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Micro-Rockets for the Classroom

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Many people are fascinated with rocketry, as evidenced by hundreds of thousands of visitors to the Kennedy Space Center for Space Shuttle launches. Rockets demonstrate important basic principles of chemistry, engineering, and physics[1-5]. Even model rockets are exciting to launch. Many physics teachers take advantage of this and use model solid fuel,[6-10] and water rockets[11-14] in their teaching activities. Scientific supply companies have responded to this interest and offer a range of equipment to investigate model rocket performance.[6, 10, 12, 15] This note describes miniature solid fuel, or micro-rockets, which are made from a single safety match, oil or paraffin, and aluminum foil. These micro-rockets have a range of up to 6 meters, and can be safely launched from a candle flame inside classrooms.

Although the commercial model and water rockets available from hobby shops, science supply companies, and toy stores are larger, louder, and more reliable than micro-rockets, they have significant disadvantages. They are more hazardous and expensive. Special arrangements are typically required for an outdoor launch site, and it must have a large clear space if free flying rockets are to be recovered. Significant class time may be required to get students and equipment to the launch site and back, and windy or inclement weather may disrupt launch schedules.

Micro-rockets overcome these disadvantages in that they are constructed of inexpensive and readily available materials, and can be safely launched indoors. Students can test their own designs on their time, for examples, the length, thickness, and twist of the paper tail, type of match, aluminum foil casing design, and the exhaust chemistry can all be modified. The paper shaft (tails) of the Diamond[16] matches used in this work were cut to half width, reducing the match mass from ~ 85 to ~ 60 mg. The heads alone had a mass of ~ 35 mg. Burning the head but essentially no paper reduced the mass by ~ 17 mg. Three to 6 mg of cooking oil[17] or paraffin[18] was absorbed onto some match heads to modify the flame chemistry, as discussed below. Aluminum foil[19] casings were then added, as shown in Figure 1. The aluminum pieces had masses of ~ 6.0 and 11 mg, respectively. Before launch the paper tails were twisted for spin stabilization.

Figure 2 shows the smoke trail left by a micro-rocket launched from a small hole in a wooden dowel. The procedure used to obtain the photographs was to position the dowel so two micro-rockets were over a candle flame. When smoke first appeared from either rocket, the camera was tripped. Launching two rockets increased the odds that one would be taking off, yet still within the field of view, when the strobe flashed. The inset shows a micro-rocket that took off just before the casing burned through, misdirecting the rocket. In a room with still air, the micro-rocket's trajectory can be clearly seen for a minute or two after launch from the smoke trail shown in this figure.

Safety glasses are recommended near micro-rocket launches. Also, hot casings can melt a few carpet fibers, causing the aluminum foil casing to stick to the carpet, but not leaving observable damage to the carpets. No observable damage has been observed in several hundred micro-rocket launches under varieties of conditions. Still, hard surface surroundings are recommended, and students should be reminded of fire hazards associated with any use of candles and matches.

The dowel can be turned to vary the launch angle. Parallel holes allow multiple launches at the same angle without reloading. Many micro-rockets can be launched, making statistical analysis of rocket performance meaningful. Launch competitions can be held.

Water rockets are the easiest rockets to explain; they use the mechanical energy of compressed gases to accelerate water out the nozzle. Water provides the reaction mass, in the sense of Newton's third law, to propel the rocket. A useful classroom demonstration is to launch a water-rocket[11] according to the manufacturer's instructions except without water, in which case it rises only a few centimeters. Using the same gas pressure[20] with water, it rises ~ 20 meters (outside), dramatically illustrating the importance of reaction mass in rocket propulsion. Indoor launches with water are possible using a cord tether to stop the rocket's ascent before it reaches the ceiling. A bucket on the floor can catch most of the ejected water.

Understanding how pyrotechnic rockets work requires some reference to kinetic theory. Rocket motors generate thrust by burning propellants, converting chemical energy into kinetic energy of the combustion products, and channeling those hot products through the motor nozzle. The propellants contain both fuel(s) and oxidizer(s); their combustion provides both the energy and reaction mass. A useful way to describe such combustion is that it accomplishes a phase transition, converting solid material to plasma (hot, ionized gas).

Low explosives, such as model rocket propellants and gun powder, can generate plasma temperatures up to ~ 3000 K. Firecrackers use low explosives, typically in paper containers that confine the plasma for a brief time. By design, the paper ruptures when the internal pressure exceeds the container's strength, suddenly releasing the plasma, creating the explosion.

Low explosives will not explode without being contained. A convenient demonstration of this is accomplished by placing half-a-gram or so of black powder[21] in the fold of a paper strip a few cm from one end. When the paper is ignited on the end, it burns slowly until fire reaches the powder, which creates an energetic puff of fire and smoke. High explosives, such as nitroglycerin, do not require containers to explode, and should be avoided for rocket propellants.

Model rocket motors also typically use paper containers, but have an opening to release and direct the exhaust, preventing (hopefully) the motor from bursting. The exhaust expands as it accelerates through the nozzle, converting the plasma's heat and pressure into linear velocity of the exhaust plume. Low explosives burn faster at higher temperature and pressure, which in a rocket motor accelerates the exhaust to higher speed, increasing thrust. To achieve greater thrust while minimizing the mass of the rocket, high performance rockets operate close to conditions that cause catastrophic failures. Commercial model rocket motors presumably have substantial safety margins, but caution is advised as undetected manufacturing faults could result in explosions. Observers should follow instructions provided with model rocket kits and keep a safe distance from launchings.

Order-of-magnitude parameters useful for characterizing these processes are that propellants typically have a density on the order of ~ 1 ton/m^3, while plasmas at one atmosphere and ~ 3000 K have a density on the order of ~ 0.1 kg/m^3. So propellant combustion can result in nearly a 10^4 fold volume expansion.

Newton's second and third laws of motion applied to rocket acceleration yield, $A = F / M_R$, where F is motor thrust and M_R the rocket mass. Students can verify the penalty of increased mass for themselves by not trimming the paper tail or using more aluminum on micro-rockets.

Solid fuel rockets have been made for ~ 800 years.[22] Black powder is a good propellant, except powder grains can fall out as the rocket moves. Thiokol Corporation developed methods of casting solid propellants in rocket motors and now makes boosters for the space shuttle using aluminum[22] as the main fuel.

Understanding that many metals burn is important in rocket science. Some students express surprise, perhaps doubt, that aluminum and other metals burn. This doubt can be removed by lighting a tuft of steel wool[23] in a candle flame, and also by observing perforated aluminum micro-rocket casings.

Refractory metals, such as tungsten, also burn. This can be conveniently demonstrated by covering a standard incandescent light bulb, not electrically connected, with paper or cloth, and breaking the glass (but not the filament) with a hammer blow. When this bulb is turned on, the filament lights, but quickly burns out, making smoke and white powder, which is tungsten oxide.

Photographic flashbulbs provide another dramatic demonstration of burning metal. They have aluminum, magnesium, or zirconium wool[24] in an oxygen atmosphere inside a glass bulb covered with tough plastic, to limit the glass shattering.

Hot metal rocket engine parts will also oxidize if the exhaust contains free oxidizers. Hence, many rockets are designed so the exhaust contains excess fuel, which is equivalent to an oxidizer deficiency. The extra fuel is not burned, makes the exhaust reducing (as opposed to oxidizing), and lowers the exhaust temperature and therefore thrust. The extra fuel also adds mass which must be carried by the rocket. This is an engineering compromise, necessary to sustain rocket motor operation. A continuing evolution in metal technologies have allowed continuing improvement in rocket performance since the space age began.

Safety matches use potassium chlorate[25, 26] for oxidizer, probably in excess to facilitate paper ignition. In micro-rockets this causes combustion of aluminum casings and burn through. Casings with a single layer of tightly wrapped aluminum foil almost always burn through. Dipping the match head in cooking oil or hot paraffin before assembling, and making casings with two layers of aluminum foil, nearly eliminates this problem. Another model of a micro-rocket which incorporated a match head and oil in an otherwise all aluminum rocket, designed for vertical take-off, left oily residues on the launch pad, indicating oil not burned was ejected with the exhaust and therefore also functioned as reaction mass. Obviously there are many design variations and experiments possible with micro-rockets, which our experience shows will be approached with energy and enthusiasm by many students.

Finally, it may be useful to point out to students that chemical rocket motors are designed to convert the kinetic energy of hot gases produced by combustion into linear velocity of the rocket. Aero-braking space craft reverses that, in that it converts linear motion of the space craft back into kinetic energy of gases.

Figure 1. A Match with half the paper tail removed was placed on a 6 x 14 mm piece of aluminum foil, as shown in A. Flap 1 was folded along the dashed line and all edges wrapped around so the match head was completely covered. This object was placed on the second foil piece, as shown in B, which was 16 mm long with a 15 mm base and 5 mm top. Flap 2 was folded down and its edges wrapped around the match head, then flaps 3 and 4 were sequentially folded over and wrapped tightly. Then, flap 5 was folded so it pinched the corner of flap 4, securing the casing. Finally, the tip of a straight pin was slipped between the casing and paper tail, as at 6, on both sides of the paper, to assure exhaust gases could escape from both sides of the match.

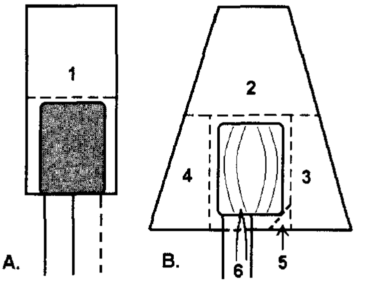
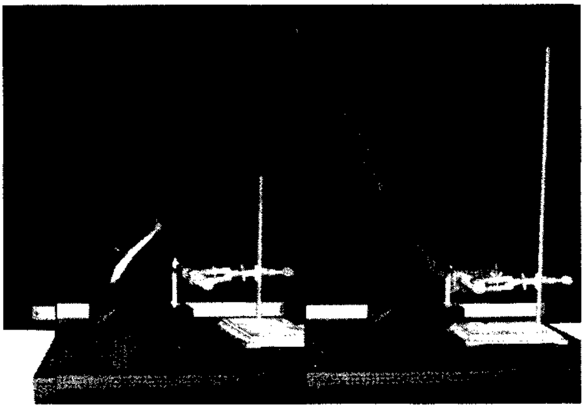


Figure 2. The smoke trails left by micro-rockets lâunched from a candle, as captured by stroboscopic flashes. The micro-rocket on the right blew the candle out when it took off. Scale is established by the meter stick on the table.The inset photo shows a micro-rocket that burned through its aluminum casing just after take off, causing it to crash.



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