宇宙航空研究開発機構
Japan Aerospace Exploration Agency

Water Rockets - Educator's Manual

Japan Aerospace Exploration Agency

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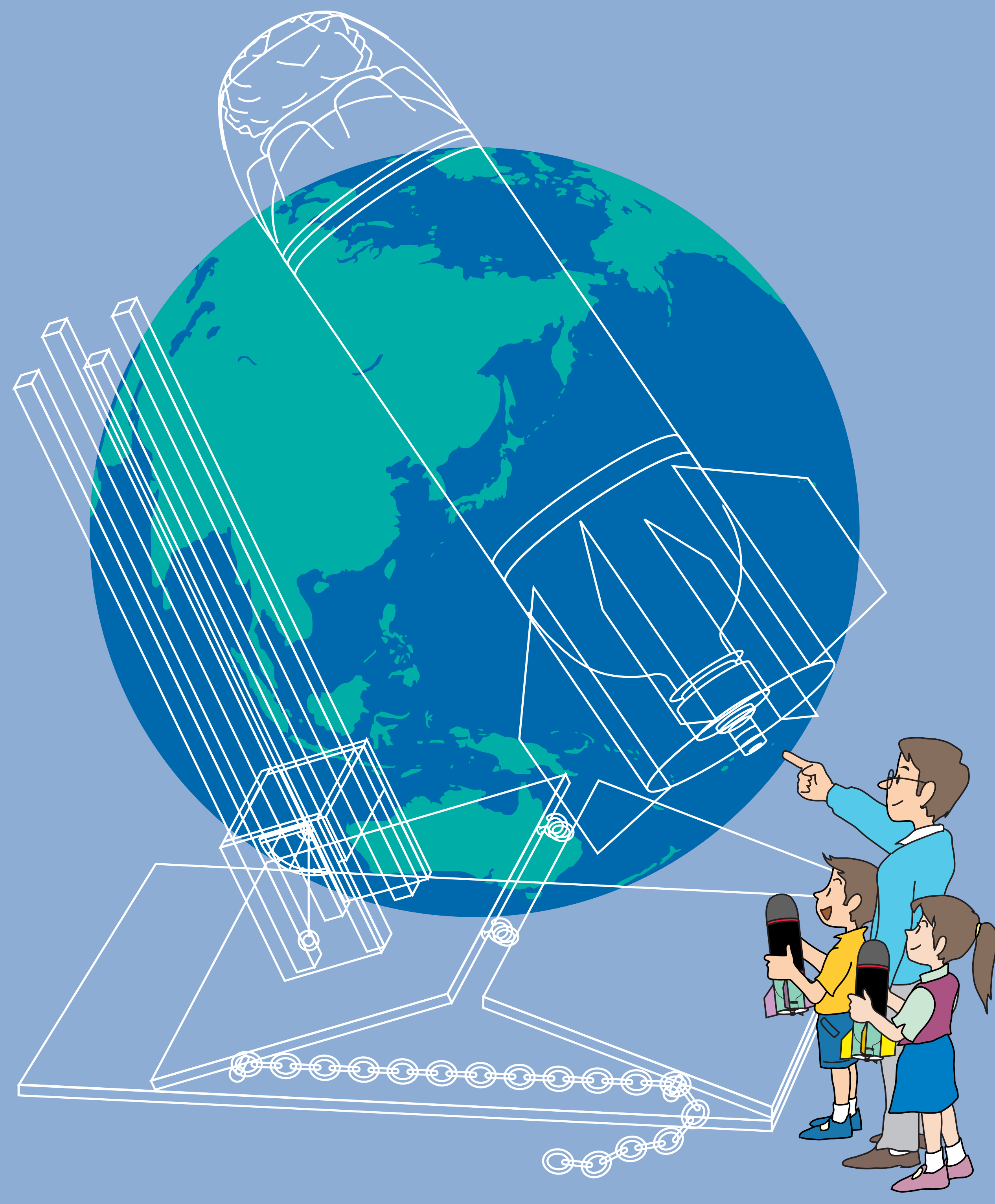
Water Rockets

Educator's Manual



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Foreword

Water rockets are easy to make and use materials found in daily life. Children will be thrilled, and their creativity stimulated, watching their hand-made rockets soar skyward to unexpected heights.

Water rockets that perform well have good science behind them. Similarly, behind every failure is a scientific concept that has been violated. So it is essential that children understand the fundamentals of water rockets. Water rockets have much in common with real rockets, allowing children to experience the same excitement that rocket engineers do.

Several key points must be remembered if your students are to succeed in making water rockets that fly high, straight and safely – and enjoy themselves in the process. Targeting teachers and instructors, this manual is designed to explain not only how to make water rockets, but also provide them with all the essentials required to make technically sound craft. In other words, this manual offers teachers and instructors the means with which to instruct children as to the key points to bear in mind when making safe, high-performance water rockets.

This manual also contains tips regarding the motivations and aspirations children should be encouraged to entertain, and abilities within each child that can be developed.

We sincerely hope this manual and the accompanying DVD will help you to develop educational programs that allow your children to learn the basics of water rockets and develop their activities as mini rocket engineers buoyed by dreams of flight yet dedicated to safety.

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Institute of Space and Astronautical Science
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Contents

Chapter 1

Water Rocket Making and Instructional Objectives

In this chapter, we will present a brief history of water rockets – from their origin to present day. Then we will explain the benefits to children from learning about water rockets.

1-1 Water rockets - past and present

To begin with, let us briefly review how water rockets were invented and how they have developed to this day. This overview may serve as a useful introduction to the study of water rocket making at school or as a community activity.

History of water rockets

In the 1960s, Japan imported water rocket toys made in Germany and the United States. In the mid-1980s, water rocket competitions were held in Scotland.

It was in 1974 in the United States that PET bottles for carbonated drinks – now the prevalent water rocket material – were first employed. The use of PET bottles became commonplace as such bottles spread among consumers. Perhaps the first-ever print material that addressed the making of PET bottle-based water rocket was the August 1983 issue of the American magazine "Mother Earth News."

Water rockets today

Today, the making and launching of water rockets are being pursued in various forms and in various parts of the world. While model rockets are popular in the United States, water rocket making events are taking place at schools, science museums and so forth, and a variety of water rocket kits are available for sale. In Europe, model rockets have been more popular than water rockets. However, water rockets have long traditions in several countries such as England, France and Scotland. In 2001, for example, England initiated a competition known as the Water Rocket Challenge.

Water rocket enthusiasts can be found throughout the world, exchanging information on original water rocket and launcher designs. Many compete with each other for altitude records with the same enthusiasm and intensity that they enjoy sports.

Turning to Asia, water rockets are becoming increasingly popular in many countries – including China, Korea, the Philippines, Indonesia, Sri Lanka, Vietnam, Singapore and India – and competitions are growing in number. In 2005, an international water rocket event targeting Asia-Pacific youth was initiated with the purpose of promoting space science education.

JAXA Space Education Center has introduced water rockets in Colombia, Chile and Spain.

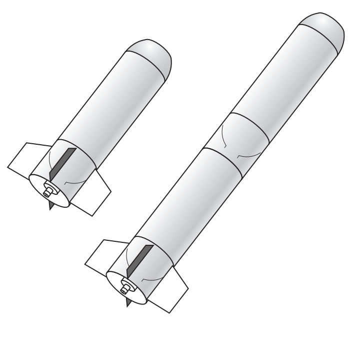
Water rockets in Japan

Inspired by water rocket toys, studies on water rockets had reportedly been made in Japan as early as the 1980s. Messrs. Hayashi and Iida, both high school teachers in Aichi Prefecture, are credited with establishing the foundation of water rocketry in Japan, having developed a variety of PET bottle water rockets, such as two-stage and cluster-type rockets (the latter combining 25 PET bottles).

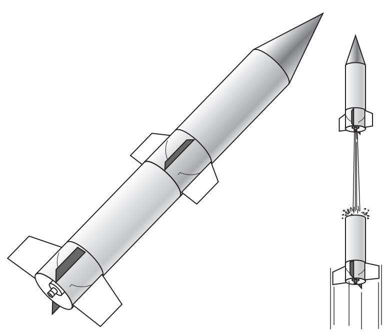
In 1994, the Young Astronauts Club-Japan saw the educational aspects of water rockets and took them up as part of its activities. Water rocketry has spread throughout Japan through the Club's various chapters. Another milestone in water rocket history was the "Idea Water Rockets Contest" staged in Kakamigahara City, Gifu Prefecture, in 1996. This was followed by the establishment of Pet bottle Craft Association, Japan Association. Building on this momentum, water rocket kits, handy launchers, safety nozzles and the like have been made commercially available and now are used by an increasing number of enthusiasts. Some science textbooks for school children carry sections on water rockets.

Applied forms of water rockets

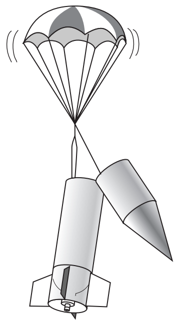
Over the years, a diversity of water rocket shapes and purposes have been proposed and devised. The simplest, most basic type uses one or two PET bottles to make the body, which is then charged with water and air. For significantly increased flight performance, two major designs predominate: cluster-type rockets based on a bundle of multiple PET bottles that expel their water simultaneously; and multi-stage rockets comprising two, three or even more rockets placed one on top of another. A great deal of ingenuity and know-how is incorporated in the mechanisms that allow multiple rockets work in tandem. Some rockets have been adapted to carrying distinctive payloads, such as one that sports a camera for aerial photography and one loaded with a parachute to ensure post-flight recovery. Various switches have been devised and refined, including those designed to allow the onboard camera to take a succession of photos when the rocket reaches apogee and others that deploy the parachute without fail.



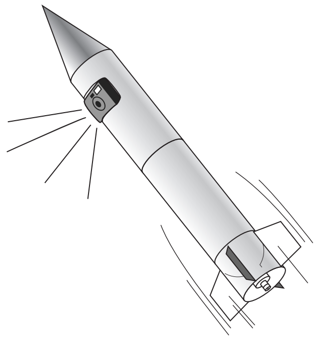
Basic-type (single stage) rocket
The simplest type of rocket, it uses one to two PET bottles.



Multi-stage rocket
Uses two, three or even more bottles.



Rocket with a built-in parachute
Designed to deploy the parachute in flight to allow recovery of the payload and rocket.



Experiment-type rocket
Performs aerial photography using onboard still or video cameras.

Water rocket competitions

Water rocket competitions, sponsored by groups, schools and the like, are being held throughout the country. Their rules vary widely. The most effective way to determine flight performance is a competition for water rocket flight distance (the horizontal distance from the launch point to the landing point). Besides horizontal distance, there are competitions for altitude (vertical height) achieved and flight duration. When a sufficiently large launch site is unavailable, competitions place less emphasis on distance and height. An example would be fixed-point flight competitions in which participants vie to land their rockets as close to a target as possible. Whatever the type of competition, fairness is critically important the amount of water to be fed and air pressure to be pumped in must be identical for each and every participant. Since it is beyond human control to ensure that participants are impacted equally by the wind, competitions should be held in windless conditions.

In addition to flight performance competitions, contests are held where participants are judged in terms of decoration and design. In a genre called idea competitions, participants are rewarded for picture quality, the angle of aerial photos and videos, or parachute recovery performance. These contests often require very high levels of technique.

Water rocket competitions

① Flight distance competitions (water rockets judged by distance flown)
There are two types: programs where air pressure and launch angle standards are constant for all participants; and programs where participants set their own standards.
② Altitude competitions (water rockets judged by height achieved)
③ Fixed-point competitions (water rocket closest to target wins)
④ Design competitions (water rocket judged according to their design)

1-2 Instructional objectives

Currently, water rocket making has a wide range of applications from school curricula to community events to other initiatives aiming to motivate students and small children to become interested in science.

Water rocketry is a truly attractive subject for children. Water rockets can arouse and develop their curiosity, which can extend the horizon of their learning and experience beyond science.
In the initial stage, children's interest will focus on how far they can fly their rockets. Next, they will begin to think in terms of what they can do to improve flight performances. In the process of exerting ingenuity and realizing their goals, they will acquire the ability to solve problems. Furthermore, they can experience a great sense of achievement and satisfaction after successfully completing their own rockets.

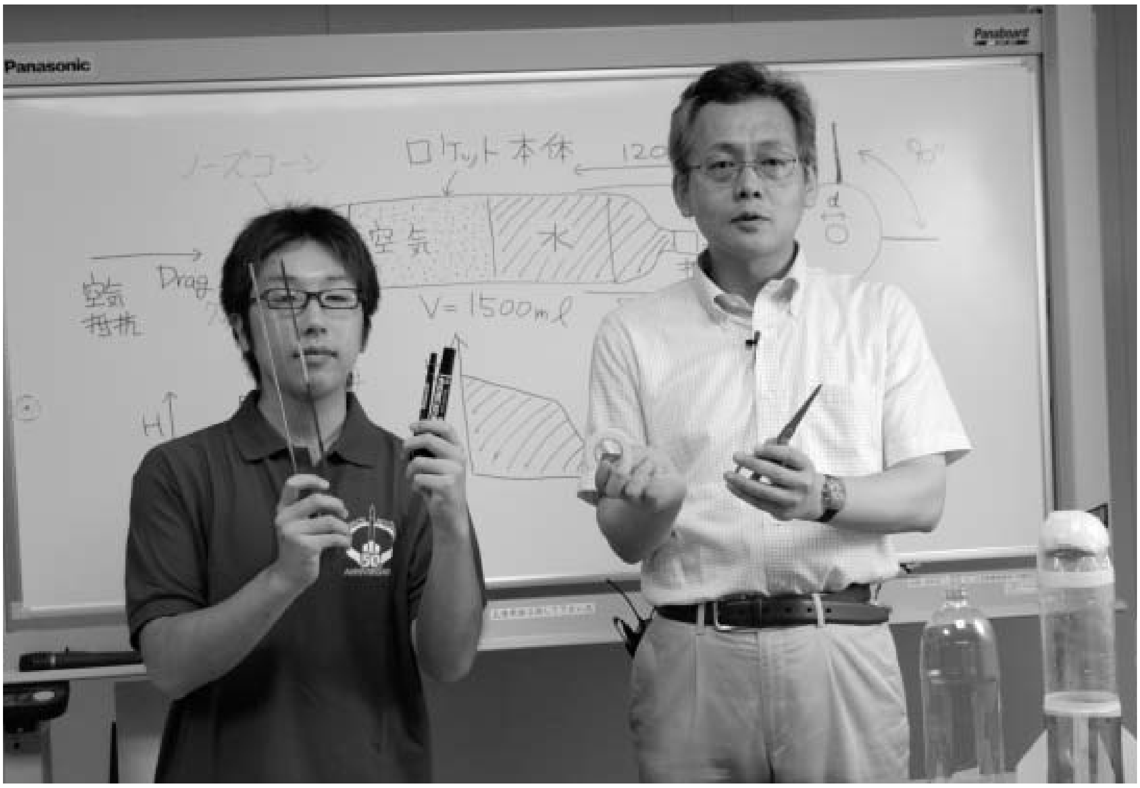
Favorable dispositions and abilities that can be fostered through initiatives for water rockets are as follows:

Individual Dispositions & Abilities Expected to be Acquired
1. Interest, positive attitude, etc ☐ Feels and experiences varying forces of water and air. ☐ Takes interest or curiosity in items and phenomena found in daily life. ☐ Develops a spirit of inquiry. ☐ Develops the ability to see undertakings through to completion. ☐ Experiences the satisfaction of success. ☐ Experiences the importance of teamwork and individual responsibility as a member of the team.
2. Scientific mindset ☐ Finds relationships between theory and practice. ☐ Develops a positive mindset. ☐ Finds the means to overcome difficulties and problems.
3. Skills and experience from experimenting and observing ☐ Appreciates the enjoyment of creation and achievement. ☐ Appreciates the usefulness of tools. ☐ Acquires skills and manners for using tools properly and safely. ☐ Acquires the ability to set up and take down events. ☐ Develops design skills. ☐ Develops the ability to turn designs into reality. ☐ Develops the ability to fly a rocket according to scientific principles. ☐ Develops the ability to predict and verify results. ☐ Appreciates the importance of information exchange and cooperation among friends.
4. Knowledge and understanding ☐ Understands the scientific characteristics of water, air and other matter which we take for granted in daily life. ☐ Understands the functions of water and air in propelling the water rocket skyward. ☐ Understands the difference between things made by Mother Nature and those made artificially. ☐ Understands that goals are achieved by collaboration among scientists and engineers.

We would like teachers and instructors to set feasible objectives tailored to the age and the number of children involved, and to enjoy the making and launching of safe yet effective water rockets.

Chapter 2

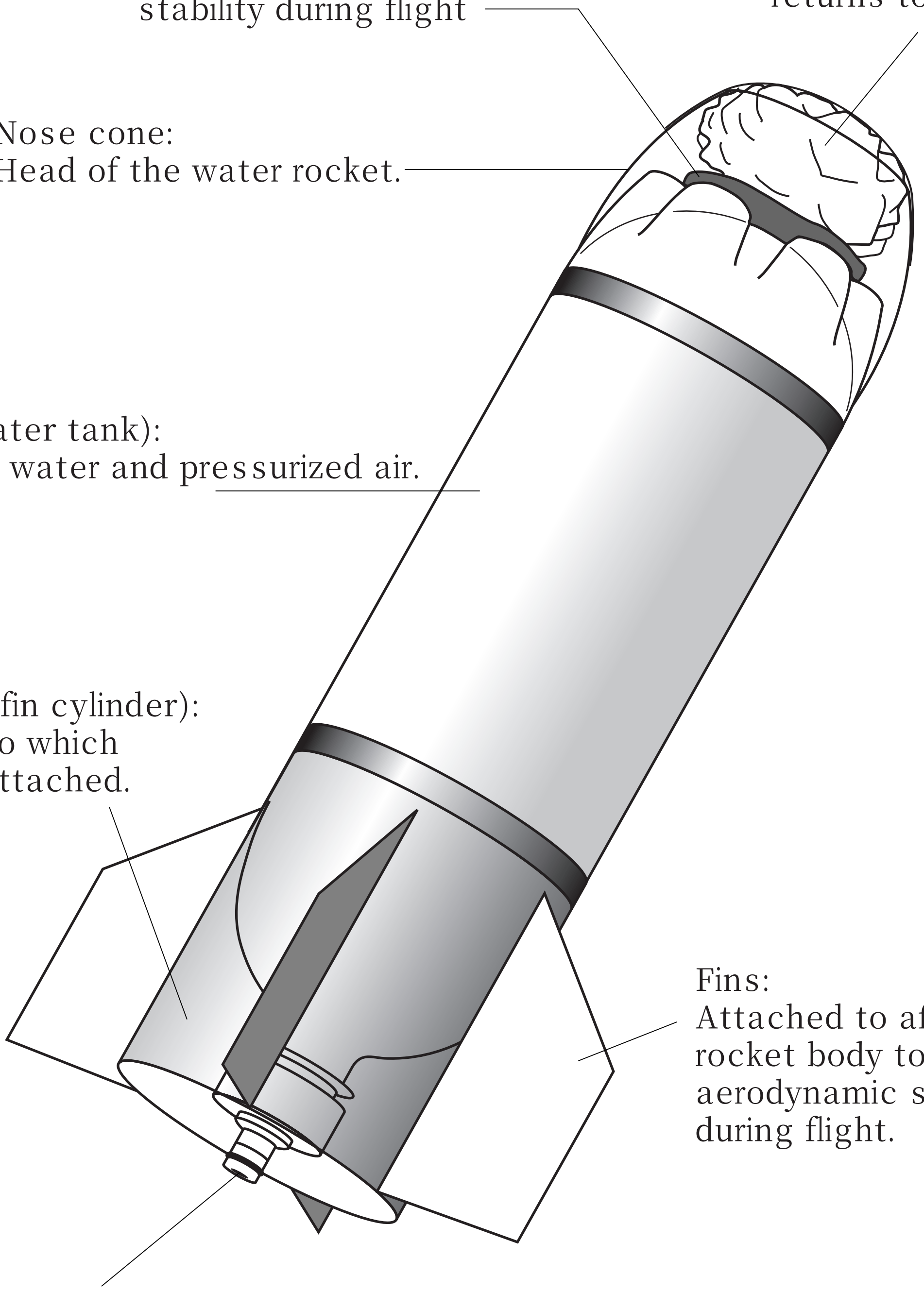
Preparations for Making Water Rockets



This chapter will introduce the terminology for water rockets, as well as materials, tools and equipment needed to make the water rocket body and launcher.

2-1 Terminology for the water rocket and launcher

Terminology for the water rocket

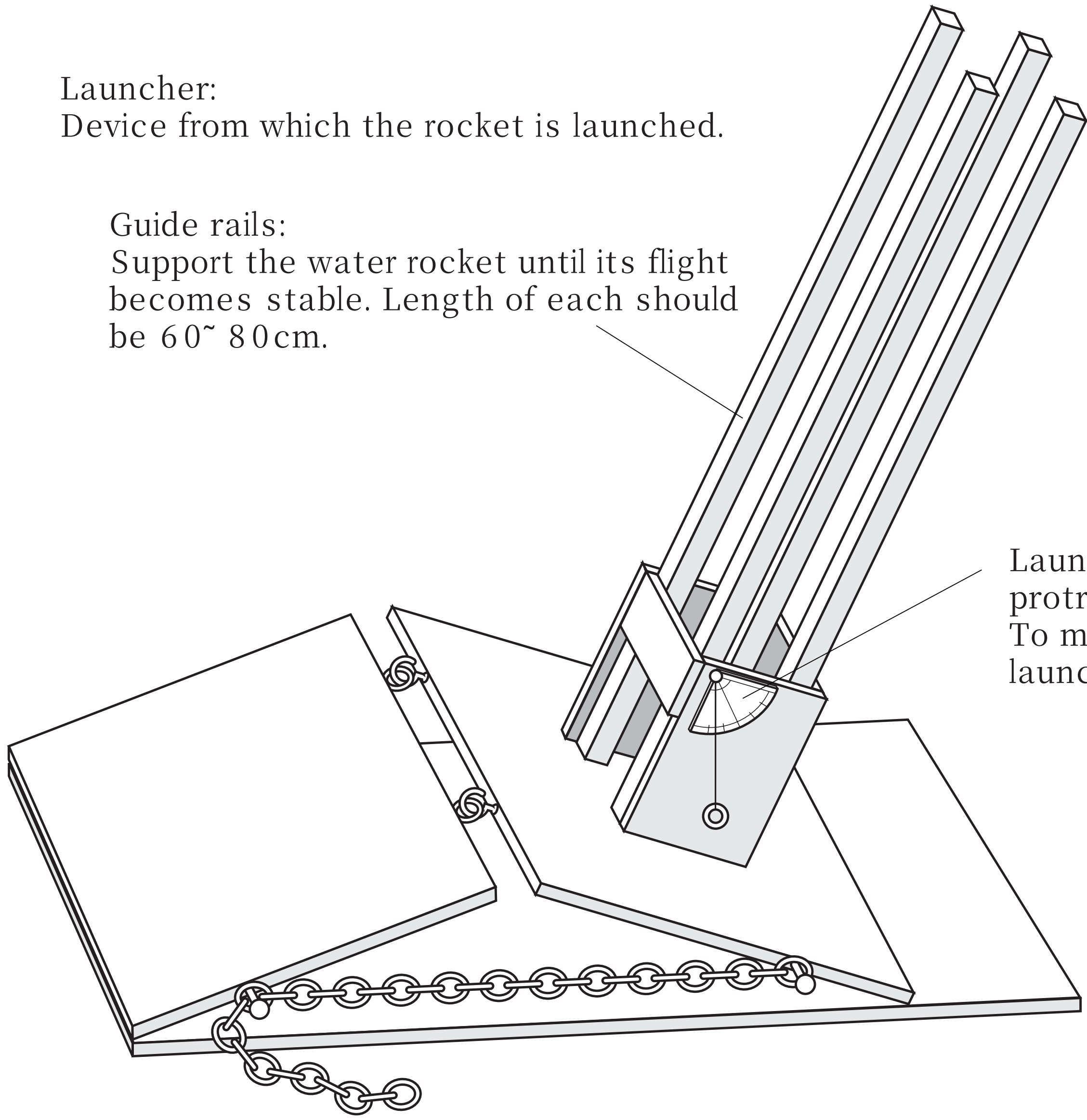


Terminology for the launcher

Launcher:
Device from which the rocket is launched.

Guide rails:
Support the water rocket until its flight becomes stable. Length of each should be 60~ 80cm.

Launch angle protractor:
To measure the launch angle.



Launch gear :

Hand-made device to launch the water rocket It is made by attaching a ready-made jointer (to set the nozzle onto) to a break bar of a bicycle.

2-2 Materials needed to make the water rocket and launcher

Essential materials and tools

①Materials needed to build one rocket

・2 PET bottles (for carbonated drinks).

Get two PET bottles that have been emptied, cleaned and dried, and had their labels removed. One bottle will be used for the rocket body, and the other to make the nose cone.

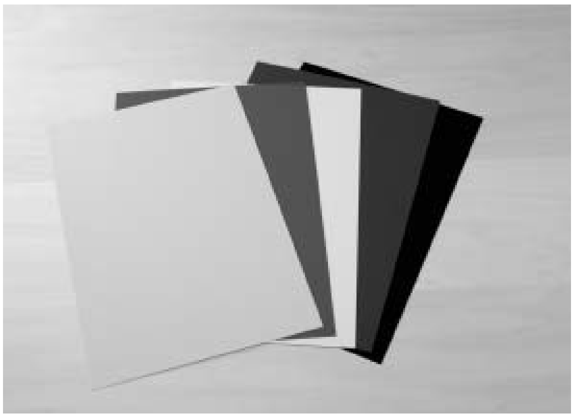
While it is usually advisable to use 1.5-liter round (cylindrical) bottles, smaller 500-milliliter bottles can also be used. However, the PET bottles must be for carbonated drinks, as these can withstand greater pressure than bottles used for non-carbonated drinks. Bottles must also be smooth and free from damage. When launching your rocket, the air pressure should not exceed 7 atmospheres. For the sake of safety, we recommend 4~5 atmospheres.

Technically speaking, only the bottle from which the rocket body will be fashioned needs to be for carbonated drinks since the rocket body, and not the cone, will be put under pressure. The other bottle, used for the nose cone, can be for other types of drinks. However, to avoid confusion during the rocket building process, it is better to use two carbonated drink bottles.

Bottles suitable for water rockets
(For carbonated use and
cylindrical)

Types of bottles unsuitable for
water rockets
(Only use round bottles.)

・PVC sheet (or any thin sheet of flexible yet sturdy plastic) 10cm × 20cm



To make fins, get a sheet of PVC that is 1~2mm in thickness. You can find these at your local do-it-yourself outlet. If PVC sheets are unavailable, you can substitute them with any type of thin, flexible yet sturdy plastic, such as writing boards made of polystyrene.

・File holder 1 sheet, A4 size approx. 21cm × 29cm

This is used to make the skirt. Available at your local stationery shop, etc.

・Modeling clay approx. 50g

Modeling clay is used as ballast. If you will be making several water rockets at one time – for example, as a school project – it is advisable to prepare a suitable number of individual lumps of clay beforehand, each weighing about 50g.

・Vinyl bag (as cushion: 45-liter capacity trash bag) 1 piece

A vinyl bag is put into the nose cone as a cushion to absorb the impact when the rocket returns to Earth. Please use one 45- to 70-liter vinyl garbage bag for each rocket.

・**Vinyl tape**

Vinyl tape is used to put parts and materials together. By offering an assortment of tapes of various colors, children can combine them to create their own colorful designs.

・**Nozzle**

As a safety precaution, we strongly recommend the use of mass-produced nozzles. While it is possible to use a rubber stopper, you run the risk of the stopper failing as air pressure increases; such unpredictability makes them a poor choice as far as safety is concerned. Commercially available nozzles also can be used repeatedly.

②**Tools and equipment**

While most of the cutting work can be done using a pair of common scissors, a cutter or specially designed pair of scissors with pointed tips is used to cut the nose cone from the second PET bottle. We advise you to take every precaution when handling these tools.

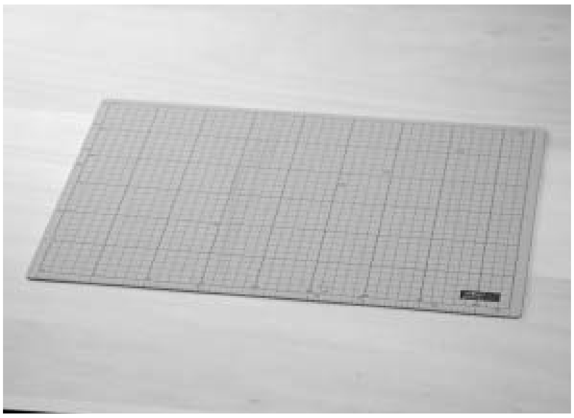
・**Scissors**

The type of scissors as shown here is used for most of the cutting, such as for the fins, skirt and nose cone. Special PET bottle scissors are also available.

・**Cutter**

A cutter is used when making the nose cone. You are tasked with explaining to the children the proper way to hold the cutter, how to handle other tools, and other safety precautions to ensure that risk of injury is reduced to a minimum.

・**Cutter mat**



When using the cutter, students should be given a mat to protect their desks.

・**Plywood**

If you will be making the rockets in a classroom, gymnasium or other similar location you might choose to place a piece of plywood on each student's desk or on the floor to prevent damage to the desk or wood floor.

・**Permanent marker**

A permanent marker is used to draw cut guidelines and names on PET bottles. The use of various color markers can enhance enjoyment of the building process as they allow your students to illustrate their rocket bodies.

Materials, tools and equipment needed build the launcher

①Materials needed to build a launcher

The launcher we describe in this manual is simple to make and uses materials and tools encountered in your daily life. The launcher is designed to be adjustable, allowing you to adjust the launch angle as desired.

- **Wood slabs: 2 types each for the guide rail and base sections**
  These wooden slabs constitute the core sections of the launcher. Strong and durable materials like waterproof plywood are recommended.

- **Square wooden rods: 4 pieces**
  These square rods are used as guide rails.

- **Hinges: 2 pieces**
  Used to connect the wooden slabs for the base section.

- **Hooks and hetons: 2 pieces each**
  Used to connect the guide rail section to the base section.

- **Protractor, kite string, weight**
  Used to make the mechanism to determine the launch angle.

- **Chain: 1 piece**
  Used to fix the launch angle.

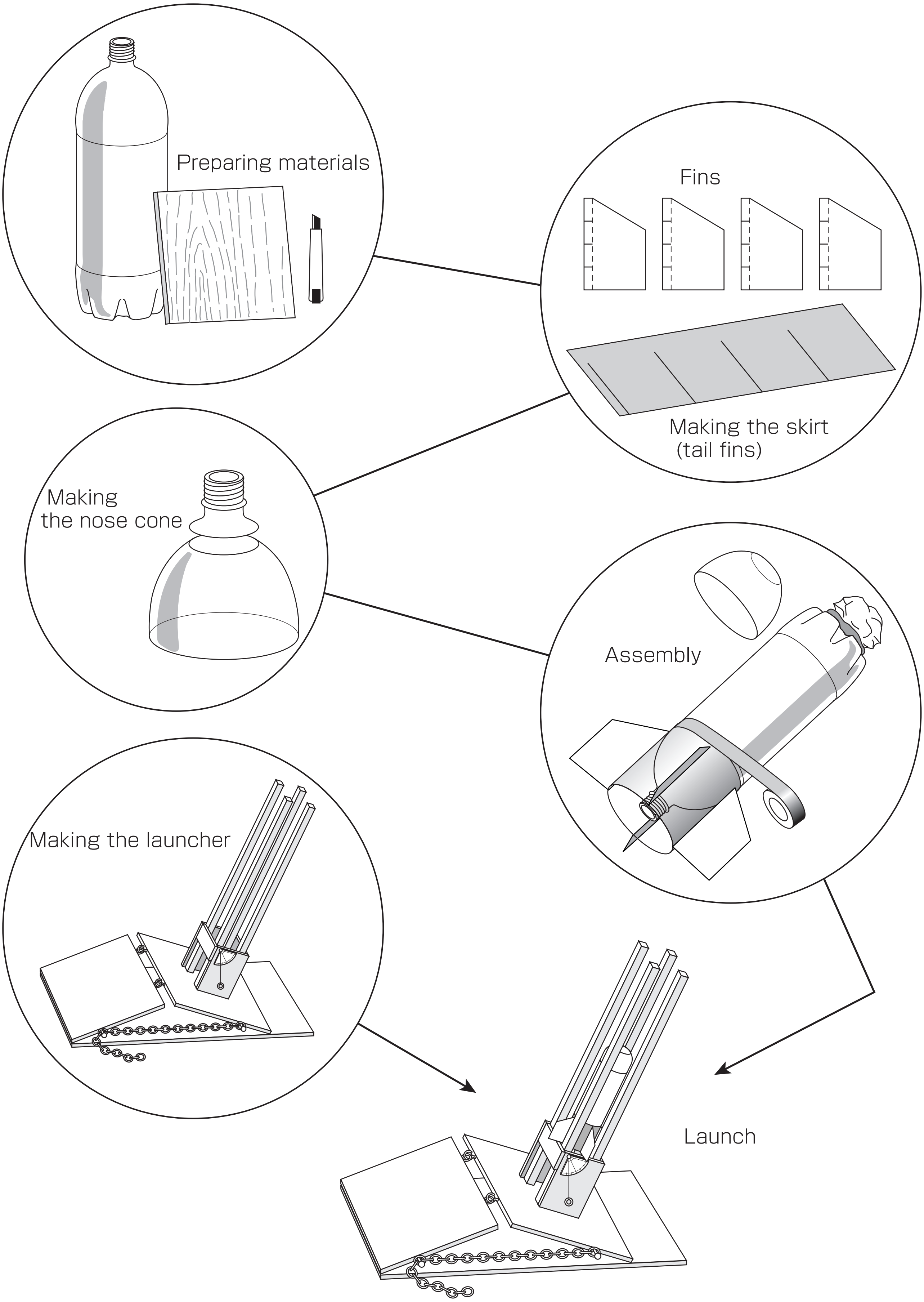
- **Nails, adhesive agent, vinyl tape**

- **Oil-based varnish for application to wooden materials**
  Since the launcher we are going to make is made of wood, we coat its entire surface with varnish to protect against water damage.

②Tools and equipment

- **Hammer**
- **Saw**
- **Wood adhesive**
- **Pencil**

2-3 Rocket flow chart: from building to launch



Chapter 3

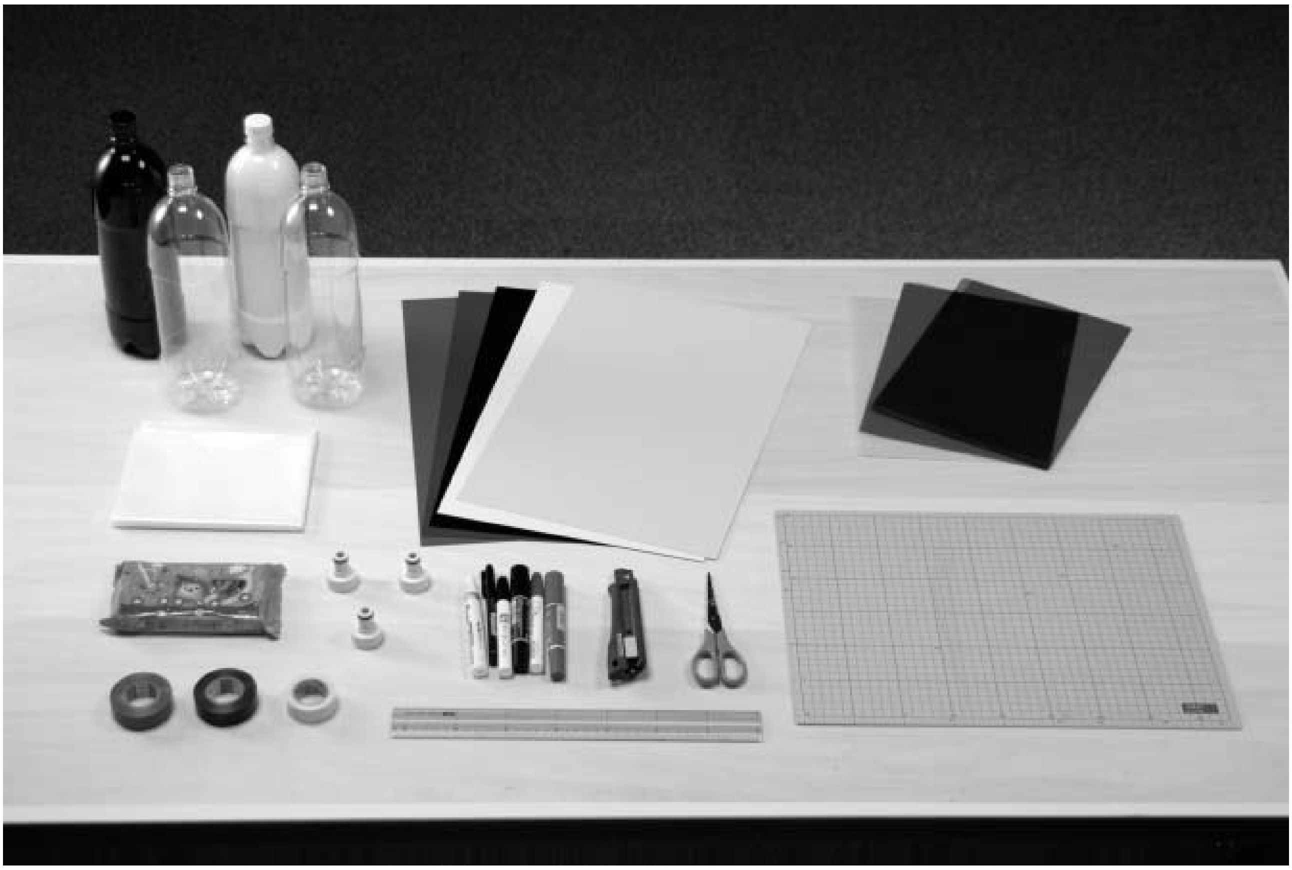
Making Your Water Rocket

The water rocket body to be introduced in this chapter will be a basic type that can be made using readily available materials; this type achieves a balance between safety and functionality.

We suggest that you begin by building a water rocket following the process suggested here so that your students can learn the basics of rocket making. After they have mastered the basic design, you can encourage your students to exert their ingenuity in the pursuit of new designs.

3-1 What you will need

Assemble the necessary materials and tools and run through the checklist before starting your class/workshop.



①2 PET bottles **②PVC sheet**
③File holder (Clear file) **④Vinyl bag (trash bag)**
⑤Modeling clay **⑥Nozzle**
⑦Permanent magic marker (oil base) **⑧Cutter**
⑨Scissors **⑩Cutting mat**
⑪Vinyl tape **⑫Scale**

Before getting started, please check the children’s PET bottles for damage or flaws.

3-2 Preparing your classroom

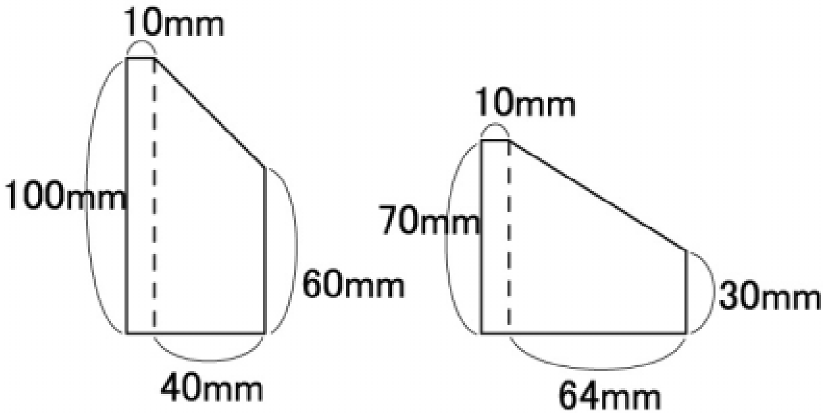
* Keep the working area well lit.

- We recommend as a venue or a classroom used for arts and crafts.
- When making water rockets in an ordinary classroom, we recommend you arrange the desks as shown in the above illustration.
- If the number of students is going to be large, use a spacious area like a gymnasium. Divide them into groups of six or seven, place a sheet of plywood in the center of a vinyl tarp spread on the floor for each group, and then let them get down to making their rockets. Place scissors, cutters and other tools in the center of the plywood so that all students in the group have access to them.
- From an educational standpoint, it's important to allow the children to participate in setting up/cleaning up the room.

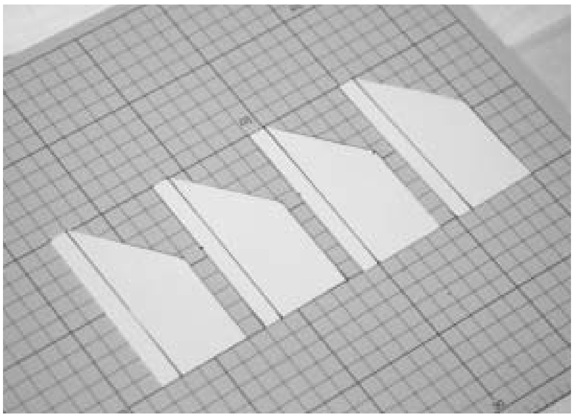
3-3 Water rocket building process

1. Making fins

1-1 Cutting out fin patterns



Various shapes of fins can be made in height and width. Let's make 4 fins of the pattern at left.

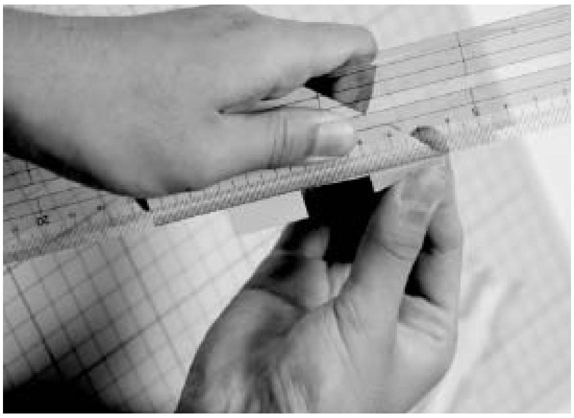


Using a permanent magic marker, draw fin pattern guidelines on a plastic sheet as shown in the illustration at left, then carefully cut out the patterns following the guidelines.

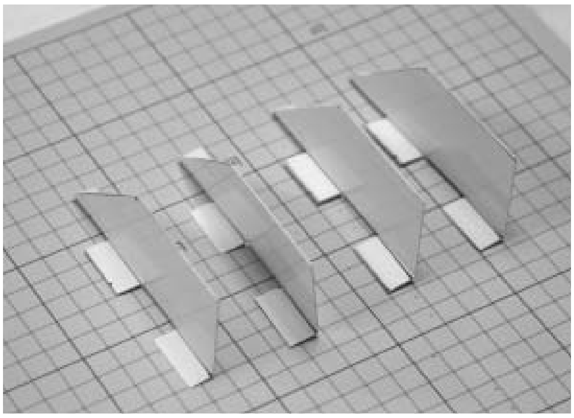
1-2 Preparing the fin base

Cut the base of the fin

Divide the base of each fin into four equal parts by drawing and then cutting three guidelines. Alternately bend the anchors to the left and right. You can ensure a straight bend by aligning the ruler along the baseline. Repeat this process for each one of the four fins.



Bend the anchors to the left and right by aligning the ruler.



Make 4 fins in the same manner

2. Making the skirt and attaching it to the rocket body

2-1 Cutting out the skirt section from a file holder (clear file)

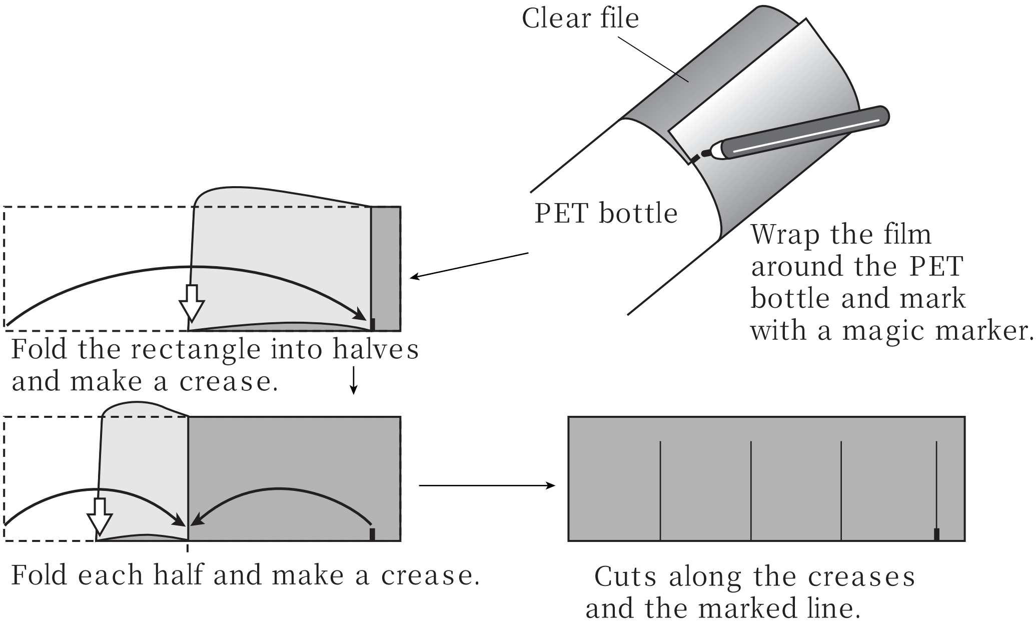
Cut the clear file into a rectangular shape :
The width : Wrap the clear file around the pet bottle and add a few centimeters to overlap at the leading edge.
The length : Wrap the sheet around the pet bottle and adjust its length so that the cylinder is slightly longer than the bottle's mouth.

2-2 Wrapping the skirt material around the rocket body

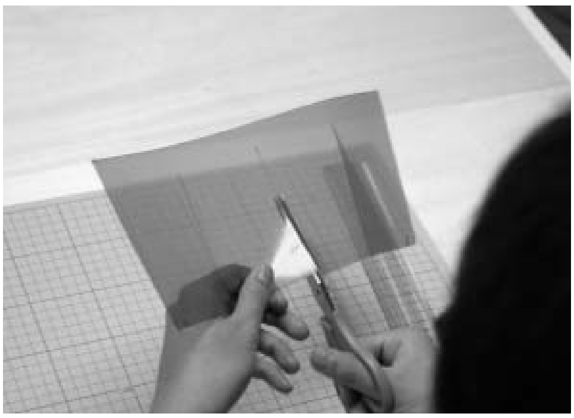
Having cut out the skirt, wrap it around the rocket body and use a magic marker to mark the position where the two edges overlap.

2-3 Dividing it into four equal parts and making creases

Spread the rectangle flat again and divide it into four equal parts, using the previously marked line as a reference point. First fold the sheet into halves, then fold each half into quarters. Mark each quarter and make creases.



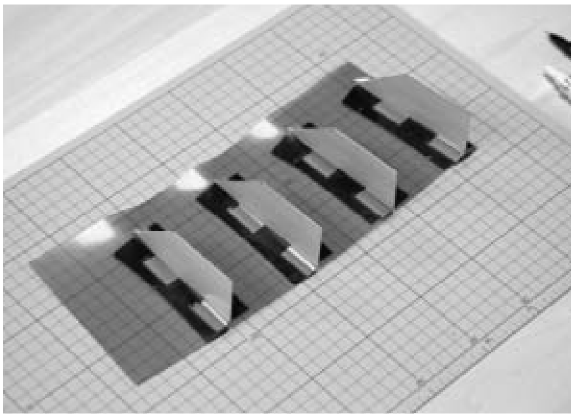
2-4 Making cuts along the creases and marked line



Make cuts along the creases and the marked line to divide the rectangle into four equal parts.

2-5 Attaching the fins

Insert the fins one by one into the skirt, then tape the slots securely from the reverse side of the skirt.



Attach the fines to the skirt.

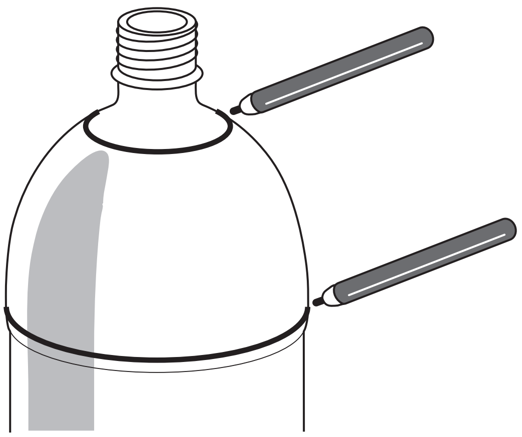
2-6 Affixing the skirt to the rocket body

Wrap the skirt around the rocket body and fasten its starting edge with vinyl tape, then use more tape to firmly fix the skirt at its leading edge.

Check to see the skirt is fixed in the right position
Check the skirt position to ensure that it extends beyond the end of the PET bottle’s mouth.

3. Making the nose cone

3-1 Marking the other bottle with cut guides

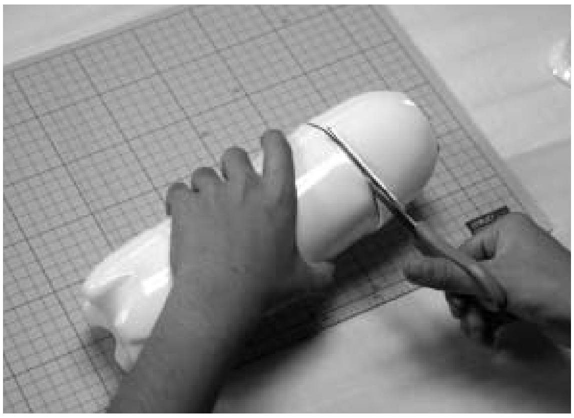


The second bottle is used to make the nose cone. Use the permanent magic marker to mark cut guidelines for the part that will become the nose cone.

3-2 Making partial cuts with a cutter

As shown in the photo, use the cutter to make partial cuts into each guideline. This is a safe way to open gaps for the use of scissors.

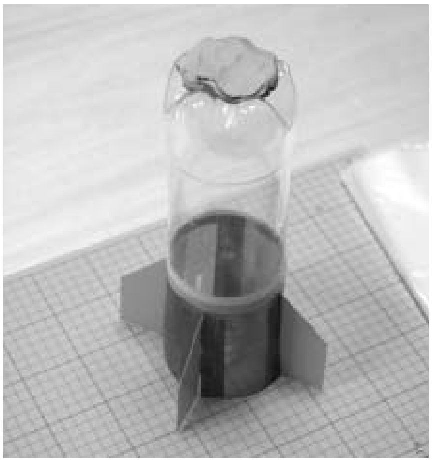
3-3 Cutting along the guidelines



Use the scissors to cut off the nose cone.
We have found that it is easier to remove the part near the bottle cap first.

4. Attaching the nose cone

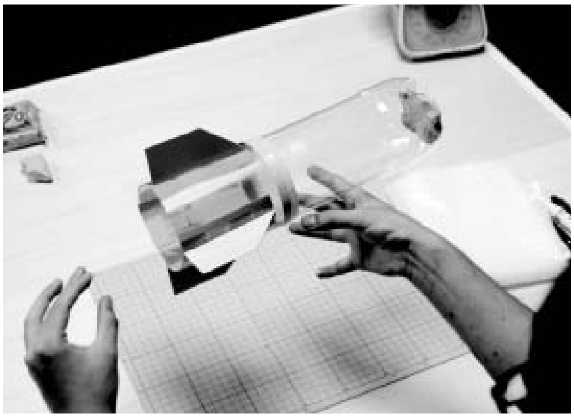
4-1 Attaching ballast

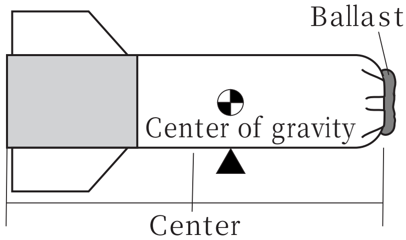


Weigh out about 50 grams of modeling clay and apply it to the bottom of the rocket's body.

4-2 Determine the center of gravity

Place the rocket on your forefinger to determine the center of gravity. The center of gravity should be closer to the nose cone and not the actual physical center of the PET bottle.





4-3 Attaching the nose cone

Push the nose cone over the rocket body and tape it securely into place.

4-4 Putting the vinyl bag into the nose cone

The vinyl bag acts as a cushion inside the nose cone. Unfold the vinyl bag and stuff it loosely into the nose cone.

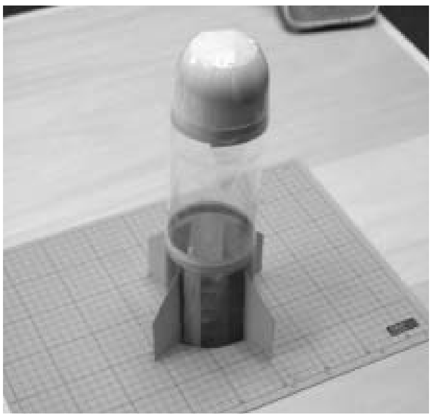
4-5 Sealing the nose cone

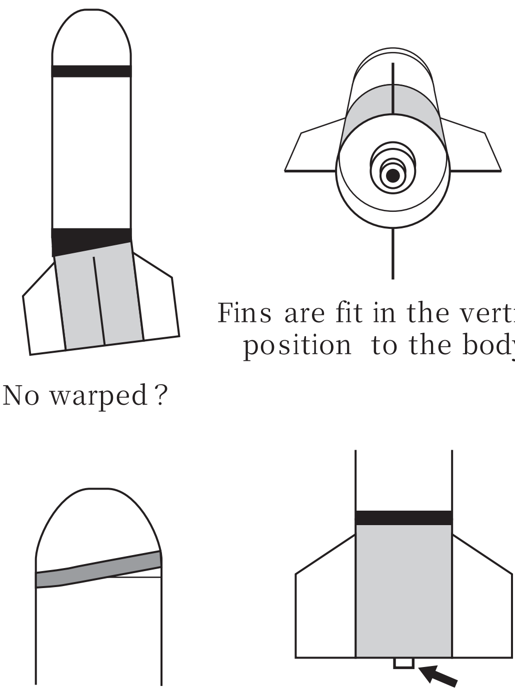
Prepare 10 to 15 strips of vinyl tape of a uniform length and use them to seal the nose cone opening.

5. Final check

The final step is to check the rocket thoroughly to ensure that it is not warped or otherwise damaged, and that all parts are firmly fixed.

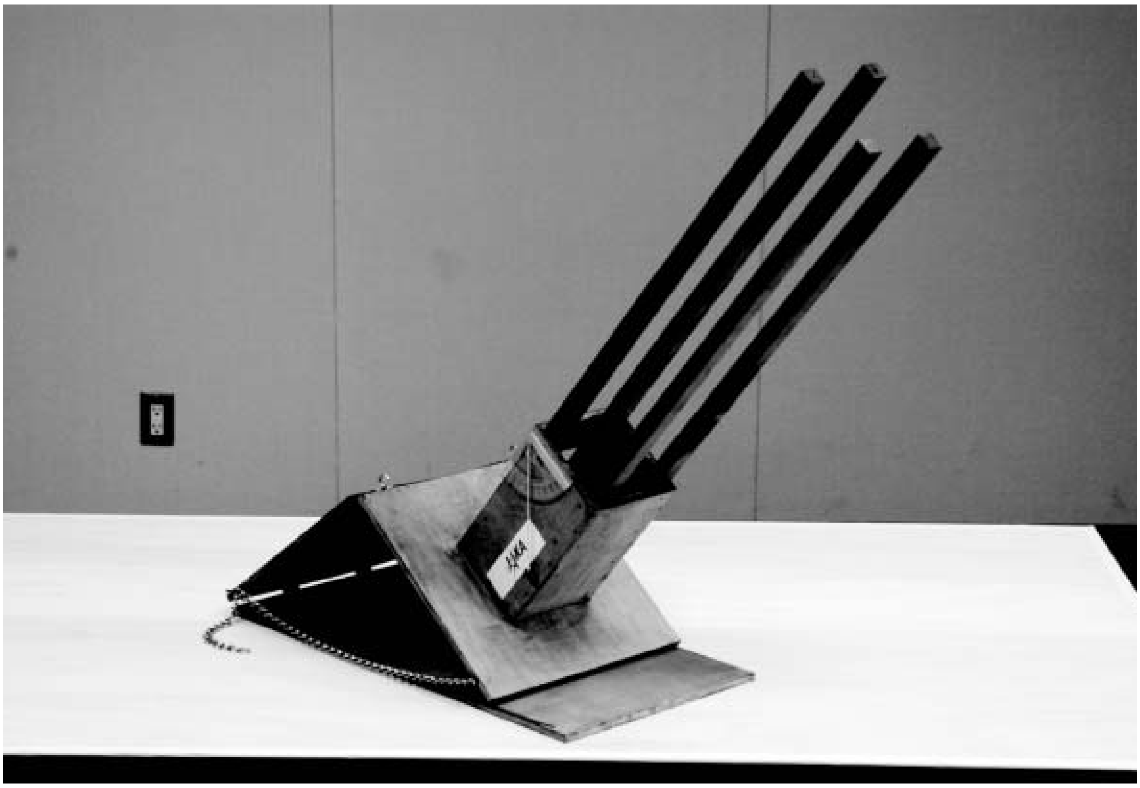
Attach the nozzle and check the length of the skirt if the top of the nozzle protrudes slightly from the skirt.





Chapter 4

Making the Launcher



While several types of launcher are available on the market, here we will offer you a design that allows you to build a launcher using low-cost materials found in daily life. It may also be fun to take up the challenge of making the tools on your own.

4-1 Devising the launcher

Rockets achieve stable flight after reaching an acceleration milestone. This makes it necessary for the rocket to maintain its attitude until achieving the required speed. By fitting the launcher with guide rails of an appropriate length, it becomes possible to stabilize attitude and ensure that the rocket proceeds in the direction you have chosen.

The launcher should be a solid structure with a low center of gravity to prevent movement during launch. We suggest that the launcher be equipped with guide rails (each 60~80cm in length) and designed to be adjustable, allowing the angle of launch to be modified as desired.

Making your own launcher

Several types of launcher are available on the market but they either come without guide rails or are outfit with guide rails that are insufficiently long. As such, prefabricated launchers are prone to undermining launch stability, compromising your ability to launch your rocket in the desired direction.

We would like to offer you a design that allows you to build a launcher using materials found in daily life. It has guide rails of sufficient length and does not cost much to build.

With this launcher, any desired launch angle can be set. What's more, it is so strongly built that it won't fail you even after sustained use.

With this launcher as reference, we hope you join forces with your children to devise and develop new designs for safe and functional launchers.

Experiment stand launcher

This launcher uses ordinary experiment stands found in school science laboratories. A metal rod fixed to the stand is used as a guide rail. The stand's two upright rods allow the angle of elevation to be adjusted.

Ready-made launcher

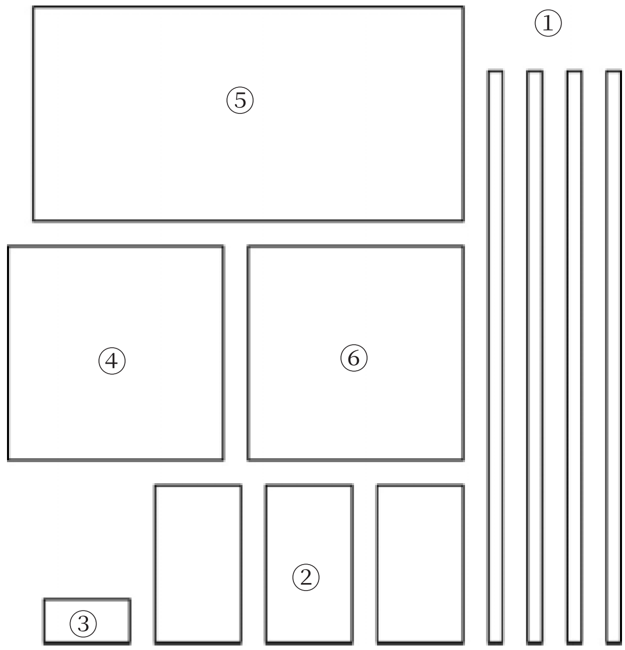
Shown here is a simple plastic launcher.
It is handy and portable.

Simple vertical launcher

Using a metal rod as a guide rail, the sole purpose of this launcher is to send the water rocket straight up into the sky. Securely attach a piece of PVC pipe to the rocket body, and pass the rocket down the guide rail to the launch platform. The launcher is a simple structure and has no mechanism for launch angle adjustment.
Suitable for launch sites of limited size.

4-2 Preparation: List of materials and tools

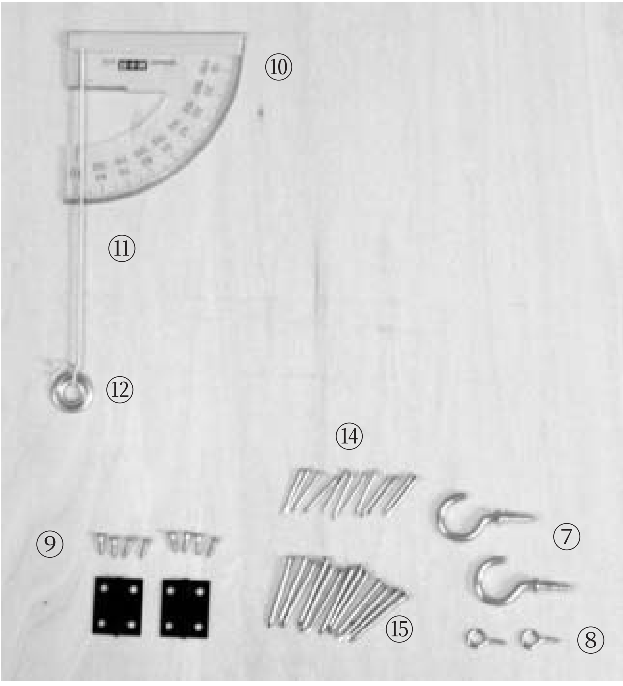
Materials



①**Guide rails**	〈 20mm× 20mm×800mm (length)〉	4
②**Guide rail plates**	〈220mm×120mm× 10mm (thickness)〉	3
③**Guide rail plate** (short)	〈 60mm×120mm× 10mm (thickness)〉	1
④**Guide rail bottom plate**	〈300mm×300mm× 10mm (thickness)〉	1
⑤**Base plate** (large)	〈600mm×300mm× 10mm (thickness)〉	1
⑥**Base plate** (small)	〈300mm×300mm× 10mm (thickness)〉	1

Treated water proof plywood is recommended for ①～⑥

Ready-made materials



⑦**Hooks** (lamp hanger fittings)	〈appro × 22mm in hook diameter〉	2
⑧**Hetons**	〈appro × 16mm in ring diameter〉	2
⑨**Hinges** (including screw bolts)		2
⑩**Protractor**		1
⑪**Kite string**		1
⑫**Weight** (washer, etc.)		1
⑬**Chain** (600mm)		1
⑭**Stainless steel nails** (small)	〈20mm～25mm in length〉	25 or more
⑮**Stainless steel nails** (large)	〈35mm～40mm in length〉	6
⑯**Adhesive agent for wood**		as reguired
⑰**Oil-type varnish for wood**		as required
⑱**Vinyl tape or adhesive double-face tape**		1

Tools

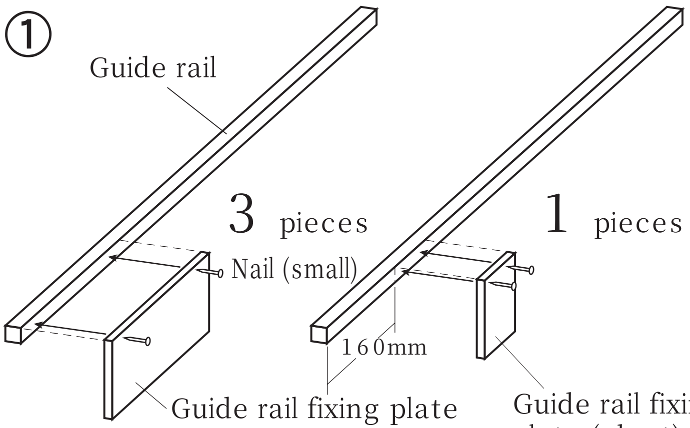
The following tools are required:

①**Hammer**
②**Saw**
③**Brush**
④**Screw driver**
⑤**Pencil**

4-3 Launcher making process

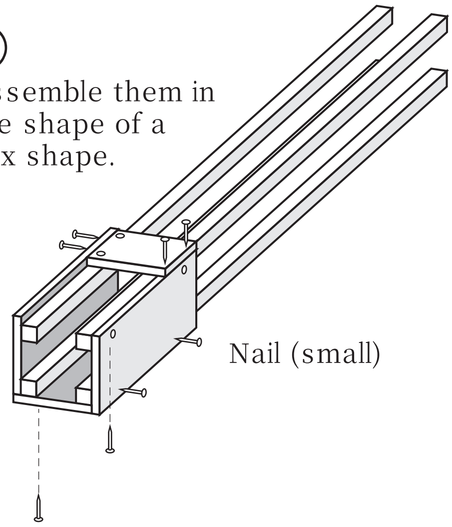
Remember to apply wood adhesive to joint parts before driving in nails.

①

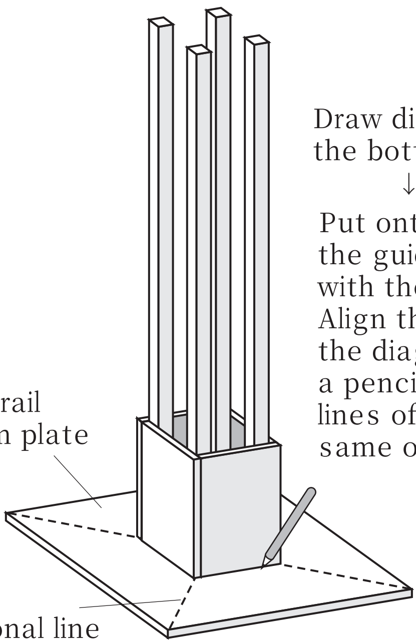


②

Assemble them in the shape of a box shape.



③

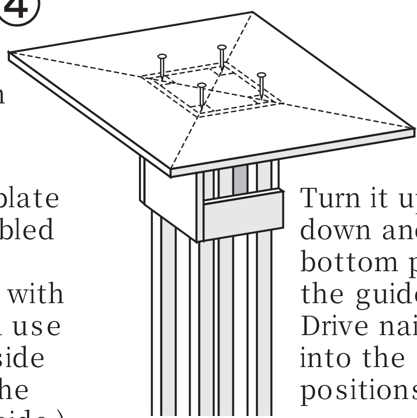


Draw diagonal lines on the bottom plate.

↓

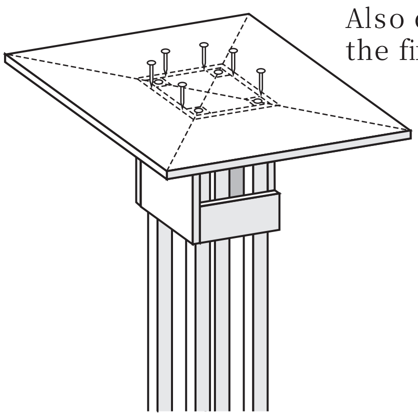
Put onto the bottom plate the guide rails assembled with the fixing plates. Align the four corners with the diagonal lines and use a pencil to trace the side lines of the box. (Do the same on the reverse side.)

④



Turn it upside down and fix the bottom plate along the guide lines. Drive nails (large) into the guide rail positions.

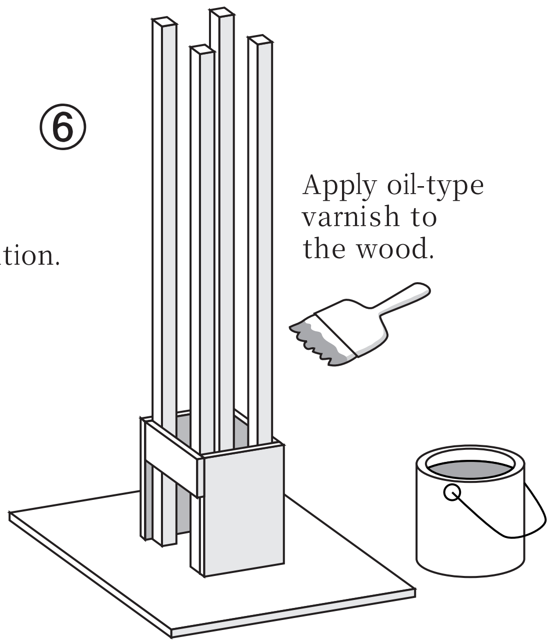
⑤



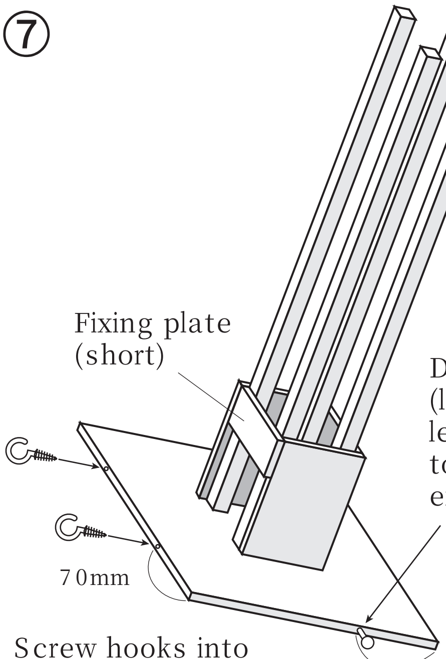
Also drive nails into the fixing plate position.

⑥

Apply oil-type varnish to the wood.

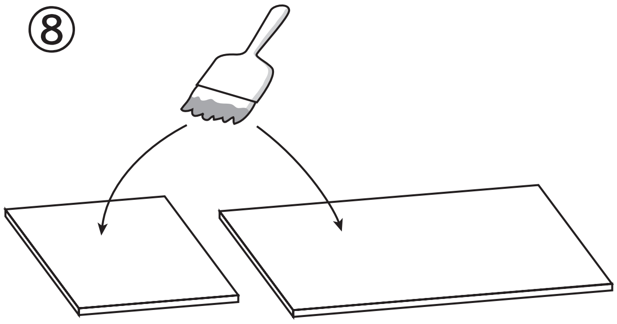


⑦



Screw hooks into points as illustrated.

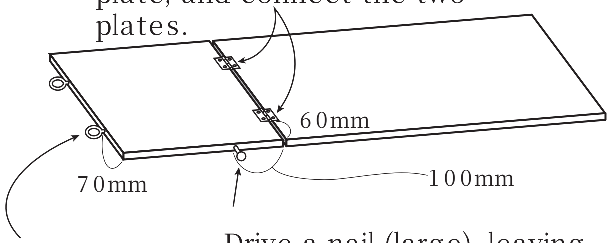
⑧



Apply varnish to both sides of the base plates.

⑨

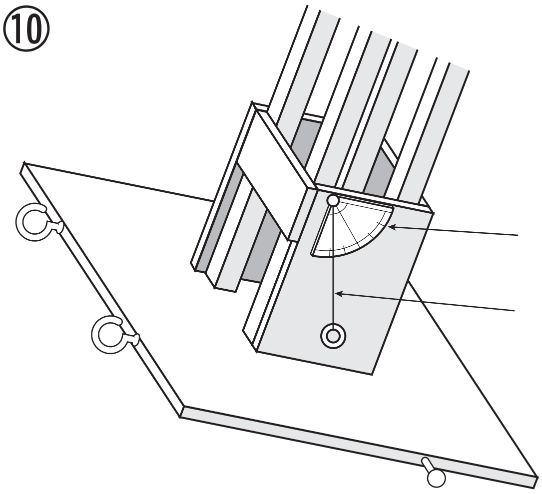
Set hinges into place, each 60cm from the edge of the plate, and connect the two plates.



Screw hetons in.

Drive a nail (large), leaving the top 10mm exposed.

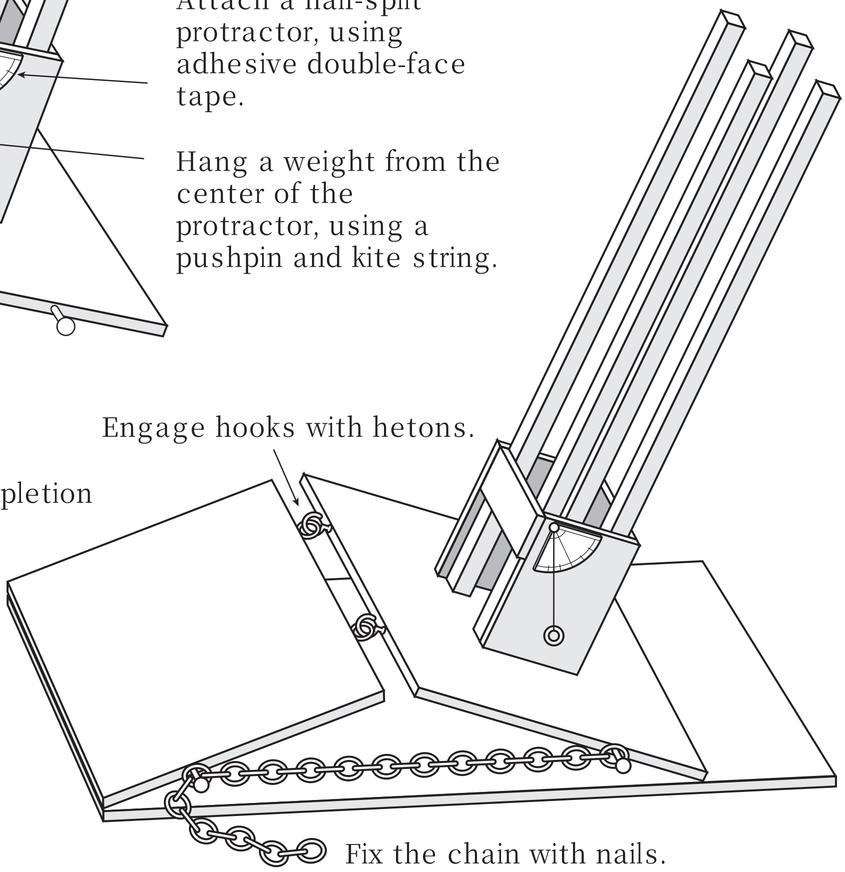
⑩



Attach a half-split protractor, using adhesive double-face tape.

Hang a weight from the center of the protractor, using a pushpin and kite string.

⑪ Completion



Chapter 5

Launching

Children are thrilled to see their water rockets fly high into the sky. To ensure safe and enjoyable launching, this chapter introduces tips on launch site locations, staff, tools and equipment, preparations to be made, launch techniques and operational aspects of competitions.

5-1 Preparing for launch

Selection of launch site

- The launch site must be at least 50m long.
- Has easy access to a supply of water.
- Is not close to an airport or airfield.

The intended site is even better if it meets the following requirements:

- Unobstructed flight is possible over a distance of 100m or more.
- The ground surface is flat and not muddy.
- Site is a safe distance from pedestrian traffic, heavy vehicle traffic, and parking lots, among others.
- Site is free of tall trees and areas with restricted access.
- Location will allow children to safely recover rockets.

Example of launch site

- Schoolyards
- Yards at public facilities
- Parks
- Dry riverbeds

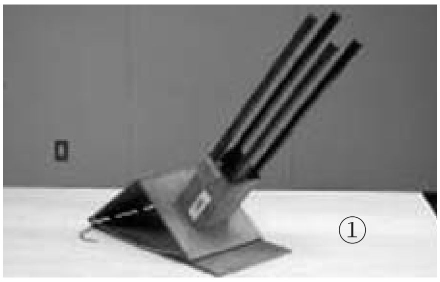
Whatever your intended launch site, there may be cases where advance permission is required. So it is advisable to inquire with the local municipal office or organization concerned.

Launch tips

- **Launchers:** : One launcher per ten participants is the standard, but this may be adjusted according to the number of rockets to be made, the number of launches, size of the launch site, time factors, etc.
- **Air pump:** : From the standpoint of safety, we recommend the use of an air pump equipped with a pressure gauge. Pumps with a long hose specifically designed for water rockets are available. Pumping refers to the process of feeding air into the rocket to pressurize it.
- **Preparation of launch area:** When the rocket blasts off, a considerable amount of water is dispelled around the launch area. We suggest you to lay a vinyl sheet beneath the launcher to prevent the launch area from becoming muddy.
- **Water supply:** Water supply will proceed efficiently if you prepare a large-size polyethylene bucket or mini-swimming pool. Use measuring cups of identical size to supply each rocket with an equal amount of water.

5-2 Tools and equipment needed for launching

①Launcher



②Funnel

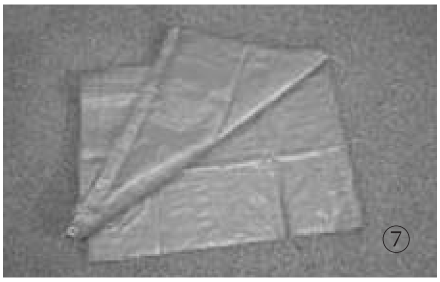
③Measuring cup

④Water tub

⑤Air pump (with pressure gauge)

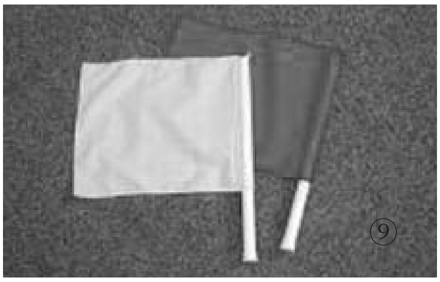
⑥Tape measure (100~200m)

⑦Vinyl sheet

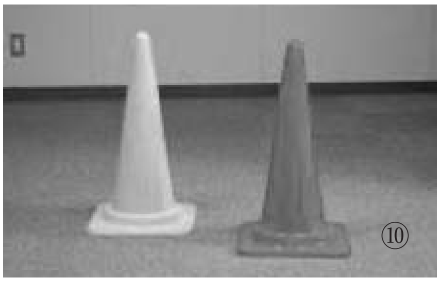


⑧Launch gear

⑨Flags



⑩Colored cones



⑪Line chalk and dispenser

⑫Megaphone/Microphone

5-3 Launch staff and their roles

Staff responsibilities

Launch control officer:

Working closely with the safety lookout officers for overall safety of the launch site, the launch control officer grants permission to launch by signaling for pumping to begin and by conducting countdown.

Safety lookout officers:

Safety lookout officers keep close watch on and around the launch site to prevent the general public from wandering into the area. After confirming that the field is clear, they use flags to signal to launch control that “the area is safe for launch.”

Recovery officers:

They are responsible for rocket recovery. Recovery officers often double as safety lookout officers.

Measuring officers:

They measure the distance the rocket has achieved after flight. Or, in the case of a fixed-point competition, they measure the difference between the landing point and the target. These officers often double as safety lookout officers.

Air pumping officers:

By engaging the water rocket nozzle to the launcher, this officer makes preparations so that the child can begin pumping. The officer also carefully checks to see that no water is leaking from the nozzle area or the rocket body. The officer lets the child pump the air by him/herself. If the child is not powerful enough to complete pumping, the officer may do it on behalf of the child. Checking air pressure is another important responsibility.

Water officer:

This officer, using a measuring cup and funnel, is responsible for filling each rocket with a predetermined amount of water.

Record officer:

This officer keeps records of flight distances and other rocket performances.

Staff

Provide two launchers for every 20 students. (Each student will make his/her own rocket.)

Launch control officer:	1
Safety lookout/recovery officers:	2~3
Measuring officers:	2 (can double as recovery officers)
Record officer:	1
Air pumping officers:	2
Water officer(s):	1~2
Total:	5~8 staffers

If the number of children involved is limited (20 to 30), it is possible that one staffer can assume more than one responsibility. Conversely, if the session is large scale, accommodating a significant number of participants or launches, the number of staffers should be increased accordingly.

When launching water rockets in a schoolyard as a class project, one or two teachers can oversee the session. A teacher serves as the launch control officer, assuming complete oversight for the operation, including safety, while leaving the other tasks to children. Make sure the children fully understand their respective tasks by giving them a thorough briefing beforehand.

5-4 Launch site setup

Launch site setup

① Demarcate the boundaries of the launch field (safe area). In doing so, it is advisable to maintain sufficient distance from surrounding structures, trees and traffic.

② Determine the position of the launcher. Usually, the launcher position is set at one of the corners of the launch field. It is advisable to secure at least 50 meters of straight, unobstructed area. Do not place the pump right behind the launcher.

③ Place the water filling area at least 3m away from and behind the launcher.

④ Determine the waiting area for students lining up to launch their rockets. This area also should be at least 3m away from and behind the launcher. Double check to ensure that the area's arrangement will prevent children from gathering around and looking into the launcher.

Staff positions during launch

① Launch control officer stands near the launcher.

② Safety lookout officers take up positions that allow them to check safety in and around the launch field.

③ Recovery/measuring officers stand by outside the filed. After the rocket has landed, they head for the rocket landing point for recovery and measurement.

④ Air pumping officers stand by near the pump.

⑤ Water officer(s) stand by at the water filling area.

Tips on launch

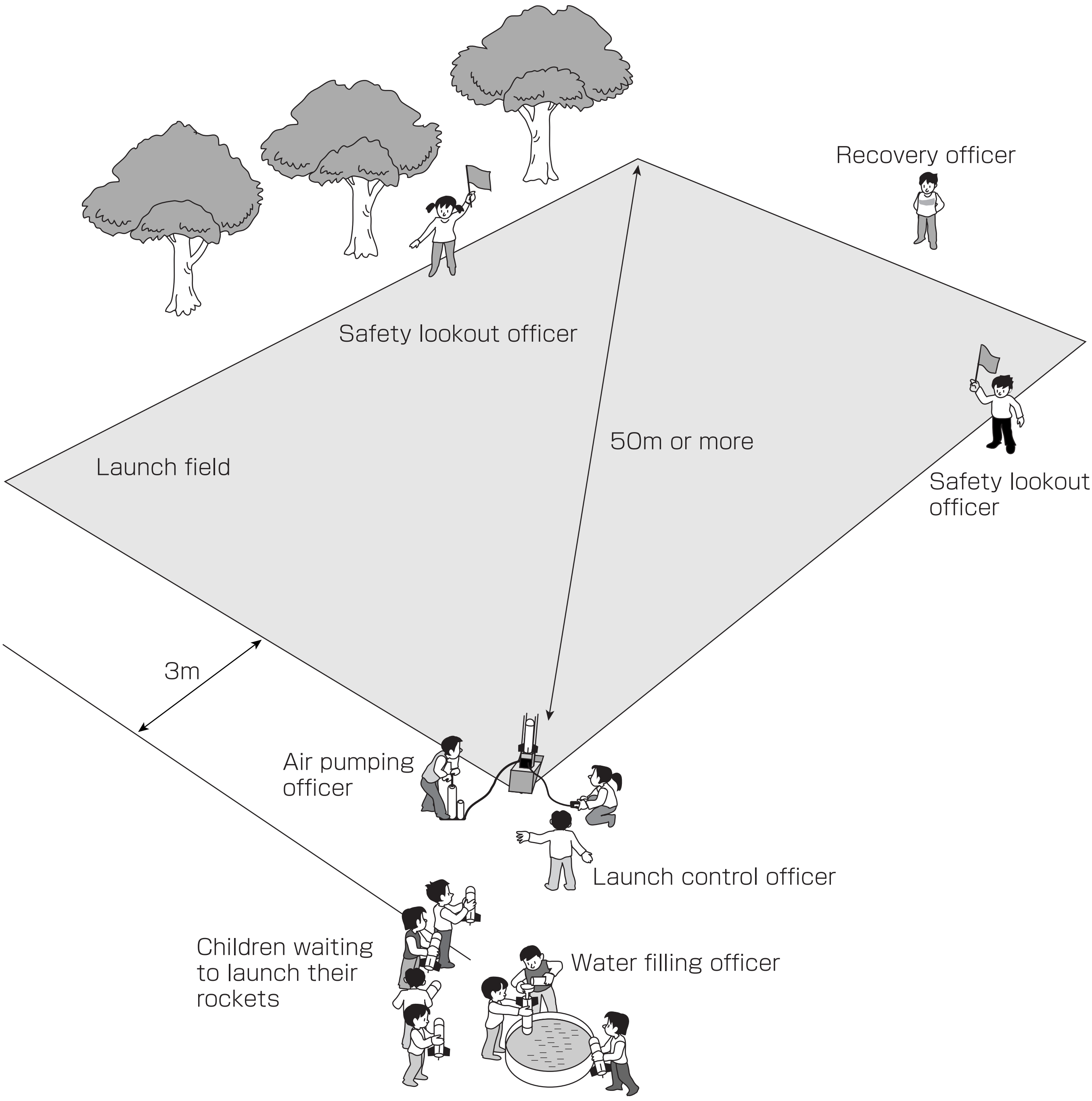
① When staging a water rocket session in parks and other pubilc areas,the staff should also pay attention to safety of the general public. It is equally important for staff to remain on the alert to prevent children from getting injured. Safety lookout officers and recovery officers, especially, are requested to tell children to stay in areas a sufficient distance away from the rocket's probable landing point.
They should reiterate that children NEVER attempt to catch a falling rocket.

② When staging a session under the heat of daytime, especially in summer, have the children wait under the shade of a tree or wear headgear.

③ When staging a competition, it is advisable to set up several tents.

④ Make sure to conduct a pre-launch rehearsal before you conduct the launch. First, conduct trial launches several times beginning with the lowest effective air pressure to check the amount of water and air pressure, the angle of launcher and wind. etc.

Example of launch site setup



5-5 Launch rehearsal

Weather conditions

It is desirable that weather conditions at the time of launch meet the standards listed below.

・Clear field of vision

・Not too windy

Launch process

Once you have relocated to the launch site, explain the launch process flow to the children.

① Check the rocket:
Check each water rocket carefully to see that there is no flaw or damage to the rocket proper. Special attention should be paid to parts subjected to pressure as damage to such parts may result in the rocket bursting. It is advisable to attach a seal to rockets that have passed the safety check.

② Check nozzle: After checking the nozzle (ensure packing and O ring are in position), screw it securely onto the rocket.

③ Fill with water: The use of a measuring cup is recommended.

④ Set rocket on launcher and adjust launch angle: An elevation angle in the range of 40~80 degrees is advised.

⑤ Confirm launch site safety and have everyone evacuate the field: Launch control officer and safety lookout officers (using flags to signal launch control) are in charge.

⑥ Start pumping: Start pumping the moment the signal is given from launch control officer. Nobody should stand directly in front of or behind the pump. Pressure equivalent to 7 atmospheres at maximum is advised.

⑦ After pumping is finished, confirm again that everyone has evacuated the landing site: Launch control officer is in charge.

⑧ Conduct countdown launch : Launch control officer is in charge.

⑨ Measure flight distance, etc. and report to recordist: Measuring officers and record officer are in charge.

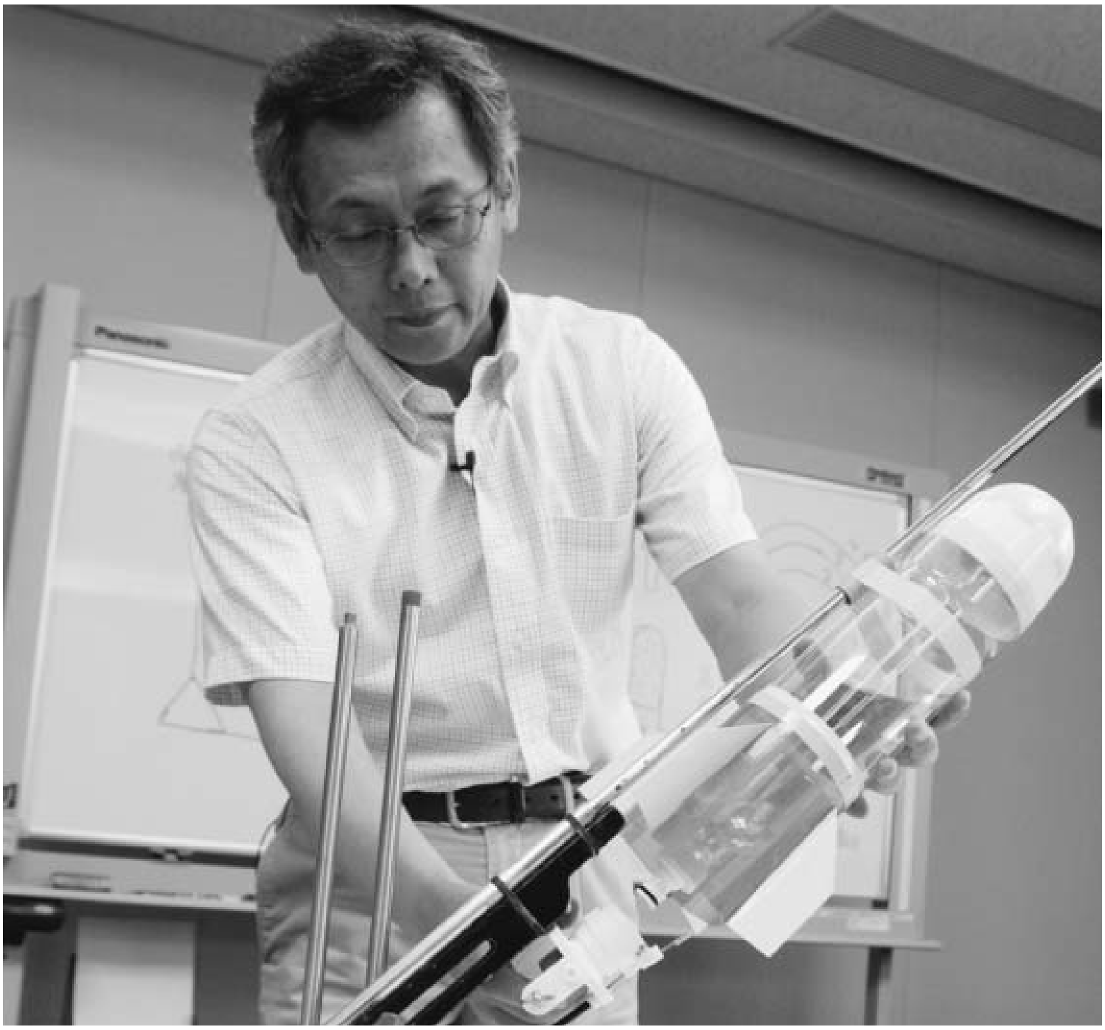
⑩ Signal to begin rocket recovery: Launch control officer is in charge.

⑪ After rocket recovery, indicate launch completion: Launch control officer is in charge.

Launch Procedure

Chapter 6

Principles of Water Rocketry



Water rockets and real rockets are impacted by the same principles of flight. Rockets that fly straight and high are backed by good science; poorly performing rockets are not.

This chapter will introduce the principles of water rocketry, which we hope will be of assistance to you as you instruct your students in the making of water rockets.

6-1 Principles governing rocket flight

Development of rockets and technological elements involved

Numerous technological elements are involved in the development of actual rockets. These include the following:

- Structural mechanics and materials engineering – to develop the rocket airframe as a structural body;
- Propulsion and combustion engineering – to develop the engine that produces thrust;
- Aerodynamics – to evaluate the impact of aerodynamic forces;
- Control engineering – to stabilize rocket attitude and guiding satellites into their targeted orbits; and
- Flight analysis – to calculate the rocket's flight performance thereby evaluating how heavy a satellite can be injected into the targeted orbit.

An incredibly enormous amount of energy is required for a rocket to escape the Earth's gravity and reach space. Therefore, fuel accounts for the greater part of the rocket's weight. Further strengthening and lightening of structural materials, further enhancement of propellant performance, and pursuit of more accurate control performance … all remain challenges for aerospace engineers.

Back in the beginning, development of the "separation mechanism" proved a very tough challenge. When assembling a multi-stage rocket, we use a mechanism known as the "separation joint" to connect the first and second stages. During the first stage combustion after launch, the separation joint, as an integral part of the rocket, must securely connect together the first and second stages. The stages must then separate without fail at the moment first stage combustion ends and the second stage prepares to ignite. Today we can choose from a variety of separation mechanisms, such as pyrotechnic devices, and these essential components benefit from improved reliability. However, everyone involved in rocket launches remain on pins and needles from the moment of launch until the artificial satellite has separated safely from the rocket's final stage.

What about water rockets?

The same concepts apply to water rockets. Rocket structure, propulsion and aerodynamics (attitude stability) are the vital factors affecting flight performance (distance, etc.). It is extremely dangerous to apply excessive pressure to the water rocket in an attempt to achieve a new distance record. From the viewpoint of safety, it is critical to understand the limitations of PET bottles in terms of structural strength and pressure resistance. When it comes to multi-stage water rockets, nerve-wracking challenges await those attempting to decide how to separate the first stage from the second, and how to ensure an uninterrupted supply of jet water. Much experience and ingenuity will be required to design, make and safely operate the separation and second stage water-jet mechanisms.

In the following sections, we will explain the kinds of forces a rocket generates while in flight. In order to ensure our explanation corresponds to the contents of your school textbooks, we will cite the Law of Action-Reaction/Newton's Third Law (= the principle of reaction propulsion) and the Law of Conservation of Momentum.

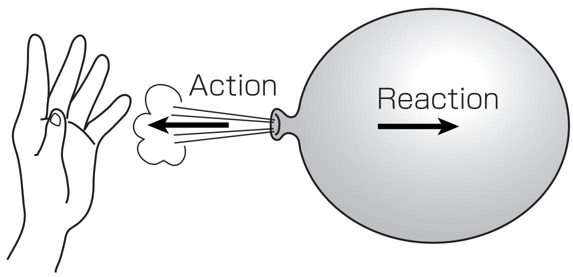
Law of Action-Reaction/Newton's Third Law (= principle of reaction propulsion)

If you release an inflated balloon, it will zip about, expelling air. A force is generated forward in "reaction" to the air being expelled backward ("action"), thus causing the balloon to take flight. This reactive force is known as "propulsion" or "thrust."

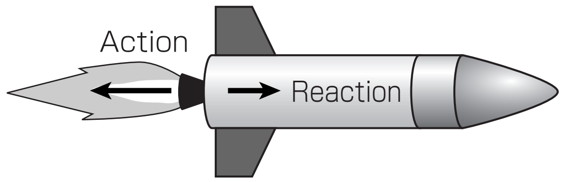
Likewise, a rocket is thrust skyward in reaction to the gas being expelled from its body. The rocket is loaded with solid or liquid fuel. A substantial amount of vertical thrust is generated by burning the fuel and jetting the resultant gas backward. Gas sufficiently pressurized in the combustion chamber is jetted out from the nozzle (action), providing the vertical thrust (reaction). In addition to fuel, the rocket is loaded with oxygen. The oxygen enables the rocket to burn its load of fuel and generate high-speed gas even in an environment devoid of air. Rockets use reactive power to achieve acceleration underwater, in the air and even in the vacuum of space.

A cannon recoils when it fires off a shell. Shooting off the shell is the action while the reaction is the recoil absorbed by the gun. You might imagine the rocket as being a cannon barrel, and not a shell, flying through space. The constant expulsion of shells (= fuel) backward allows the rocket (= cannon barrel) to keep moving forward by virtue of sustained reaction.
We call this propulsion mechanism "reaction propulsion."

Balloon expels air to achieve flight.



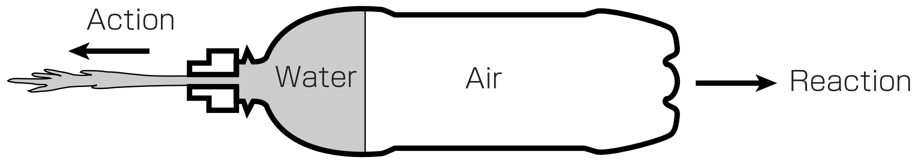
Rocket expels fuel to gain altitude.



The principle of a rocket and a balloon is basically the same.
They move forward by expelling pressurized gas backward..

What about water rockets?

A water rocket also flies by means of reaction propulsion. It flies taking advantage of a reaction resulting from water being jetted out by the compressed air it is carrying. Junior high school textbooks take up the subject of water rockets as an extended example of action and reaction, stating, “a water rocket is driven forward with a reactive force generated by releasing air compressed inside the rocket body that causes the water to jet out from the nozzle.



A water rocket flies by means of reaction propulsion.

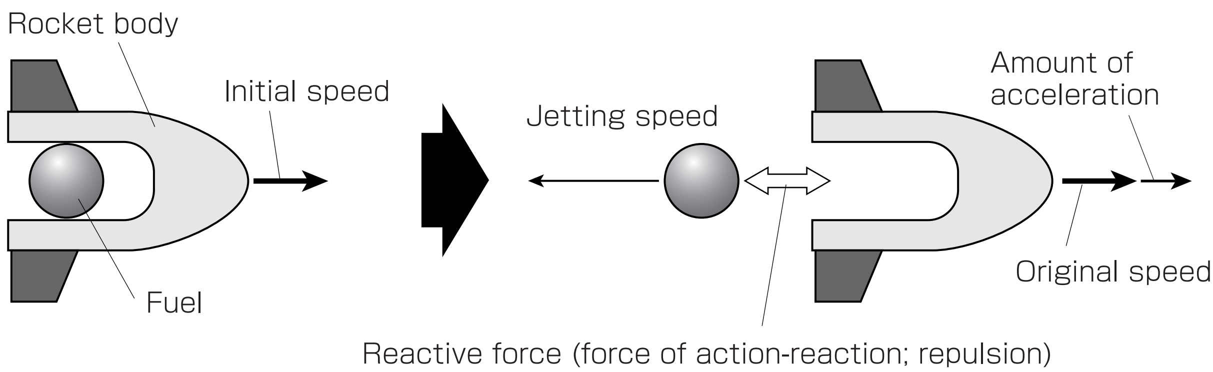
Law of Conservation of Momentum

Mass multiplied by speed equals “momentum.” It is expressed by the equation:

Momentum=mass×speed

Every object exhibits the propensity to maintain constant momentum before and after a motion. This is what is known as the “Law of Conservation of Momentum.” Here we will cite and apply this law to explain the physics of rockets. For the sake of simplicity, let’s assume that a rocket at rest has a certain mass: Mass=M+m, with “M” being the mass of the rocket body and “m” the mass of fuel. The rocket burns its fuel in an instant and expels backward gas with a mass “m” at a speed “V_e.” The value “V” is the speed the rocket has acquired by jetting out fuel (assuming air resistance=0).

As the rocket’s speed before jetting out fuel is 0, momentum is naturally 0. The momentum “p” of the fuel expelled is expressed as $p=m\times(-V_e)$, and the momentum “P” of the rocket that has begun to move due to the reactive force is expressed as $P=M\times V$. Thus the total of the two momentums is: $P+p=MV-mV_e$. With this equation, the minus symbol in $-mV_e$ means that the direction of the fuel expelled is opposite to the direction to which the rocket moves.



A rocket is accelerated with a reactive force by expelling the fuel backward.

Momentum before motion = momentum after motion = total of the rocket's momentum and the momentum of fuel expelled. This is expressed as:

$O= MV-mV_e$.

From this equation, the following equation is deduced:

$V= (m/M)\ V_e$ …… (A)

In other words, it means that the rocket moves forward so as to compensate for the momentum of the fuel that has been expelled. In this way, we can think about the rocket's motion in an easy-to-understand way by employing the concept of momentum. Note, however, that with a real rocket the fuel is burned over a fixed period of time and not in an instant. Therefore, the rocket's eventual speed is equal to the speed obtained by successively summing up the above equation (A).

For example, the speed required by an artificial satellite orbiting the Earth is approximately 7.9km/s, i.e. 28,500km/hr – almost equivalent to a surprising Mach 23. What needs to be done to allow the rocket to achieve such an amazing speed?

To accelerate the rocket as in the above-mentioned equation (A), the following three approaches are feasible:

Increase speed of gas being expelled

An effective way to increase the speed of the gas being expelled is to reduce the gas' molecular weight. Assuming the pressure inside the combustion chamber is constant, the lower the gas' molecular weight the greater the acceleration, enabling the combustion chamber to expel the gas at higher speeds. In this respect, rocket engines that employ as fuel a mixture of liquid oxygen and liquid hydrogen are known to be superior in performance as the resultant combustion gas (= steam) has a lower molecular weight. The molecular weights of combustion gases deriving from alcoholic liquid fuel and solid fuel are greater than that of steam. As such, their jetting speeds are lower.

We can also achieve higher gas expulsion speeds by increasing pressure during combustion. However, applying excessive pressure may result in damage to the combustion chamber and/or pipes. The materials used for the chamber and piping each have a maximum acceptable pressure. Furthermore, the rocket structure (including the engine) must be as light as possible, since a heavier body means a greater fuel requirement. Making the combustion chamber heavier and stronger is not advisable.

As for liquid propellant rocket engines, we enhance their thrust performance by employing a turbo pump system that utilizes combustion gas to rotate the pump, and by employing a regenerative cooling system designed to effectively transfer the heat inside the combustion chamber to the pre-combustion low-temperature fuel.

A bell-shaped device, or "nozzle," is attached to the combustion chamber's point of egress. The shape of the nozzle contributes to accelerating the jetting gas. Inside the chamber, the passage becomes increasingly narrower toward the point of egress, accelerating the combustion gas to the speed of sound. As it passes through the nozzle, the gas gradually expands and accelerates further, finally jetting out in a supersonic stream. The nozzle's function is to accelerate the speed of the jetting gas.

Increase the mass (m) of fuel to be expelled

To increase fuel mass “m,” you need to load the rocket with lot of fuel. However, an increased amount of fuel inevitably requires a proportionately larger fuel tank. What’s more, the rocket’s structure and other related components and joints must also be enlarged or increased. Putting it another way, increased fuel mass “m” results in increased rocket mass “M.” It follows that increasing “m” alone without increasing “M” is, in effect, exactly the same as reducing the rocket airframe’s mass “M.”

As discussed in (1) above, it is advisable to reduce the gas’ molecular weight in order to increase gas-jetting speed. The gas’ molecular weight can be translated as the weight of fuel that is expelled at one time. Meanwhile, fuel mass “m” means the accumulating amount of gas mass expelled. In short, it is possible to enhance thrust performance by expelling a lot of gas, which has lower molecular weight, over a long period of time. In the case of jetting gas that has a lower molecular weight, however, acceleration takes longer due to decreased thrust, although higher speeds eventually will be obtained. Therefore, during the first stage of flight, which requires the greatest amount of thrust, Japan’s H-IIA rocket and the U.S. Space Shuttle employ a solid-fuel booster.

Reduce rocket airframe mass “M”

To reduce the rocket airframe’s mass, or “M,” engineers turn to lightweight yet strong materials. Multi-stage rockets are used since each stage can be jettisoned once its fuel has been depleted. Discarding useless stages is an effective way to increase the speed of the rocket.

Using modern technology, the mass of the rocket’s airframe structure (including the fuel tank, engine, etc.) has been reduced to approximately 20% of the rocket’s total mass (including fuel). Further reductions in airframe structure mass (i.e. to the single-digit level) rely on the development of innovative materials and structural components, which will open up new horizons for space rocket development in the future.

What about water rockets?

Measures to enhance the thrust performance of water rockets are basically the same as those applied to real rockets. In the case of a water rocket, its ability to reach great distances depends on having achieved a sufficiently fast speed by the time its “fuel” – water and pressurized air – has been depleted. You can increase the speed of your rocket in three ways:

Increase water-jetting speed

The most straightforward way to increase water-jetting speed is to increase the pressure inside the tank. However, be warned: Excessive pressure may result in the PET bottle bursting. So it is advisable to determine pressure only after giving due consideration to your bottle’s maximum safe pressure. Please also confirm well beforehand that your bottle has no flaws. Use of a liquid lighter than water may also work to increase jetting speed. However, DO NOT use inflammable liquids, such as alcohol, as they are very dangerous.

Will using a heavy, high-density material like salt water really affect performance? What would happen if you used carbonated water, which generates gas when the pressure inside the tank decreases? … Challenge yourself by conducting experiments to find answers to these questions.

What will happen if you change the size of the nozzle opening? Well, the bigger the nozzle opening, the lower the jetting speed since internal pressure reduces at a much quicker rate. On the other hand, the smaller the opening, the longer the acceleration since it takes more time for the water to be expelled. There must be an optimum opening size.

Increase amount of water to be jetted

The greater the amount of water, the longer it takes for the rocket to accelerate. However, too much water means a proportionately smaller volume of air, reducing internal air pressure. Sufficient jetting speed cannot be obtained when you must also accelerate a rocket body heavily loaded with water. Taking it to the opposite extreme, sufficient speed will not be obtained if the amount of water is insufficient; remember, thrust is generated by the water being expelled from the rocket. The amount of water should be about one-fourth or one-third the bottle’s cubic volume. If you want to increase the amount of water while maintaining the volume of pressurized air, you could design a rocket with independent water and air tanks.

This approach is similar to making a large-size water rocket with a large-capacity tank. We encourage you to exercise your imagination in addressing this problem, but caution you to make sure your water rocket is strong and safe. Please make sure all joints and connections are free of leaks.

Decrease mass of water rocket

NEVER attempt to shave or otherwise reduce the weight of the PET bottle since you run the risk of the bottle bursting. The key point is to make the rocket body light in weight by eliminating unnecessary accessories. Remember, however, that accessories include fins, the skirt and modeling clay ballast – all of which are important for achieving stable flight. In fact, the rocket cannot fly straight without the fins and modeling clay ballast. Too much is as bad as too little. What is the minimum acceptable size and weight of these important parts?

Minimize air resistance

It is also very important to minimize air resistance during flight. Therefore, it is advisable to make the rocket’s exterior as slim and smooth as possible and minimize protruding parts and unnecessary accessories.

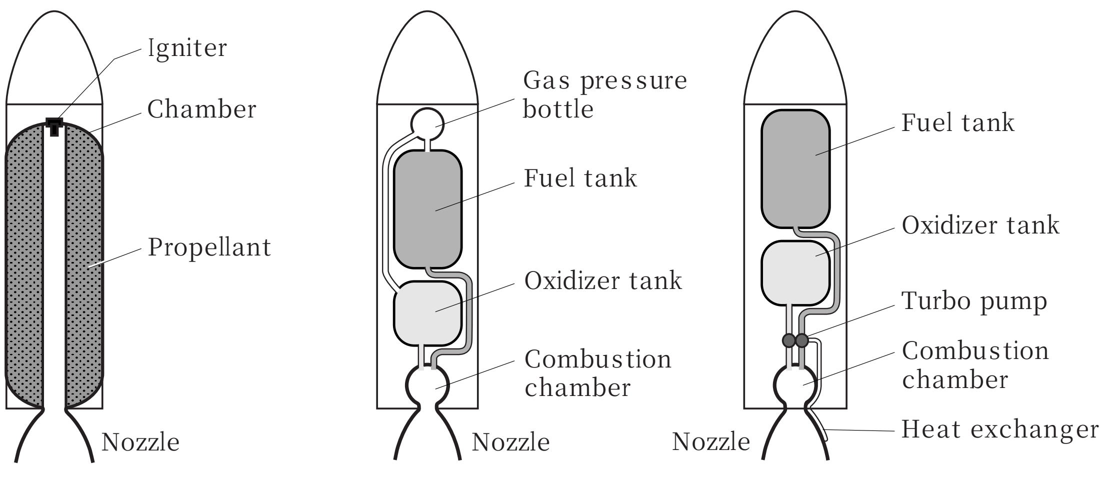
6-2 Various forms of rocket propulsion

Rockets obtain thrust by jetting fuel rearward at high speeds. Over the years various propulsion systems have been proposed. The key to creating high-performance rocket propulsion is efficiently converting chemical energy stored in the rocket to heat energy. Rockets that create propulsion by converting chemical energy to kinetic energy are known as "chemical rockets," while those that convert electric energy or heat energy to kinetic energy by methods other than combustion are called "non-chemical rockets." In the following discussion, we introduce the characteristics of these two rocket types and compare them with a water rocket's propulsion mechanism.

Chemical rockets

Chemical rockets create propulsion by utilizing the chemical that is generated when a substance burns. Rockets must perform in an environment where air is extremely thin; when it comes to putting an artificial satellite into orbit, the environment is more or less a vacuum. Naturally, the oxygen needed to burn the fuel that creates propulsion is not available. The rocket must therefore carry not only fuel but oxygen (the oxidizer) as well. This, then, is the essential difference between rocket and jet engines. Jet-powered aircraft carry fuel only. They create propulsion by drawing in ambient air containing oxygen and using it to burn their fuel.

To create propulsion, chemical rockets are designed to generate high-temperature, high-pressure gas via a chemical reaction (combustion), jetting out the resulting gas. Within the category of chemical rockets, solid rockets use solid propellants and oxidizers; liquid rockets use liquid propellants, and hybrid rockets use both. Solid rockets burn a propellant which contains a granular oxidizer. With liquid rockets, liquid fuel and liquid oxidizer, stored in separate tanks, are mixed in the combustion chamber and burned. As for hybrid rockets, a liquid oxidizer is sprayed onto the solid fuel, which is then burned. All of the large-size launch vehicles currently in use around the world – Japan's H-IIA and M-V rockets, the U.S. Space Shuttle, the Ariane rocket of Europe, and Russia's Soyuz – are chemical rockets.



Solid rocket　　Liquid rocket (pressure-fed type)　　Liquid rocket (turbo pump type)

[Non-chemical rockets

Instead of using a chemical reaction (burning), non-chemical rockets utilize electric energy or heat energy to accelerate and then expel the propellant. Non-chemical rockets come in a variety of types, representative of which are ion propulsion rockets which jet ionized particles by accelerating them in the electro-magnetic field; and nuclear energy rockets and nuclear fusion propulsion rockets, which expel high-temperature gas created by heating lightweight particles (such as hydrogen) in a nuclear reactor. There are a number of new ideas for generating high-speed particles, such as the light quantum rocket designed to generate light via reaction between matter and anti-matter. Yet another idea is a system in which the rocket itself does not carry an energy source but relies on an external energy supply that it converts to kinetic energy. One such example is a rocket that relies on a ground-based laser to excite its sub-critical fuel mass. Another example is the solar sail – a huge membrane that deploys in outer space and employs solar energy to move the rocket, much as a sail moves a yacht.

Two types of non-chemical rockets have now reached the stage of practical application: the ion engine used on board the asteroid probe “HAYABUSA,” which recently landed on asteroid “Itokawa;” and the plasma engine being used on a satellite in geosynchronous orbit. These two engines are called “low-thrust propulsion” engines due to their low level of thrust. They can accelerate efficiently using a limited amount of fuel and therefore are suitable for use controlling artificial satellites as well as interplanetary missions involving flights of significant distances. The other types of non-chemical rocket are at the developmental stage.

What about water rockets?

Water rockets do not utilize any chemical reaction but obtain thrust by using pressurized air to jet water out. As such, you might say they fall into the category of non-chemical rockets. On the other hand, water rockets also have something in common with chemical rockets as they fly by generating a relatively large thrust in a short period of time. To put it another way, water rockets undergo a process of energy conversion: air compression energy → air kinetic energy (expansion) → water kinetic energy (jetting), whereas chemical rockets undergo a process of chemical energy → heat energy → kinetic energy.

6-3 To ensure flight stability

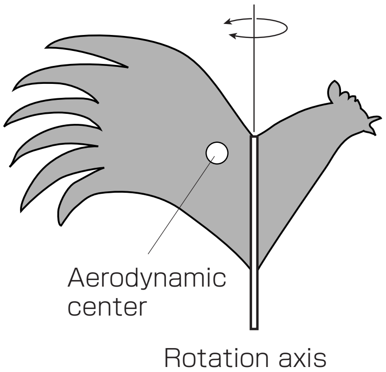
However great the thrust may be, rockets cannot achieve sufficiently high speeds unless attitude and direction of acceleration are properly controlled. If the rocket spins like a rotating firework, forward acceleration will be impossible. Real rockets bound for space require extremely high accuracy for attitude and orbit control. The duration of a rocket's flight through the Earth's atmosphere is very short. Most of its time will be spent in outer space, where the impact of aerodynamic force is negligible. As such, attitude control (attitude stability) is extremely important. In this section, we will focus on water rockets and discuss how to ensure attitude stability under the impact of aerodynamic force.

Center of gravity and center of aerodynamic force

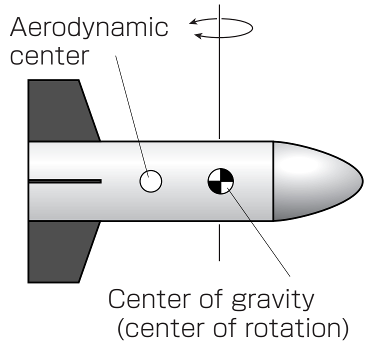
The Earth's gravity affects everything that has a mass. The center of gravity is the point from which the weight of a body or system may be considered to act. When a rocket is subjected to an external force, such as a side wind, the rocket rotates around its center of gravity. Therefore, it can be said that the rocket's center of gravity during flight coincides with the center of attitude rotation. During flight, a rocket is impacted by the air streaming around it. When it comes to airplanes and gliders, aerodynamic force can be broken down into air resistance, lift, attitude rotational force and so on. We refer to aerodynamic force's action center as the aerodynamic center. While, in the strictest sense, the definition of the aerodynamic center is different from that of aerodynamic force's action center, we call it the aerodynamic center for the sake of simplicity. In the case of rockets with fins, the nose cone, rocket body (airframe) and fins are subjected to aerodynamic force, in that order. Given that the aerodynamic center is the action center of the aerodynamic force, the larger the rocket's fins are, the greater the aerodynamic force affecting the fins, thus causing the aerodynamic center to shift toward the rocket's rear end (fin side).

Weathercock stability (aerodynamic stability)

An attitude stabilizing system based on aerodynamic force is referred to as aerodynamic stability. It is also known as weathercock stability due to the resemblance to a weathercock, which always faces windward. Whether the rocket can maintain its stability, i.e., whether the weathercock faces windward as desired, depends on the positional relationship between its rotational center and aerodynamic center. Looking at a weathercock, you can see its rear half (the section from the rotation axis rearward) has greater area than the front half. This difference in area means a difference in the amount (pressure) of wind on each section, and this generates rotary motion around the axis. When the wind hits the side of the weathercock, it pushes and rotates the weathercock leeward because the rear half is subject to greater pressure than the front half. This imbalance enables the weathercock to rotate. When the weathercock is aligned with the wind flow direction (= facing windward), it ceases to rotate. This is known as weathercock stability.



Stability of weathercock



Aerodynamic stability of rocket

The rocket's attitude rotates around the center of gravity. In other words, the rocket's center of gravity is its axis of rotation. With finless rockets, it is usually the case that the aerodynamic force's center of action (aerodynamic center) moves frontward away from the rocket's center of gravity. If the aerodynamic force remains unchecked it will cause the rocket to turn toward its aerodynamic center. This will cause the rocket's nose to face leeward, i.e., rearward. Fins shift the aerodynamic center rearward from the center of gravity. When the rocket is subjected to aerodynamic force, the fins will turn leeward with the rocket's front end turning forward. This explains why a rocket firework can fly straight skyward. The firework is attached to the tip of a long rod. If the rod is too short, the firework cannot achieve stable flight.

When in flight, a rocket receives wind from the direction it is heading. Fins orient the rocket's nose to the direction of movement at all times. Therefore, the larger the fins are, the more attitude stability will be obtained. However, the fins should be of moderate size; fins that are too large will add too much weight to the rocket.

Enlarging fin size is not the only way to achieve weathercock stability. Ballast (the lump of modeling clay for water rockets) attached to the tip of the rocket can also shift the center of gravity frontward. In effect, this moves the aerodynamic center rearward from the center of gravity, thereby contributing to aerodynamic stability. This point is taken into account with real rockets as well; heavy payloads, such as observation equipment, are always placed as far frontward as possible.

Let's take a moment to discuss the vital role played by the launcher's guide rails. A weathercock-stabilized rocket flies windward. If sufficiently accelerated, the rocket receives a wind from the windward direction, which enables it to fly straight along the angle set on the launcher. If the rocket is subjected to a sudden side wind before achieving sufficient speed, its attitude will shift and the rocket will turn in the direction of the side wind. Herein lies the importance of the guide rails. Since the guide rails allow the rocket to maintain its attitude until it reaches a sufficient speed, the rocket won't turn sideward even if it's buffeted by strong side winds.

Do you know that many large-size rockets do not have fins? While fins can stabilize a rocket's attitude, they may also cause flight direction to shift in the direction of a side wind. In other words, fins are vulnerable to wind. What's more, fin-assisted aerodynamic stability does not function in outer space where air is scarce and aerodynamic force does not come into play. For rockets whose primary mission is to deploy an artificial satellite into its predetermined orbit with the greatest possible accuracy, the drawbacks of fins can mean the failure of a mission. Large rockets armed with high-precision control equipment can be launched despite aerodynamic instability. Instead of fins, their onboard attitude control system ensures attitude stability.

Spin stabilization

Spin stabilization, based on rotation force, is a method for stabilizing rocket attitude without having to resort to aerodynamic force. A cannon shell, provided with high-speed rotation by the cannon's rifled barrel, can fly toward the target while maintaining its attitude. In fact, spin stabilization, which achieves attitude stability by rotating the body, is often employed with rockets and satellites.

What about water rockets?

The foregoing also applies to water rockets. Aerodynamic stability (weathercock stability) is necessary if the water rocket is to fly straight. It needs fins to shift the aerodynamic center rearward relative to the center of gravity. In addition, ballast (modeling clay) is attached to the rocket's nose to bring the center of gravity frontward. Is it better to reduce ballast weight and enlarge fin size? Or is it better to attach small fins and employ a proportionately larger amount of ballast? Which is the best solution if you need to reduce the overall mass while maintaining aerodynamic stability? Yet another question arises as to how to harmonize the difference between the center of gravity immediately after launch, when plenty of water remains in the bottle, and the center of gravity after all the water has been expelled. These can be intriguing challenges as you search for the means to improve your rocket.

Fins attached at an angle of less than 90 degrees will lead to rotational force being generated by aerodynamic force in the course of flight, providing spin stabilization. Aerodynamic stability leaves the rocket vulnerable to side winds. Spin stabilization makes the rocket invulnerable to side winds, allowing it to hold its initial attitude. In terms of a rocket's ballistic trajectory, aerodynamically stabilized rockets fly along their trajectory whereas spin-stabilized rockets have a propensity to continue to fly while holding their initial attitude. In other words, when falling to the ground, the former fall with their noses pointed downward while the latter fall with their noses upward. What differences will you see between rockets with fins that rotate while flying, and those that fly without rotating?

6-4 Strength of PET bottles

Strength tests for real rockets

So far we have warned you about the risk of bottle burst due to excess air pressure. What is the specific point of danger? How can we know when it is approaching? We have also warned you never to attempt to answer these questions since doing so is rather dangerous. When it comes to actual rockets, we need to accurately grasp the pressure required to jet the fuel – known as "combustion pressure" – while acknowledging that it will be limited by the strength of the structural materials employed to build the combustion chamber. How can we determine the combustion chamber's pressure ceiling? The only way is to try out various models and conduct breakdown tests. It is not advisable to use gas, such as air, when conducting pressure tests. We use a liquid, such as water, to determine the pressure immediately before breakdown. By thus simulating potentially dangerous phenomena in a safe environment, we are testing the unknown and that which we wish to know. To facilitate such endeavors, we are undertaking a variety of approaches – devising liquid-based pressure testing equipment, using remote control devices that allow us to conduct experiments at inaccessible locations, and using reinforced buildings, among others.

Water rockets have much in common with real rockets. This makes the making of water rockets interesting as well as challenging. At the same time, it means that participants can be seriously injured if the wrong approach is taken. Please make sure you understand the fundamentals of water rocketry so that you can safely enjoy water rocket making together with your students.

Resources

Web site of water rockets

☐JAXA Space Education Center:
http://edu.jaxa.jp/
This manual and the related DVD for educators are posted on the web site.

Conducting a search for Web sites dedicated to “water rockets” will yield a large selection covering the spectrum from entertainment to education. Some are Web sites produced by water rocket enthusiasts who are eager to develop new designs or who are competing for the world launch record.

The following are some of the water rocket Web sites that we think will be of interest to educators:

☐Wikipedia
Good place to start: It explains how water rockets work, safety concerns, competitions, and provides external links.
http://en.wikipedia.org/wiki/Water_rocket

☐“A guide to building and understanding the physics of water rockets”
by Dr. Michaer de Podesta and NPL
www.npl.co.uk/waterrockets
This booklet explains how water rockets work, how to build them and optimize their performance, as well as the physics behind them. It is linked to the NPL Water Rocket Challenge, which includes school, youth and adult categories, as well as offering guidelines for organizing your own water rocket competition.

☐Water rocketry by NASA
http://exploration.grc.nasa.gov/education/rocket/rktbot.html
This site is recommended for science teachers, especially those teaching in junior and senior high schools. It provides materials that include the scientific principles and mathematics related to water rocketry, simulator programs, lesson plans, a safety guide, etc.

Where to find water rocket parts

We recommend the use of ready-made nozzles to ensure launch safety. Although such nozzles are available from Japanese dealers, most of them only deal with the local market. For your information, here are their contact details:

Yumegoya: Tel/Fax:0583-71-3453
http://www5f.biglobe.ne.jp/~yumegoya/TOP

Pet Bottle Craft Association, Japan: Tel:0429-69-1710 Fax:0429-69-1707
For online purchases:
http://pcaj-i.jp/

Water Rockets

Educator's Manual

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First Edition November, 2006

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Printed by Taiyo Printing Co., Ltd