precision work; allows illumination from the correct angle to avoid shadows.

Element	Key Requirement	Purpose
Ventilation	Work in a well-ventilated area (e.g., near an open window), or use a small fan.	Essential because many adhesives and paints emit fumes; never use these products in a confined space.

§ 1.2. Fundamental Safety Rules: Eye Protection and Fire Safety

Eye Protection: Safety glasses must be worn whenever cutting, sanding, or handling adhesives. A single slip can have permanent consequences.

Fire Safety: The workshop should be a no-flame zone. Keep all chemicals, paints, and propellant materials away from heat sources. Have a fire extinguisher rated for Class B (flammable liquids) and Class C (electrical fires) accessible and know how to use it.

§ 1.3. Organizing Your Tools: Storage and Quick Access

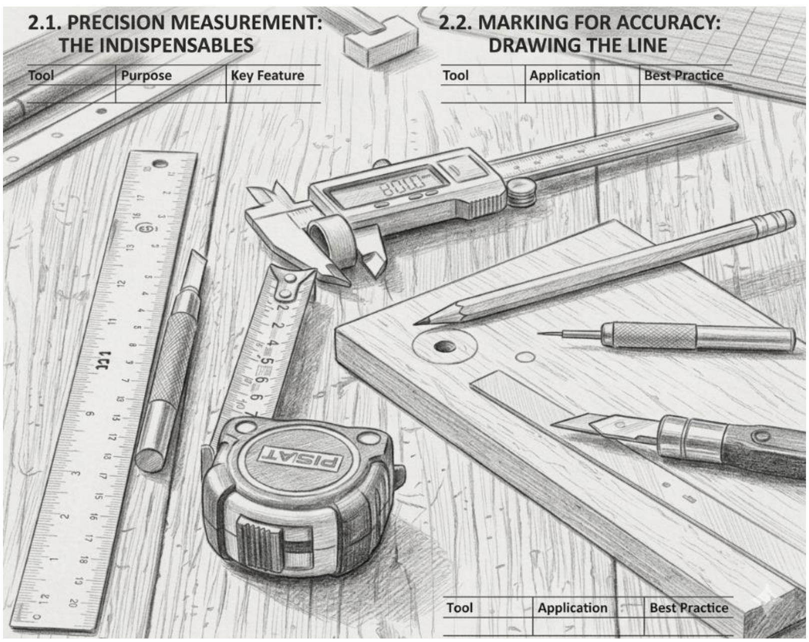
Use jars, trays, or a toolbox with small compartments to keep tools organized and within reach. A clean workspace is a safe workspace. Regularly clear away debris, scrap materials, and adhesive residue to prevent accidents and maintain tool functionality.

§ 2. Measuring, Marking, and Layout Tools

Precision in rocketry begins with accurate measurement and layout. This section covers the essential tools required to transfer your design specifications perfectly onto your materials.

2.1. Precision Measurement: The Indispensables

Tool	Purpose	Key Feature
Steel Ruler	Measuring straight lengths and acting as a guide for cutting.	Indispensable straight-edge for guiding hobby knife cuts. A 12-inch (30 cm) model is standard.
Tape Measure	Taking longer, more flexible measurements.	Necessary for checking body tube Length and other large dimensions.
Calliper	Achieving extremely precise internal and external measurements.	Used for checking tube wall thickness, cantering ring diameters, and motor dimensions to ensure perfect fits.



2.2. Marking for Accuracy: Drawing the Line

Tool	Application	Best Practice
Sharp Pencils	Making fine, accurate layout lines.	Use a mechanical pencil with HB lead for fine lines on wood and body tubes.
Scribing Tool / Awl	Scratching fine lines and marking drill holes.	Used to scratch fine lines into materials or to precisely mark the centres of holes to be drilled.
Marking Knife	Creating precise guidelines on wood.	A shallow cut with a hobby knife along a straight edge provides the most accurate guide for cutting wood.

2.3. Advanced Layout: Ensuring Stability

These specialised tools are critical for translating 2D plans into a stable 3D rocket.

Fin Alignment Guide

This is a *specialised jig* that holds the rocket body and fins in perfect position while the glue dries. It is arguably the most valuable tool for ensuring a *straight and stable rocket.*

Angle Finders and Protractors

These are essential for any complex design, such as *scale models* or rockets requiring *canted (angled) fins* for spin stabilization. They allow you to measure and set specific angles for attachment accurately.

§ 3. Cutting and Material Removal Tools

The right cutting tool ensures clean, precise parts.

§ 3.1. Cutting Body Tubes and Sheets: Hobby Knives, Razor Saws, and Tubing Cutters

Hobby Knife: The #11 blade is the most common and versatile for general cutting, shaping, and trimming. Always use a sharp blade; a dull blade requires more force and is dangerous. *Razor Saw*: A small saw with fine teeth is perfect for cutting through thicker materials like wood dowels or high-power motor mounts cleanly and without splintering.

Tubing Cutter: A commercial tubing cutter or a simple jig ensures a perfect 90-degree cut on body tubes every time.

§ 3.2. Shaping Wood and Plastic: The Role of Files and Rasps

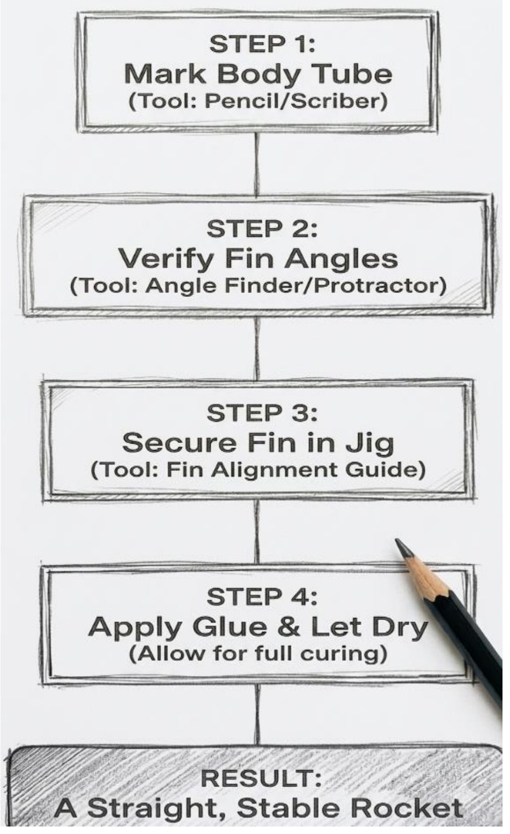
Files: Needle files in various shapes (round, flat, triangular) are used for precise shaping of small parts, such as cleaning up fin slots or shaping complex details.

Rasps: A wood rasp is used for the rapid, rough shaping of balsa or basswood nose cones and fins before final sanding.

This workflow shows how layout tools guarantee that fins are attached perfectly, which is essential for stable flight.

§ 3.3. Sanding for Perfection: Sanding Blocks, Power Sanders, and Grit Selection

Sanding Blocks: Always sand wood fins using a sanding block to maintain flat, even surfaces. A block can be as simple as a wood scrap wrapped with sandpaper.



Sandpaper Grits: Keep a range from coarse (80-100 grit for rough shaping) to medium (150-220 grit for general smoothing) to fine (400-600 grit for preparing surfaces for painting).

Power Sanders: A small rotary tool (like a Dremel) with sanding drums and discs can significantly speed up shaping tasks but requires a careful touch to avoid removing too much material.

§ 4. Joining and Adhesive Application

Selecting and using the correct adhesive is critical for the structural integrity of your project.

§ 4.1. Selecting the Right Fevicol / Glue: White Glue, Fevikwik, Epoxy, and Wood Glues

White Glue (e.g., Fevicol MR): This is your all-purpose *safed fevicol*. It is excellent for porous materials like paper, cardboard, and wood. It dries clear and is easy to clean with water. Ideal for general, low-Strength craft projects and basic model-making.

Cyanoacrylate (CA / "Fevikwik" or "Super Glue"): This is the *instant jod* that bonds almost anything quickly. The thin variety is very watery and seeps into tight joints, while the thick, gel-type is good for filling gaps. For best results on porous surfaces, use an accelerator spray to make it set instantly.

Epoxy (e.g., Araldite): This is a two-part adhesive (a resin and a hardener you mix together) that gives the strongest, most durable bonds. The 5-minute epoxy is good for quick fixes, while the 30-minute or slower-setting varieties are much stronger. Use this for critical load-bearing joints and major reinforcements in high-stress projects.

Wood Glue (Yellow, e.g., Fevicol SpeedX): This yellow glue is stronger and can be sanded smoothly after drying, unlike white glue. It is the preferred choice for strong wood-to-wood bonds, like attaching fins to a rocket body.

§ 4.2. Application Techniques: Using Brushes, Syringes, and Toothpicks

Do not apply glue directly from the bottle. Instead, take a small amount out on a non-porous surface like a piece of waste chocolate *patti* (foil backing), a plastic lid, or a tile.

Use toothpicks, an old paintbrush, or a fine-tip syringe (like an ink syringe or medical *syringe*) to apply the glue. This gives you proper control to put the adhesive exactly where it's needed.

§ 4.3. Creating Strong Bonds: The Science of Curing Times and Clamping

Curing vs. Drying: Remember, "drying" is just the water or solvent evaporating and the surface feeling dry. "Curing" is the full chemical process for the glue to achieve its final strength. Always respect the full cure time mentioned on the packet for a strong bond.

Clamping / Jamming: Use rubber bands, clothes pegs, or masking tape to firmly hold the parts together while the adhesive cures. This *jamming* ensures a tight, *mazboot* bond. Don't disturb the joint until the curing time is over.

§ 5. Building Blocks: Materials for Model Rocket Construction

Understanding the characteristics of different materials is crucial for picking the *right component* for a strong and stable rocket.

Body Tubes: Paper, Phenolic, and Composites

Paper Tubes (Cardboard Tubes):

The *standard go-to* for low- and mid-power models. They are *lightweight,* easy to cut with a simple *cutter* (blade) or scissors, and *easy on the pocket.* Commonly found in the form of mailing tubes or speciality craft tubes.

Phenolic Tubes:

Made from paper treated and bonded with phenolic resin. These are *much stronger, highly rigid*, and more *heat-tolerant* than simple paper—ideal for high-power rocketry where forces and motor heat are intense.

Carbon Fibre and Fibreglass (Composites):

The *ultimate choice* for maximum Strength with minimal weight, mainly used in a*dvanced high-power rockets.* Note that these tough materials need *specialised tools* (like diamond cutting wheels) and techniques for neat finishing.

📏 *Fin Materials: From Balsa to Plywood*

The fins need to be rigid enough to handle the thrust and air pressure.

Balsa Wood:

Extremely lightweight and easy to shape (like the balsa wood used for aeroplane models). Perfect for small, *low-power rockets* where minimum weight is critical. However, they are *quite fragile* and need careful handling.

Basswood:

Denser and stronger than balsa, yet still relatively easy to work with. A much better and more durable choice for *mid-power rockets* that experience higher launch speeds.

Plywood (Usually 3mm or thicker):

Offers *excellent, robust strength,* especially for the large fins used on *high-power rockets.* You can laminate (stack and glue) thinner sheets for even greater stiffness and Strength, ensuring the fins don't flutter under thrust.

Plastic and Composite Fins:

Often *injection-moulded*, providing a very consistent shape and *great durability.* Remember, these usually require special *CA or plastic-specific adhesives* (like those used for plastic kits).

Nose Cones: Shape for Speed

The nose cone cuts through the air and houses the recovery system.

Moulded Plastic:

The *most common type* in Indian kits is available in many aerodynamic shapes (like parabolic or conical). They are lightweight and provide good flight characteristics.

Turned Wood (Balsa or Basswood):

Allows for *full customisation* of the cone's shape—perfect for scale model rockets or unique designs. They can be easily sanded and finished to achieve a very smooth, high-quality *surface. Composite (Fibreglass or Carbon Fibre):*

Used in *high-performance, heavy-duty rockets* due to their superior *strength-to-weight ratio* and ability to withstand high speeds and recovery forces.

§ 6. Finishing Tools and Supplies

A good finish protects the rocket and reduces aerodynamic drag.

§ 6.1. Surface Preparation: Fillers, Putties, and Primers

Fillers: Lightweight spackling or modelling putty (e.g., Bondo spot putty) is used to fill the wood grain of balsa fins and any seams or imperfections. Apply, let dry, and then sand to a smooth finish.

Primer: A sandable primer (usually grey or white) is applied after the filling is complete. It seals the surface and reveals any remaining flaws. Sanding between coats of primer is the secret to a flawless paint job.

§ 6.2. Painting Techniques: Brush Painting vs. Spray Painting

Brush Painting: Suitable for small details and touch-ups. Can leave brush strokes if not done carefully.

Spray Painting: Provides the most professional, even finish. Use spray paints designed for plastics and models. Apply multiple light "dusting coats" instead of one heavy coat to prevent runs.

§ 6.3. Achieving a Professional Finish: Masking, Decaling, and Clear Coats

Masking Tape: Use low-tack painter's tape to mask off areas for multi-colour paint schemes. Ensure the first colour is completely dry before masking.

Decals: Apply water-slide decals over a smooth, glossy surface for best adhesion. Use decal setting solutions to help them conform to curved surfaces.

Clear Coat: A final clear coat (gloss, satin, or matte) protects the paint and decals, unifying the finish and providing a durable protective layer.

11. ROCKET CONSTRUCTION TECHNIQUES

The design of a rocket lives on paper, but its flight performance is born in the workshop. Proper construction techniques are what transform components into a reliable, stable, and high-performing vehicle. This chapter provides a systematic guide to assembling your model rocket, from basic principles to advanced methods for scale modelling.

§ 1. Core Body Assembly

The body tube is the backbone of your rocket, housing the recovery system and Motor while providing the mounting structure for fins and nose cone.

§ 1.1. Preparing the Body Tube

Cutting to Length: Use a sharp hobby knife and a metal ruler. Roll the tube slightly while applying pressure for a clean, square cut. Sand the cut edge smooth.

Sealing and Reinforcing: Lightly sand the outer surface with fine-grit sandpaper to provide a better grip for paint and adhesives. Apply a thin coat of CA (cyanoacrylate) glue or wood glue to the inside of the tube ends to prevent splintering and Strengthen the area where components press fit.

Marking Centrelines: Using a pencil and a length of string or a commercially available marking guide, draw at least two perpendicular lines along the length of the tube. These are crucial for aligning fins and launch lugs with precision.

§ 1.2. Installing the Motor Mount

Components: A typical Motor mount consists of the Motor tube, cantering rings, and an Motor retainer (hook or block).

Friction-Fit Method (Basic): The Motor is held in place by a tight fit within the tube. An Motor hook—a metal clip extending from a slit in the Motor tube—provides secure retention while allowing spent Motors to be removed.

Screw-On Retainer Method (Advanced): For high-power rockets, a plastic or aluminum retainer screws onto the aft end of the Motor mount, physically preventing the motor from ejecting. This is the most secure method.

Assembly: Dry-fit all components first. Glue the Motor hook in place, then attach the forward cantering ring to the Motor tube. Apply adhesive to the ring and slide the assembly into the body tube, ensuring it is square. Finally, glue the aft cantering ring into place.

§ 1.3. Bulkhead Installation for Avionics Bays and Payload *Sections*

Purpose: Bulkheads are disks that create sealed compartments within the body tube. A forward bulkhead in a payload section protects the recovery system; two bulkheads can form an avionics bay for electronic altimeters.

Installation: Bulkheads are typically press-fit and glued into place. Ensure they are perfectly perpendicular to the body tube's long axis. For avionics bays, drill small holes for switch access and wiring.

🛠 *Assembly Techniques: Building a Robust Rocket*

The goal is to create joints that are light, strong, and aerodynamic.

1. 📏 *Marking and Alignment (The Foundation)*

Before any glue is applied, accurate marking is vital for a straight-flying rocket.

Fin Alignment Lines: Use a simple method to draw straight lines for your fins. A "V" notch in a piece of cardboard or wood, or even a straight edge of a door frame, can be used to hold the pencil steady while you rotate the body tube.

Spacing: Fins must be equally spaced. For a 3-fin design, divide the tube's circumference by 3 (120° apart). For 4 fins, divide by 4 (90° apart). Mark these points accurately at the bottom of the tube and extend the straight line up using your V-notch guide.

2. • *Fin Attachment: The Strongest Joint*

The joint where the fin meets the body tube is under immense stress during flight.

Preparation is Key: Lightly roughen both the root edge of the fin (the edge that touches the body tube) and the corresponding area on the body tube with fine sandpaper (*regmaal*). This helps the glue grip the surface.

Apply a thin, even bead of Wood Glue (Fevicol SH) or medium-viscosity CA (Super Glue) along the fin line. Press the fin firmly onto the body tube, ensuring it is perfectly perpendicular (90 degrees). Use a fin alignment guide (a homemade jig or a simple set square/ruler) to hold it straight while the glue sets (use CA for instant setting, or hold with tape for Wood Glue).

For high-power/heavy rockets, a "through-the-wall" method is best: the fin root passes through a slit in the body tube and is glued directly to the inner motor mount, creating a mechanical and chemical lock.

3. ✨ *The Fin Fillet: The Secret to Strength and Aerodynamics*

A fillet (*pronounced fill-it*) is a smooth, rounded bead of glue applied in the corner where the fin meets the body tube. It does two things:

1) Massively increases Strength by spreading the stress over a larger area.

2) Reduces drag (wind resistance) by smoothing the sharp corner.

<u>*Material:*</u> For low to mid-power, use Wood Glue (Yellow Glue). For high-power/Plywood fins, use Epoxy (Araldite).

Application:

- <u>*Apply a uniform bead*</u> of your chosen adhesive along the entire fin-body joint.
- <u>*Immediately smooth*</u> the bead using a damp fingertip (for Wood Glue) or the rounded end of a toothpick/matchstick (for Epoxy). The goal is a smooth, concave curve.
- <u>*Wipe away any excess*</u> glue instantly.
- Important: Do only one side of one fin at a time, then let it cure or dry partially before rotating the rocket to do the next side. This prevents the wet fillet from drooping or flattening. Repeat the fillet process 2-3 times for maximum Strength.

4. ⬬ Launch Lug Attachment

The launch lug (a small plastic or paper tube) holds the rocket onto the launch rod.

Placement: The lug is attached parallel to one of the fins. Use small dabs of CA or Epoxy.

Fillets are recommended: Use a small fillet of glue (like a mini-fin fillet) where the lug touches the body tube for a secure bond that won't snap off during transport or launch.

5. 🩹 Shock Cord Mount

The shock cord (a piece of elastic/nylon) connects the nose cone to the body tube, preventing them from separating after the parachute is ejected.

Anchor: A strong anchor is needed inside the body tube. The simplest method is a paper shock cord mount (a rectangle of thick paper or card) that is glued inside the body tube, usually using White Glue (Fevicol MR), in a position that won't interfere with the Motor mount or nose cone. The shock cord is then tied through a hole in this anchor.

§ 2. Fin Design and Attachment

Fins provide the necessary aerodynamic stability to keep the rocket flying straight. Their precise attachment is the single most important factor in a stable flight.

§ 2.1. Fin Design Fundamentals

Planform: The shape of the fin as viewed from the side. Common shapes include rectangular, clipped delta, and elliptical. The choice affects drag, Strength, and stability.

Airfoil: The cross-sectional shape. For model rockets, a simple rounded leading edge and tapered trailing edge significantly reduce drag compared to a flat plate.

Root Chord: The length of the fin where it attaches to the body tube. A longer root chord provides a stronger attachment point.

§ 2.2. Fabricating Fins

Transferring the Pattern: Use carbon paper or spray adhesive to temporarily attach a printed fin template to your material (balsa, basswood, plywood).

Cutting: Cut just outside the line with a sharp hobby knife or fine-tooth scroll saw.

Sanding to Shape: Sand precisely to the line using a sanding block. Then, sand the edges to create a symmetrical airfoil: round the leading edge and taper the trailing edge to a sharp finish.

§ 2.3. Fin Alignment Techniques

The Fin Alignment Guide: This is the most critical tool for this step. It holds the rocket body and fins in perfect position while the glue sets.

Using the Guide:

Apply a small amount of glue to the root edge of a fin.

Slide the fin into the guide's slot, aligning it with one of the centerlines on the body tube.

Press the fin against the body tube and hold for a few seconds until the glue grabs.

Repeat for all fins. Allow the initial glue joints to cure fully before removing the guide.

§ 2.4. Creating Adhesive Fillets

Purpose: Fillets are beads of adhesive placed at the joint between the fin and the body tube. They dramatically increase the joint's

Strength and improve aerodynamics by smoothing airflow.

Technique:

Mix a small batch of epoxy or use a thick gap-filling CA glue.

Using a finger (in a glove) or a craft stick, apply a smooth, consistent bead along both sides of the fin-body tube joint.

Smooth the bead with a tool dipped in isopropyl alcohol (for epoxy) or a specialized CA accelerator (for CA) to create a concave, aerodynamic profile.

Allow to cure completely without disturbing.

§ 3. Nose Cones and Payload Sections

§ 3.1. Types of Nose Cones

Common Shapes: Ogive (tangent or secant) for low drag, *Conical* for simplicity, *Parabolic* for high-speed stability, and *Blunted* for safer recovery.

Materials: Moulded plastic is most common; turned balsa or basswood allows for customization; composite materials (fibreglass) are used for high-performance rockets.

§ 3.2. Balancing for Stability

Center of Gravity (CG): For a rocket to be stable, the CG must be ahead of the Center of Pressure (CP).

Adding Weight: If your rocket is marginally stable, add non-drying clay or small fishing weights into the tip of the nose cone. Re-check the CG after each addition.

CG Test: Balance the fully assembled rocket (without Motor) on the edge of a ruler. Mark the balance point; this is your CG.

§ 3.3. Constructing a Functional Payload Bay

Purpose: To carry scientific experiments, cameras, or altimeters.

Construction: A payload bay is simply an extra section of body tube, capped by two bulkheads.

Access: One bulkhead is typically fixed, while the other is part of a removable nose cone or section. Use screws, shear pins, or a friction fit to secure the removable section.

§ 4. Recovery System Construction

A successful flight requires a safe return.

§ 4.1. Parachute and Streamer Design

Streamers: For lightweight rockets or low altitudes. Cut from bright plastic or Mylar, 1-2 inches wide and 4-8 times the rocket's length.

Parachutes: For heavier rockets and slower, controlled descents.

Shroud Lines: Use strong, lightweight string (e.g., Kevlar thread). Attach 3-6 lines evenly spaced around the canopy.

Canopy: Cut from a thin plastic bag or specialized rip-stop nylon. A simple hexagon or circle is effective. A spill hole in the centre prevents oscillation during descent.

§ 4.2. Shock Cord Attachment

Function: To absorb the force of the ejection charge and connect the rocket sections.

Materials: Elastic cord is good for low-power; *Kevlar® cord* is heat-resistant and strong for high-power.

Mounting: Never glue the cord directly to the body tube. Attach it to a sturdy anchor point, such as an eye-hook screwed into a forward bulkhead or a Kevlar strap epoxied to the inside of the body tube.

§ 4.3. Packing the Recovery System

Protect from Heat: Fold a Nomex® cloth or cellulose-based recovery wadding and insert it into the body tube above the Motor. This protects the parachute from the hot ejection gases.

Fold the Parachute: Lay the parachute flat, gather the shroud lines, and fold the canopy in a "Z" or "burrito" pattern.

Pack Gently: Place the folded parachute and shock cord into the body tube. Do not force it. The ejection charge should have enough pressure to push it out easily.

§ 5. Launch System Interface

§ 5.1. Launch Lugs

Placement: Glue one lug near the rocket's centre of gravity and a second one nearer to the aft end, both aligned with a body tube centreline. This prevents the rocket from "bowing" around the rod during launch.

§ 5.2. Rail Buttons

Installation: One button is installed near the CG, the other near the aft end. Screw them into pre-drilled holes in the body tube, reinforced with epoxy or a wooden block on the inside.

§ 6. Advanced Construction: Building a Scale Model

§ 6.1. Reading Scale Data and Blueprints

Find technical drawings or detailed photographs of the full-scale rocket.

Determine Scale: Choose a scale (e.g., 1:100) and calculate the dimensions of every part of your model based on the real rocket's dimensions.

§ 6.2. Techniques for Adding Surface Details

Laser-Cut Parts: Use for complex gussets and fins.

3D Printing: Ideal for creating intricate nose cones, nozzles, and other small details.

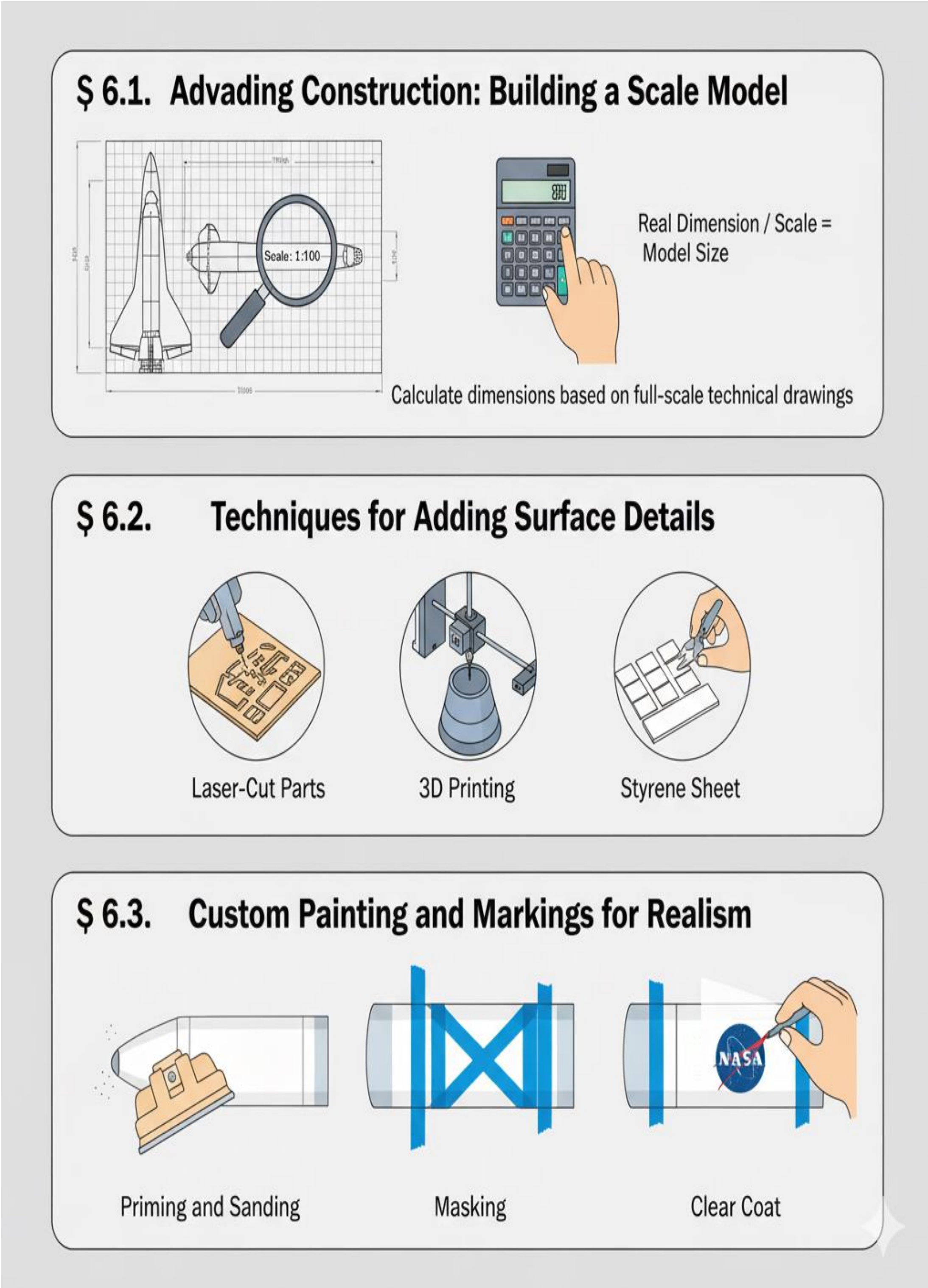
Styrene Sheet: Can be cut and glued to add panel lines, vents, and other surface features.

§ 6.3. Custom Painting and Markings for Realism

Priming and Sanding: Essential for a smooth, scale-like finish. Multiple cycles of priming and sanding may be needed.

Masking: Use low-tack modelling tape to create sharp, clean colour separations.

Decals: Use water-slide decals or custom-cut vinyl to apply accurate logos and markings. Seal with a clear coat to protect them.



§ 6.1. Advading Construction: Building a Scale Model
Scale: 1:100
Real Dimension / Scale = Model Size
Calculate dimensions based on full-scale technical drawings
§ 6.2. Techniques for Adding Surface Details
Laser-Cut Parts
3D Printing
Styrene Sheet
§ 6.3. Custom Painting and Markings for Realism
NASA
Priming and Sanding
Masking
Clear Coat

12. LAUNCH SYSTEMS & OPERATIONS

A successful and safe model rocket flight depends as much on the ground support equipment and procedures as it does on the rocket itself. This chapter covers the essential hardware and standardised operations for preparing, launching, and recovering your rocket.

§ 1. Launch Pad Fundamentals

The launch pad's primary function is to hold the rocket perfectly vertical and guide it in a straight path for the first few meters of flight, until it has achieved sufficient aerodynamic stability and velocity.

§ 1.1. Launch Rods: Length, Diameter, and Material

Purpose: The launch rod provides a stable guide for the rocket's initial acceleration, preventing it from tipping over in the critical moment of lift-off.

Length: The rod must be long enough to allow the rocket to reach a stable speed before it leaves the guide.

Rule of Thumb: Minimum length is 3-4 times the rocket's body length. For larger or heavier rockets, a longer rod (1.5 to 2 meters) is essential.

Diameter: Must match the size of the rocket's launch lug.

Common sizes are 1/8", 3/16", and 1/4". The lug should slide freely but without excessive play.

Material:

- *Mild Steel:* Common and inexpensive, but can rust.

Stainless Steel: Corrosion-resistant and highly recommended for durability.

Aluminium: Lightweight and rust-proof, but can bend if mishandled.

§ 1.2. Launch Rails and Rail Buttons for High-Power Rockets

The Limitation of Rods: For heavy, high-power rockets, the friction and whip of a long, thin rod become problematic.

The Rail Solution: A launch rail is a sturdy, extruded aluminium track (e.g., 1010, 1515) that provides a much more rigid, longer guide.

Rail Buttons: Instead of a paper lug, the rocket uses two plastic or nylon "buttons" that slide within the rail channel.

One button is typically placed near the rocket's center of gravity, and the other near the aft end, providing maximum stability during guide-out.

Rail buttons are essential for all mid- and high-power rocketry.

§ 1.3. Building a Stable Launch Pad Base

Function: The base must support the rod or rail and resist tipping over from wind or the force of the rocket's ignition.

Design Principles:

Wide Legs: A tripod design with legs that splay out widely provides excellent stability.

Mass: A heavy base plate (e.g., a concrete patio block or a heavy steel plate) is a simple and effective solution.

Ground Spikes: For portable launch pads, legs with spikes can be driven into the ground to prevent movement.

Alignment: The base must allow for precise levelling to ensure the rod/rail is perfectly vertical. A small bubble level is an invaluable addition to any launch pad.

§ 2. Launch Controller Electronics

The launch controller is a remote ignition system that allows the operator to be a safe distance away from the rocket during launch.

§ 2.1. Circuit Design: Continuity Indicators, Safety Keys, and Arming Switches

A safe controller is more than just a battery and a switch. It incorporates multiple safety layers.

Continuity Indicator: This is a crucial safety and diagnostic feature. A small light (LED or bulb) in the circuit illuminates when there is a complete electrical path through the igniter, confirming it is properly installed and not broken. *Warning:* The current for the continuity check must be very low (using a high-resistance resistor) to prevent accidental ignition.

Safety Key: A removable physical key that completes the circuit. The controller is "dead" without the key inserted, preventing accidental use.

Arming Switch: A guarded switch that must be deliberately activated to supply full power to the launch circuit. The launch button itself is the final step in the sequence.

§ 2.2. Power Requirements: Matching Batteries to Igniter Current

The Goal: To deliver sufficient current (Amps) to heat the igniter's bridge wire to incandescence instantly.

Igniter Needs: Standard Estes-style igniters require 2-4 Amps. Larger composite-motor igniters may require 12 Volts and higher current.

Battery Selection:

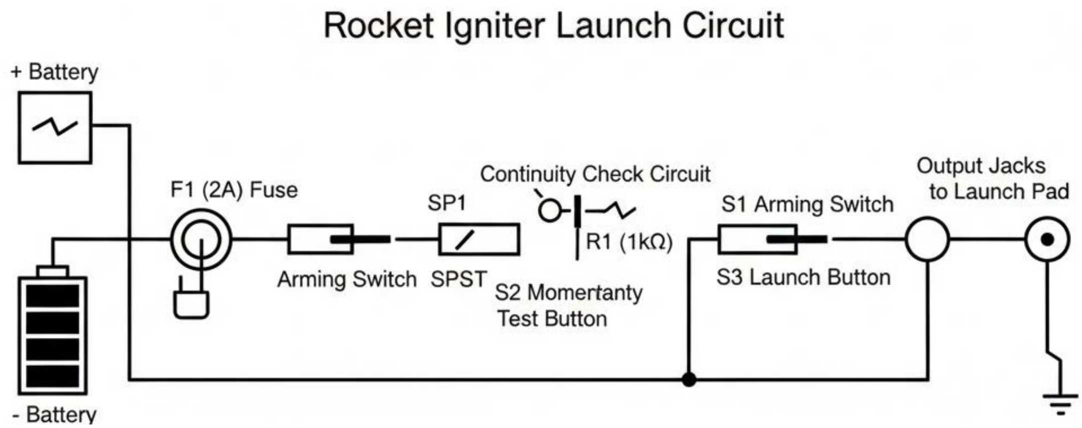
9-Volt Transistor Battery: Marginal for some igniters; can be unreliable in cold weather.

AA or C-Cell Batteries (in series): A pack of 4 C-cells (6V) provides robust and reliable current for most low-power rockets.

12V Sealed Lead-Acid (SLA) or LiPo Packs: Essential for high-power controllers and reliable ignition of composite motors.

§ 2.3. Building Your Own Launch Controller: A Sample Circuit

Below is a simple, safe, and effective circuit you can build.



[SCHEMATIC DESCRIPTION]

+ (Battery + Terminal) -->

[Fuse, 2A] -->

[Safety Key Jack] -->

[Arming Switch] -->

[Continuity Check Circuit: A low-current LED in series with a 1kΩ Resistor, with a "Momentary Test" Button across it] -->

[Launch Button (Momentary)] -->

[Output Jacks to Launch Pad] -->

- (Battery - Terminal)

Components List:

Component Name	Specification	Purpose
Power Source	4x C-Cell Battery Holder (Approx 6V DC)	Provides the power to fire the igniter.
Enclosure	Plastic Project Enclosure	Houses the electronics and controls safely.
Safety	2A Fuse and Fuse Holder	Protects against short circuits and excessive current.
Safety Disconnect	Safety Key (Jack with shorting plug)	Physically breaks the circuit when removed.
Control 1	SPST Toggle Switch (Arming Switch)	The main switch to enable the launch system.
Control 2	Momentary Push Button (Launch Button)	Fires the igniter when pressed.
Check	Momentary Push Button (Continuity Check)	Allows testing the igniter connection.
Indicator	LED and 1kΩ Resistor	Lights up if the igniter circuit is complete (good continuity).
Connection	Output Jacks and long, two-conductor launch wire	Connects the controller to the remote igniter.

Operation:

Insert Safety Key.

Press the Continuity Check button. The LED should light, confirming the igniter is installed correctly.

Flip the Arming Switch ON.

Press and hold the Launch Button until the rocket ignites (usually 1-2 seconds).

§ 3. Pre-Launch Procedures

Standardised procedures are the bedrock of safety and success at a launch event.

§ 3.1. The Range Safety Officer (RSO) Checklist: Airspace, Weather, and Crowd

Before any rocket is launched, a safety check of the environment is mandatory.

Airspace: Is the launch site clear of overhead obstructions (power lines, trees, buildings)? Is it under a flight path? Ensure the planned altitude will not conflict with aircraft.

Weather: Check wind speed and direction. High winds can carry rockets far off course, making recovery dangerous. Avoid launching in rain or near thunderstorms.

Crowd & Ground Safety: Ensure all spectators are behind a designated safety line. The launch area downrange must be clear of people, dry grass, and flammable materials.

§ 3.2. Pad Manager Checklist: Installing the Rocket and *Connecting Igniters*

This is the hands-on preparation of the rocket itself.

Install Rocket: Slide the rocket onto the rod or rail, ensuring it moves freely.

Check Stability: Verify the pad is level and the rocket is vertical.

Install Igniter: Carefully insert the igniter into the motor nozzle, ensuring the pyrogen tip is in contact with the propellant. Secure it with a plastic plug or masking tape.

Connect Wires: Attach the launch controller clips to the igniter leads. *Keep the clips separated* to prevent accidental arcing.

Verify Continuity: From a safe distance, the operator performs a continuity check. The RSO may confirm "Clear to Arm."

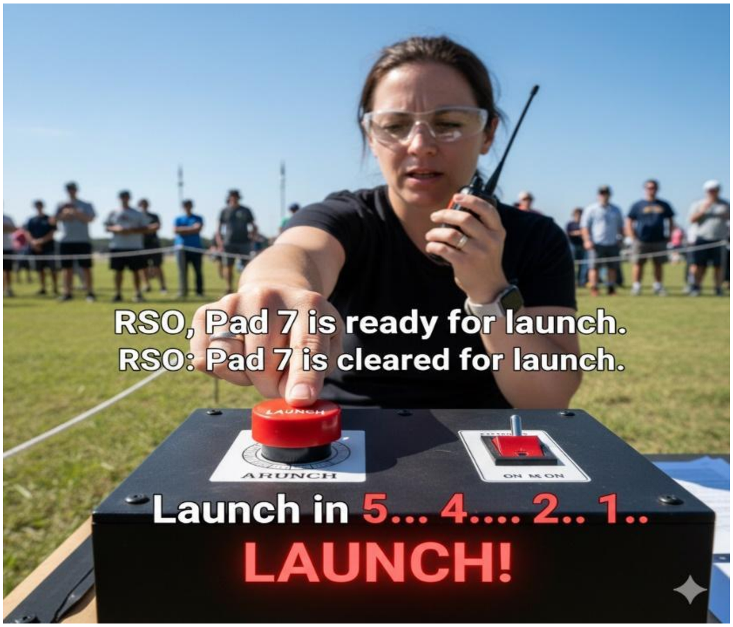
§ 3.3. The Countdown: A Standardised Sequence for a Safe Launch

A clear, audible countdown ensures everyone is aware of the launch status.

"RSO, Pad [Number] is ready for launch."

RSO: "Pad [Number] is cleared for launch."

Operator: "Launch in 5... 4... 3... 2... 1... **Launch!**" (Press and hold the launch button).



§ 4. Launch Day and Post-Flight

§ 4.1. Setting Up a Launch Range and Safety Perimeter

- *Organise the launch area* with pads spaced adequately apart.
- *Establish a clear "Ready Box"* where rockets are prepared.
- Define a safety line at least 15-30 feet from the nearest launch pad for low-power, and 100+ feet for high-power.
- Position the launch control console behind the safety line.

§ 4.2. Tracking Your Rocket in Flight

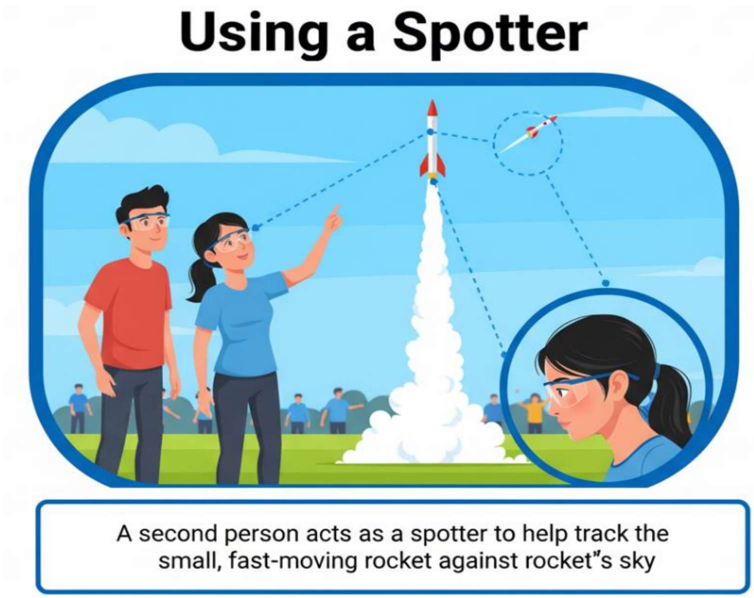
Tracking a model rocket after launch is crucial for assessing its performance and ensuring its recovery. There are several key techniques and practices to follow throughout the flight.

Maintaining a Clear Sight Line

The moment the countdown begins, you must focus your attention and **keep your eyes on the rocket.** Don't look away or look up too soon; keeping your head down and watching the base of the rocket's travel ensures you catch the initial, high-speed boost phase, which is the easiest time to lose sight of the vehicle.

Using a Spotter

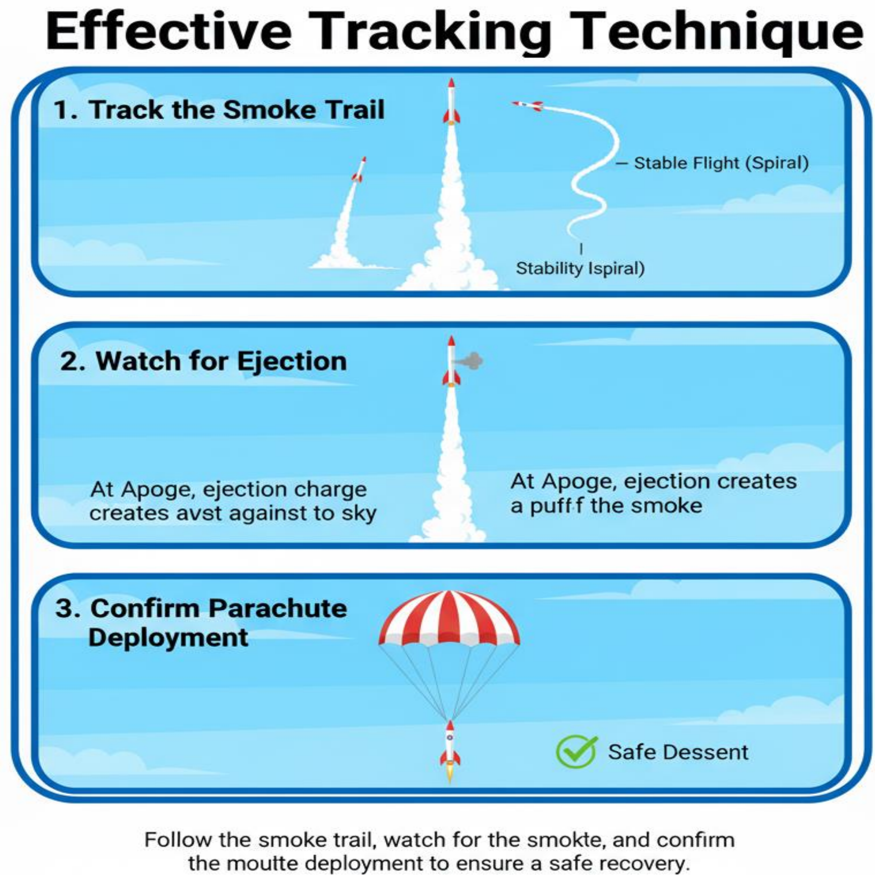
It is highly recommended to *have a friend act as a dedicated spotter.* Model rockets are often small, fly very fast, and can be easily lost against a bright blue or hazy sky. A second pair of eyes focusing solely on the ascending vehicle significantly increases the chance of maintaining continuous visual contact from liftoff through recovery.



A second person acts as a spotter to help track the small, fast-moving rocket against rocket"s sky

Effective Tracking Technique

The most reliable method for following the rocket is to *track the smoke trail* left by the motor. Pay close attention to the flight path: a *straight boost* indicates a successful, stable flight, while observing *a spiral or curve* could be an important indication of a stability issue that may need to be addressed before the next launch. As the rocket coasts to apogee (the highest point), *watch closely for the ejection charge smoke.* This smoke signals that the recovery system, usually a parachute or streamer, should deploy. Confirming *parachute deployment* is the final and most important step in tracking, as it determines the rocket's safe landing zone.



§ 4.3. Recovery and Post-Flight Inspection

Approach with Caution

Always prioritize safety during recovery. Never rush towards a landed rocket. *Wait at least a minute* **after** *landing* before approaching, as spent motors can be extremely hot and may cause burns. Be aware of the landing environment; the rocket might be *tangled in a tree or power line*, in which case specialized tools or professional help might be needed to retrieve it safely. Never attempt to retrieve a rocket from a power line yourself.

Inspection:

a) *Check the airframe, fins, and nose cone for damage*.

b) *Examine the shock cord and parachute for burns or tears.*

c) *Remove the spent motor casing and properly dispose of it.*

Data Review

If you equipped your rocket with an altimeter or other onboard data logging devices, this is the time to download and analyze the flight data. Correlate the data—such as altitude, speed, and acceleration—with your visual observations from tracking the flight. This comprehensive review is a critical learning **tool**. It helps you understand the rocket's actual performance compared to your predictions and provides invaluable insights for improving your next design and flight.

After a successful flight and tracking, the next crucial steps involve safely recovering your rocket and conducting a thorough post-flight inspection. This process is vital for safety, data analysis, and preparing for future launches.

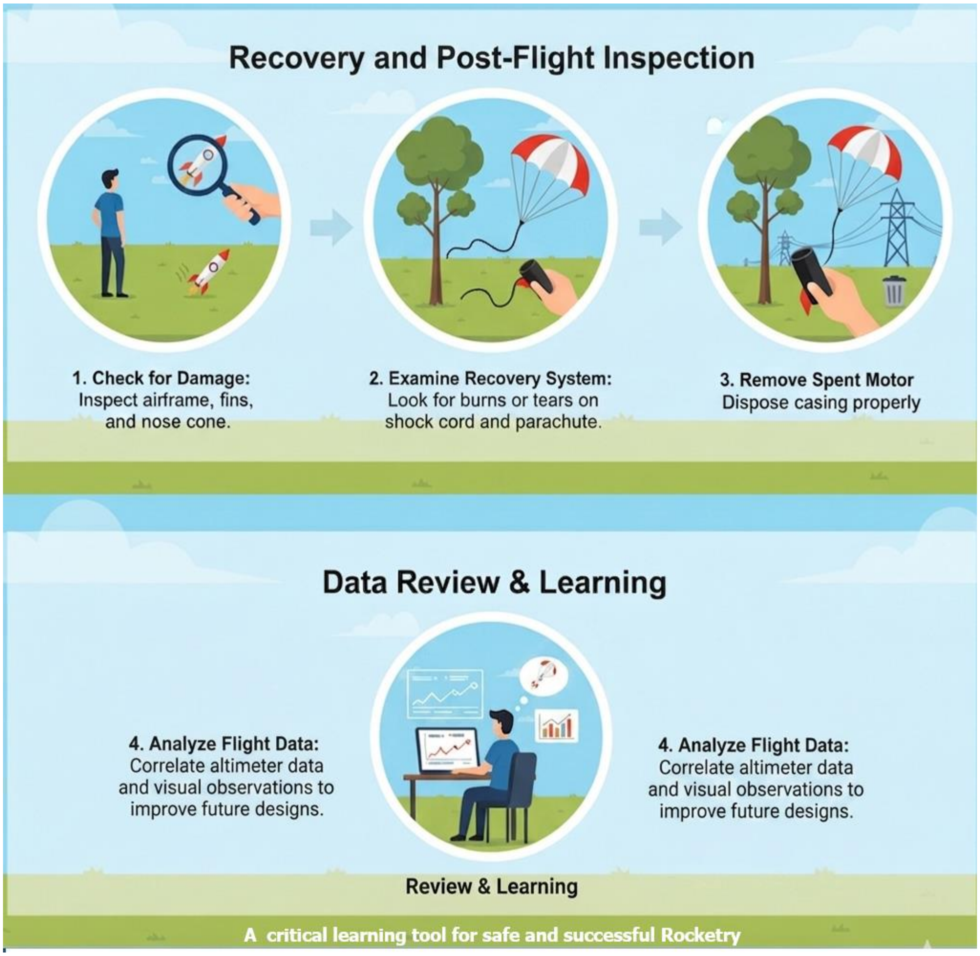
Post-Flight Inspection

Once it's safe to approach, perform a detailed inspection of your rocket.

Airframe, Fins, and Nose Cone: Carefully check the entire body of the rocket, including the fins and nose cone, for any signs of **damage**. Look for cracks, dents, loose components, or stress marks that might indicate an impact or flight issue.

Recovery System: Thoroughly *examine the shock cord and parachute (or streamer).* Look for any *burns, tears, or excessive stretching* that could compromise the recovery system's integrity in future flights. The shock cord is particularly vulnerable to heat from the ejection charge.

<u>Motor Casing: Remove the spent motor casing</u> from the motor mount. This is important for preparing the rocket for its next flight and for *<u>properly disposing of the used casing</u>* according to local regulations and manufacturer guidelines.



Let's Launch a Rocket!

Launching Safely is Part of the Fun!

Welcome, future rocket scientists!

Before you start dreaming about powerful Motors and cool designs, there's one thing we need to talk about first: **safety**. Just as you follow rules in a science lab or while crossing the road, building and launching rockets has its own set of important rules. We call this the **Model Rocket Safety Code**.

Think of this code as your mission's flight computer—it's there to guide you and make sure your launch is a success and, most importantly, safe for everyone. No matter how amazing your final rocket looks, you must follow these guidelines from the very beginning. Let's build them into your design right from the start!

Here are the key rules you need to know:

1) *Safe Materials*: Use only lightweight materials like cardboard, wood, or plastic for the body, fins, and nose. No metal parts, please!

2) *Ready-Made Motors Only*: Always use certified, store-bought rocket motors. Never try to make your own or use them in a way the manufacturer doesn't recommend.

3) *Electrical Launch:* Launch your rocket only with an electrical launch system. Your launch controller must have a safety key and a switch that turns off automatically when you let go.

4) *Misfire Protocol:* If your rocket doesn't launch, don't go near it! Remove the safety key, disconnect the battery, and wait for a full 60 seconds before you or anyone else approaches it.

5) *Clear for Launch:* Always do a countdown! Make sure everyone is standing at a safe distance—at least 15 feet for smaller rockets (D motors and below) and 30 feet for bigger ones. If you're launching more than 10 rockets together, keep a distance of 1.5 times the maximum height you expect the rocket to reach.

6) *Stable Launcher:* Use a launch rod or rail and keep it pointing nearly straight up. Always use a blast deflector to protect the ground. Keep the top of the launch

rod above eye level or put a cap on it when not in use to prevent accidents.

7) *<u>Size Limits:</u>* Your rocket should not weigh more than 1,500 grams at launch and should not have more than 125 grams of propellant fuel.

8) *<u>Safe Flight Path:</u>* Never launch your rocket at people, animals, buildings, or airplanes. Don't put any flammable or explosive items inside your rocket.

9) *<u>The Right Launch Site:</u>* Launch only in a big, open outdoor area. The size of the field should match your rocket's Motor power (see the simple guide below). Don't launch if it's too windy (over 20 mph) or if there is dry grass around that could catch fire.

10) *<u>Come Back Safely</u>*: Your rocket must have a recovery system like a streamer or parachute to bring it back gently. Always use special flame-resistant 'wadding' paper to protect the parachute from the Motor's heat.

11) *<u>Safe Recovery:</u>* If your rocket gets stuck in a tall tree, on a building, or near power lines, do NOT try to climb and get it. It's not worth the risk. Sometimes, you have to let it go.

Remember This Golden Rule:

Your rocket should be designed for the size of the field you have, not the other way around. A bigger rocket needs a bigger field. Always choose a launch site that is safe for your rocket's power.

Here is a simple guide to help you pick the right field:

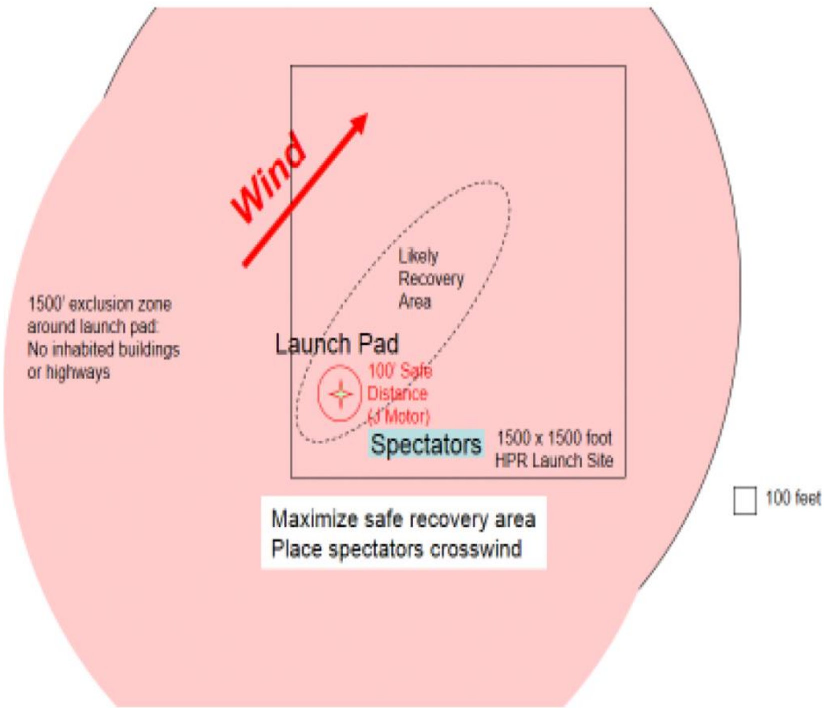
Most of all, be safe and launch for the field size, NOT the rocket size.

LAUNCH SITE DIMENSIONS

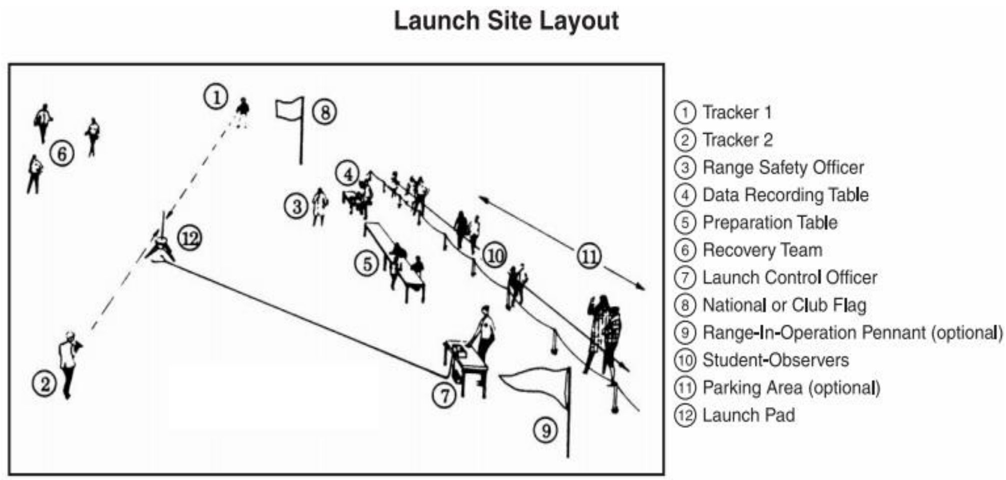
Installed Total Impulse (N-sec)	Equivalent Motor Type	Minimum Site Dimensions (ft.)
0.00--1.25	1/4A, 1/2A	50

1.26--2.50	A	100
2.51--5.00	B	200
5.01--10.00	C	400
10.01--20.00	D	500
20.01--40.00	E	1,000
40.01--80.00	F	1,000
80.01--160.00	G	1,000
160.01--320.00	Two Gs	1,500

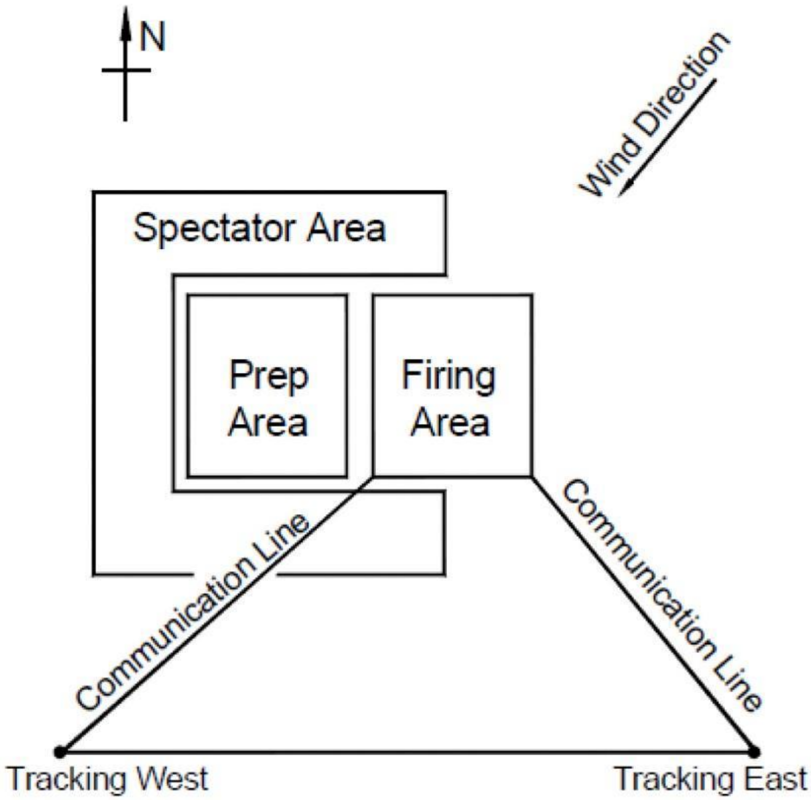
Ideal launch site layout for small fields



Small Launch Site Layout

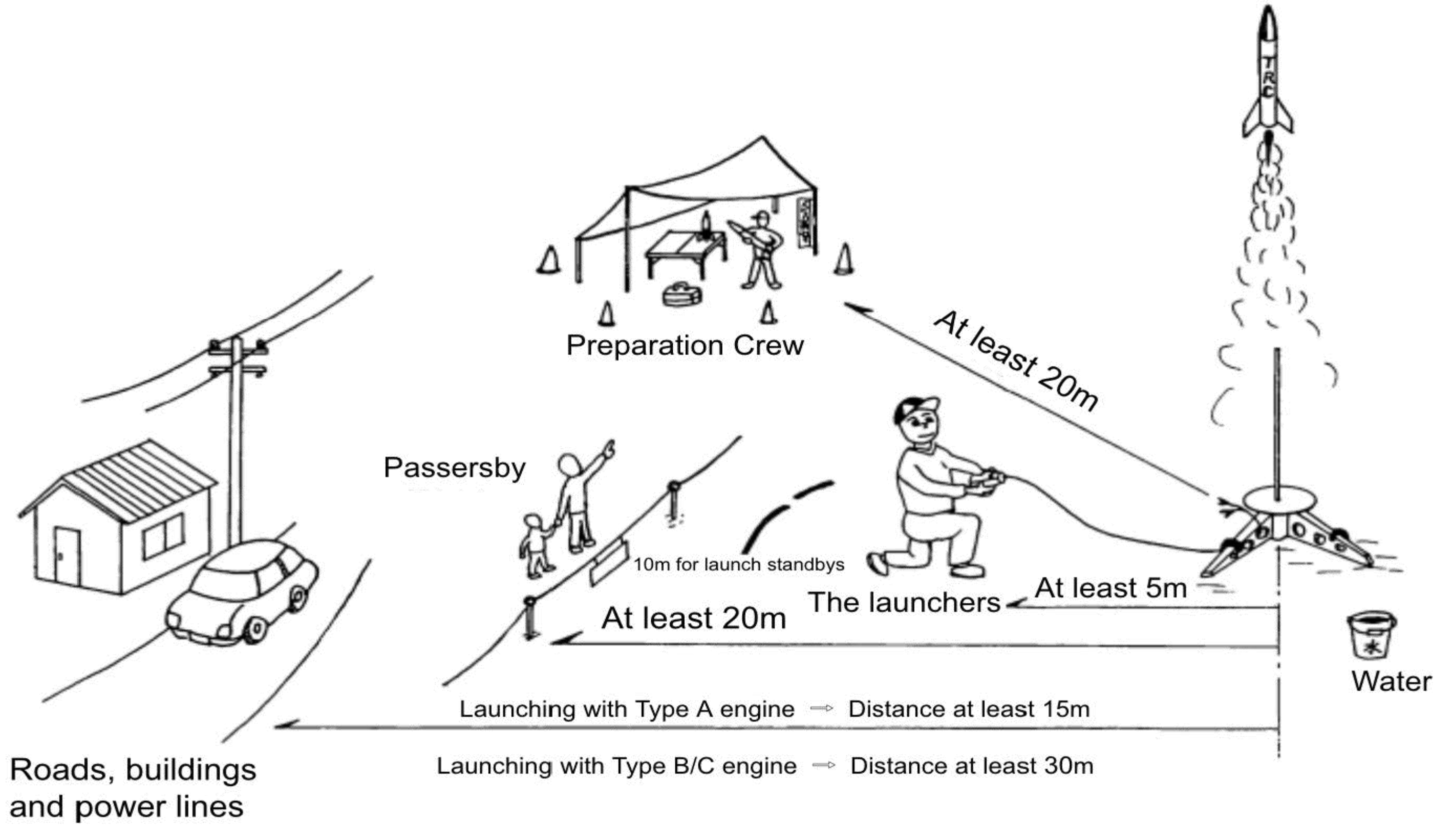


A Generalized Model Rocket Range



Generalized Model Rocket Range

★ The Distances From the Launchpad



MODEL ROCKETRY IN INDIA- From an idea to today's nascent stage .... what I have seen.......

I returned from the middle of the Russia-Ukraine war and settled down in Nagpur. I felt that one Lifecyle has made its complete circle. I could realise... I returned home from where I started my journey. Since I had been away from India for many years, I was not aware of the development of Model Rocketry in our country. Surprisingly, I came across one Mr MRK Menon and the Model Rocketry Society. Upon calling him, I found a very simple person prepared to share his knowledge and dedicate his life to developing Aerospace talent amongst our children. I immediately took off to Thrissur, Kerala, where we met and had many conversations on the subject of Rocketry and Space. He is an excellent host, and our friendship and mutual admiration blossomed. MRK was making small Balsa Rockets and using Solid propellants obtained from Diwali Rockets to launch his Rockets to a height of 300 Feet using an Electrical Launch System. It proved to be a simple and exciting way to engage students at low cost without compromising on safety.

In 2016, the Aeromodellers Association of India (AMAI) held its National Aeromodelling Competition at Amrelli in Gujarat. I met up with MRK there, and we gave a demonstration of High-Power Model Rocketry as the grand finale of the AMAI Event. The same evening at the Awards Function the AMAI gave us a Certificate recognising our contribution to Model Rocketry. I am very sure that MRK had something to do with the presentation, and I cherish the Award very much. It is framed and displayed in my Office at Nagpur. Subsequent to this I visited Kerala many times and jointly with MRK conducted many Rocket Launches in various engineering Colleges. He and I would make presentations to the students, and then we would launch a simple Rocket to the delight of the young would-be Motorers.

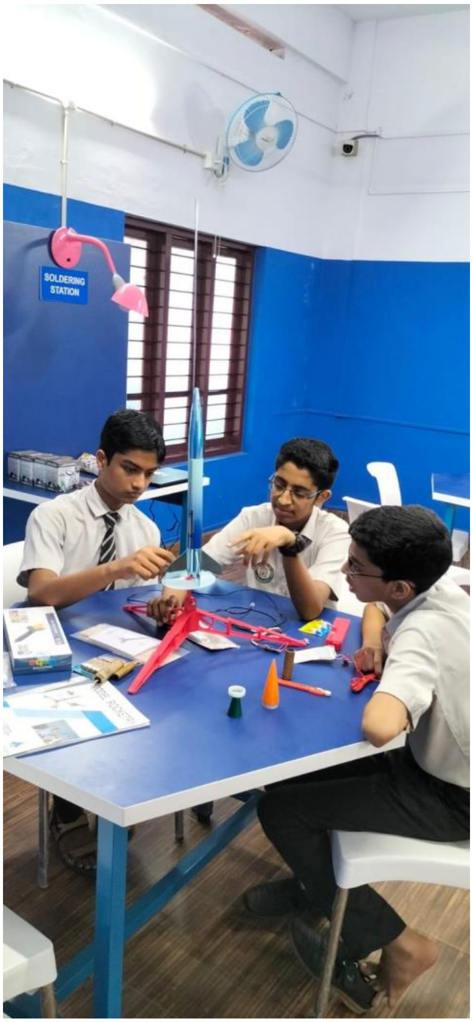
I lost contact with MRK as I had to go back to my Defence Industrial Complex work ecosystem in Kyiv, 5 years before the current war. When I returned, MRK had become Dr MRK, having received an Honorary Doctorate from a private Australian University for promoting STEM and Aerospace in India. I felt very happy that my friend's efforts had finally been recognised. We continued our friendship and discussed many joint ventures in the field of Rocketry and Satellite Development in Schools and Colleges. This took us to the VSSUT University Campus at Sambalpur, Odisha, where we did a 2 Day Rocketry and Space Seminar in front of Senior ISRO Officials. Big promises were made to us, but sadly, this government-funded project did not materialise. However, we gained in exposure. We then met again at the National Space Exhibition in Bangalore in 2022, where our Vihaan Spacetech team had put up a Stall and exhibited our 50 Km range Rocket. We were very lucky to have a visit and interaction with Ex-ISRO Chairman Dr S. Somnath, who was very impressed with our efforts as Space Entrepreneurs.

It was good that both Dr MRK and I shared the same vision of being of service to the Indian youth. He went on to develop his company, GLOBAL AEROSPORTS, to great heights, and I focused on setting up my Rocketry manufacturing company in Nagpur.

Together, we are planning a Space Museum and a Student Rocket Launch to enter Space. As with many entrepreneurs, Funding is the main problem, and together we keep working on our respective projects and keeping our hopes alive!

The photos on this Page will showcase our efforts to promote Aerospace activities in India over the past many years, silently, at the grassroots level. In conclusion, I must add that MRK has been a source of great support and encouragement to me and my efforts to promote something BIG in the field of Rocketry and Space Technology.

JAI HIND!



MODEL ROCKETRY SOCIETY

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4-H 503 Rockets Away (Solid-Fuel Model Rockets) by Robert L. Horton.