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The Apollo 1 Fire: A Case Study in the Flammability of Fabrics

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This January marked the 52nd anniversary of the Apollo 1 fire. On Jan. 27, 1967, the interior of NASA's AS-204 command module (CM), occupied by American astronauts Roger Chaffee, Virgil "Gus" Grissom, and Ed White, caught fire during a rehearsal of its scheduled Feb. 21 launch (Fig. 1). By the time the ground crew was able to open the hatch, the three astronauts had perished. On April 24, 1967, NASA announced that the flight would be officially re-designated "Apollo 1." In this case study, we conduct a basic *horizontal* flame test, patterned after the protocols set forth by the Environmental Protection Agency (EPA) to measure the ignitability of solids. The laboratory activity is a complementary exercise to the *vertical* flame test described in our previous article that examined the initial source of fuel for the fire that destroyed the massive German zeppelin *Hindenburg* in 1937.¹ Combining techniques from both case studies gives students a quantitative understanding of how the flammability of materials is tested and how a forensics approach to physics can be used to understand significant historical events.



Fig. 1. The primary crew of Apollo 1. Left to right: Edward H. White II (Lt. Col., USAF – Senior Pilot), Virgil I. “Gus” Grissom (Lt. Col., USAF – Command Pilot), and Roger B. Chaffee (Lt. Cdr., USN – Pilot). (Photo courtesy of NASA)

Commanding the first manned Apollo mission was 40-year-old veteran astronaut, Virgil I. Grissom, Lieutenant Colonel, USAF. A native of Mitchell, IN, and 1950 graduate of Purdue University's mechanical engineering program, Grissom was one of NASA's original class of astronauts—the famed “Mercury 7 Astronauts.” Preferring to be called “Gus,” Grissom previously commanded the second suborbital Mercury flight as well as the first manned Gemini mission. As the command pilot aboard Apollo 1, Grissom was seated in the left-most seat (facing the cockpit dash) and had access to the emergency cabin pressure relief valve, to be opened in the event of a cabin fire. The senior pilot aboard Apollo 1 was another space veteran, 36-year-old Edward H. White II, Lieutenant Colonel,

USAF. Born in San Antonio, TX, White graduated from West Point and flew aboard Gemini 4, becoming the first American astronaut to perform a spacewalk on June 3, 1965. As senior pilot aboard Apollo 1, White was seated in the center and was responsible for opening the main hatch if the crew had to make an emergency egress from the cockpit. Rounding out the crew of Apollo 1 was 31-year-old Grand Rapids, MI, native and pilot Roger B. Chaffee, Lieutenant Commander, USN. Like Grissom, Chaffee was a graduate of Purdue University, earning his bachelor's of aeronautical engineering in 1957. As one of the youngest astronauts selected by NASA, Chaffee was to take his first flight into space on Apollo 1. During the flight rehearsal, he was seated in the right-most seat and charged with maintaining communications with ground controllers in the event of an emergency. Additional biographical information on the astronauts can be found in our supplemental material (see the online appendix for details).^{2,3}

“Go fever!”

To meet President Kennedy's challenge of landing a man on the Moon before 1970, NASA had to develop an unprecedented amount of flight hardware, training protocols, and mission procedures in just a few short years. In this high-stakes, high-risk atmosphere, the U.S. space industry developed what is commonly referred to today as “go fever”—a group-think phenomenon in which people push themselves, despite great danger, to meet a previously chosen goal. Unfortunately, “go fever” was causing concern for the primary and backup crews of Apollo 1. For example, during a spacecraft review meeting held on August 19, 1966, the astronauts expressed worry about having so much flammable VELCRO® inside the cabin.⁴ Despite these concerns, engineers kept the flammable material in the capsule to facilitate the securing of tools and equipment. Engineers marched forward with their planned Feb. 21 launch.

Cape Kennedy Air Force Station Launch Complex 34A was the site for the “Plugs Out Integrated Test” of the AS-204 spacecraft on Jan. 27, 1967. The “plugs out” moniker describes a test of the vehicle to see how it performs under internal power, with no umbilicals supplying off-board power to the ship. The rehearsal was dubbed “non-hazardous” since no pyrotechnic systems were armed nor was the rocket fueled. At 1:00 p.m., the crew climbed into the capsule and was strapped into their seats. Grissom immediately reported a foul odor of “sour buttermilk” circulating through his suit. The simulated countdown was suspended at 1:20 p.m. and resumed at 2:42 p.m. when engineers could not identify a cause of the odor. At this point, the complicated three-layered hatch was closed. The air in the cockpit was then replaced by pure oxygen, pressurized to 16.7 psi, to drive out any air that entered the cockpit

as the crew boarded as well as to seal the plug door. Such a door seals itself by taking advantage of a pressure difference established across its two sides. As the cabin is pressurized, a wedge-shaped door is forced into a socket, forming a seal that prevents it from being opened until the cabin pressure can be released. Most commercial aircraft in service today use a plug door design. The decision to use a pure oxygen environment, over a dual-gas nitrogen-oxygen system, makes sense for several reasons: it is simpler to design, weighs less, and eliminates the possibility of decompression sickness (i.e., “the bends”). Once the capsule was in space during an actual flight, the pure oxygen atmosphere would have been lowered to 5 psi to reduce the risk of fire while still sealing the hatch against the almost zero pressure of space.

“We’ve got a fire in the cockpit”

Problems plagued Apollo 1 all afternoon, most of them involving the communications system. The countdown was suspended again at 5:40 p.m. while engineers tried to debug the problems. At 6:30 p.m., the countdown remained on hold. Grissom’s microphone was stuck on (recording the audio used to determine what happened) and controllers heard him question: “How are we going to get to the Moon if we can’t talk between two or three buildings?” In the midst of all of this “go fever,” something was about to “go” terribly wrong.

The Apollo 204 Review Board’s reconstruction of events estimates the fire to have progressed as follows: At exactly 6:30:55 p.m., engineers detected a power surge that accompanied an electrical short, probably sparked by a chafed wire, somewhere in the lower left side of the CM near the environmental control unit below Grissom’s seat. The Apollo 1 fire now had its ignition source. The initial source of fuel for the fire was the polyethylene tubing that covered the wires running throughout the capsule. Several large patches of adhesive VELCRO hooks that were attached to the wall panels of the CM, leg-rests, and seats were the next materials to ignite. Eventually, the fire reached the astronauts. At 6:31:04 p.m., a crew member (an audio analysis is inconclusive as to the identity) shouted: “Hey!” or “Fire!” At 6:31:06 p.m., Chaffee reported: “We’ve got a fire in the cockpit.” White struggled to open the main hatch while Grissom, blocked by a wall of flames, tried to reach the emergency cabin pressure vent valve. To prevent the hatch from accidentally opening upon splash-down, the hatch had been redesigned with no explosive bolts to blow it open. As the fire burned, pressure inside the cabin increased, sealing the plug door tighter and tighter. At 6:31:13 p.m., a badly garbled voice (believed to be White’s) shouted: “We’ve got a bad fire. . . . Let’s get out . . . We’re burning up,” followed by a prolonged scream of pain.⁵ At 6:31:19 p.m., the interior pressure reached 29 psi and burst the inner wall of the CM, allowing ambient air into the cabin. All transmissions of voice and data from the spacecraft terminated by 6:31:22, three seconds after the CM’s inner wall burst. A secondary fire broke out as flammable materials inside the cabin (i.e., polyethylene tubing, VELCRO netting, nylon suits, etc.) burned (Fig. 2).



Fig. 2. The badly charred interior of the AS-204 Command Module in the aftermath of the fire. (Photo courtesy of NASA).³

By roughly 6:36 p.m., ground controllers opened the hatch—only five minutes had elapsed since the first report of a fire. Smoke and lethal gases from the fire had asphyxiated the astronauts. The nylon outer covering of the astronauts’ space suits and life-support hoses were melted and their bodies were fused to the interior of the cockpit. Seven and a half hours after the fire, the bodies were removed. Autopsies confirmed that all three crewmen died from carbon monoxide poisoning, resulting in cerebral hypoxia and cardiac arrest. Burns suffered by the crew were not believed to have contributed to their deaths as they occurred postmortem. Details of the fire are provided in our supplemental material (see the online appendix for details).^{2,3} Finally, a number of multimedia resources are available to portray events to students in the classroom. For example, the episode “Apollo 1,” from the 12-part 1998 HBO docudrama miniseries “From the Earth to the Moon,” does a fantastic job dramatizing the Apollo 1 tragedy and the ensuing Congressional investigation. There is another scene, “This is what we did instead of sleep,” that exemplifies the fast-paced “go fever” mindset that plagued the mission.^{6,7}

Apollo 1 in the physics laboratory

In our prior work, we investigated how fabrics burn vertically after the source of ignition is removed. The activity was modeled after ASTM D 6413-99—The Standard Test Method for Flame Resistance of Textiles (Vertical Test), which has been adopted as an accepted Federal Test Standard.^{1,8} We now add a horizontal flame test to our repertoire of laboratory activities. This test is modeled after EPA Method 1030—Ignitability of Solids.⁹ Although the method is used primarily to test pastes, granular materials, and powdery substances, it works on any solid material that can be cut into strips. Since the procedures for the vertical flame test were already described in our previous publication, we now describe only the procedures for the horizontal flame test yet report results for both orientations.¹ Also, since English units are used in the ASTM protocols, we also use English units in our analysis. The equipment and materials needed to run this activity cost under \$30 and were readily obtained from local hardware and

fabric stores. We piloted our activity on a cohort of undergraduate students.

• **Sample preparation:** We purchased a ceramic plate (24 in×6 in×5/16 in) at a local hardware store. Using a permanent marker, we drew two lines, 4.0 in apart, centered on the plate. The burn rate of samples would be measured between these two lines. Several combustible materials were factors in the Apollo 1 fire; however, polyethylene tubing and VELCRO (both hook and loop sides) were the primary culprits and thus formed the basis of our laboratory exercise. We made no attempt to purchase fabrics or tubing with the exact specifications of those aboard Apollo 1. Instead, we chose to test the readily available modern-day versions of these materials. We are aware that the materials manufactured today are different from those aboard Apollo 1, especially since flame-retardant technologies have dramatically evolved over the last 50 years. With this in mind, we next purchased polyethylene wire covering that we rolled flat and swatches of VELCRO hooks and loops that we ironed flat. These three materials were then distributed to students who trimmed them into five 12-in-×-3-in strips and weighed each strip (the weight of each sample is only needed for the vertical burn test). Each strip was placed into a frame of sheet metal that secured the strip on its two long sides, leaving its two short edges exposed. The strips were clamped to the frame at four locations with simple binder clips. Using this sample preparation technique allows students to test samples in either the horizontal or vertical orientations.

• **Testing and results:** We placed the ceramic plate on the floor of a safety hood. We then set the metal frame 1 in over the center of the plate by balancing the corners of the frame on stacks of 2-in-×-2-in ceramic tiles [Fig. 3(a)]. We oriented the long axis of the frame perpendicular to the airflow of the safety hood, which was held at 0.7 to 1 m/s, and took precautions to minimize drafts in the hood. To enhance the filming of flames, we dimmed the lights and placed a black poster inside the hood to serve as a background. We made no attempt to control ambient temperature nor to create an oxygen-rich pressured atmosphere. Each of the three samples was tested five times and the average was reported per sample. In agreement with the literature, our burn rates were repeatable to within 10%.⁹ A Bunsen burner, with 10-mm inside diameter barrel, was used to create a 1.5-in high, 99%-pure methane flame. The burner could be swiveled so that the tip of the flame was brought to the exposed edge of the sample. The flame was applied for 12 ± 0.5 s (flame to strip), as measured by a stopwatch. Note that EPA Method 1030 (horizontal flame test) recommends that the flame be applied for 2 min, while ASTM D 6413-99 (vertical flame test) recommends that the flame be applied for only 12 s. In order to present students with a uniform testing procedure, we adopted the 12-s application for both types of test. Also, beware that many synthetic materials are prone to “sputtering”—a phenomenon whereby burning particles of fabric are sporadically ejected several inches from the propagating flame front. Although fascinating

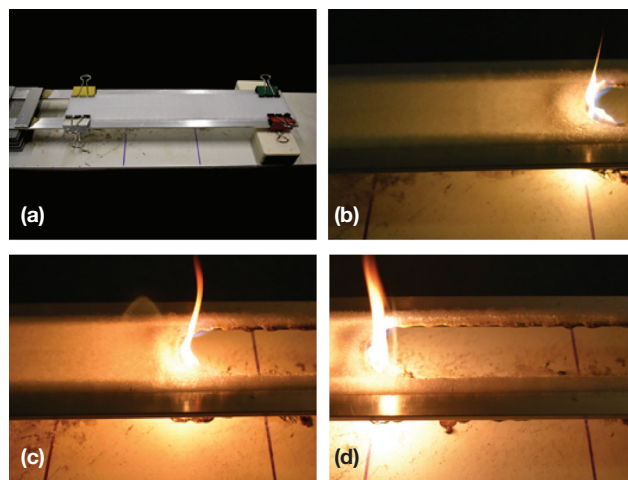


Fig. 3. Our apparatus for horizontal flame testing. (a) Start of test. (b) A flame front crosses the beginning of the 4-in testing zone. (c) A flame front propagates across the 4-in testing zone. (d) A flame front crosses the end of the 4-in testing zone.

to observe, sputtering can be especially problematic during the vertical flame test, so be sure that the students completely close the window to the safety hood once they remove the flame from the sample. Students filmed each trial using cell phone cameras in slow-motion mode. Once the flame was removed, students continued to film the strip until any visual flame or glow self-extinguished [Fig. 3(b), (c), and (d)]. These videos are used to determine the duration of time, to 0.1-s resolution, that the samples needed to burn across the 4-in distance marked by the permanent lines on the ceramic plate. Any signs of melting, dripping, or sputtering were noted.

As students conduct their trials, the propagation of flames, accompanied by the sputtering, dripping, and melting of fabrics and tubing, is striking to see. Even in the absence of a pressurized oxygen environment, students dramatically observe the highly dangerous conditions that must have consumed the interior of the Apollo 1 cockpit! Table I shows data from a typical run of our activity. Data from the horizontal flame tests indicate that without the pressurized oxygen environment, a fire consuming pure polyethylene or VELCRO as its fuel would need 40 to 90 min to travel a distance equal to the diameter of the CM. In the case of the vertical flame tests, such a fire would need 15 to 25 min to propagate a distance equal to the height of the CM. Thus, regardless of orientation, the samples do not burn at fast enough rates to consume a ship the size of an Apollo CM in the timeframe observed during the Apollo 1 fire (i.e., half a minute). Students in our cohort quickly realized that the atmospheric burn rates of these materials are much slower than those observed inside the capsule, demonstrating that the pressurized pure oxygen environment dramatically changed the flammability of the interior fabrics and was critical to the rapid spread of the fire inside the capsule. In fact, literature indicates that polyethylene and VELCRO burn over twice as fast in oxygen at a pressure of 16.5 psi than at 5 psi. Therefore, before the inner wall of the CM ruptured, the primary fuels for the fire burned more than twice as fast as they did under the conditions for which they were evaluated.¹⁰ Even more incredibly, transcripts from

a Senate hearing indicate that the polyethylene and VELCRO inside Apollo 1 may have even burned at a rate of 2.5 in/s, which would have indeed consumed a ship the size of an Apollo CM in under a minute.¹¹ In short, the pressurized oxygen atmosphere made almost every material inside the cabin, even materials not normally considered highly flammable, prone to burst into flames when given a spark. Finally, we discuss with students that three phenomena would have increased the spread

rate of the fire in the capsule over that measured in small scale propagation studies similar to our laboratory activities: convection currents generated by the fire itself; dripping of burning materials resulting in a liquefied molten stream that spreads the fire; and sputtering of burning materials that projects burning particles several inches from their origin.

Conclusions

A compelling case can be made for bringing the anniversary of the Apollo 1 fire into the introductory physics classroom. First, the physics of flammability can be treated appropriately at the introductory level since only careful measurements of time, distance, and weight are needed. Second, the case study is interdisciplinary. While we piloted this case study in a science education class, it may also be useful in introductory engineering classes, senior engineering ethics classes, and fiber science classes. The fire can even serve as the basis of a senior-level capstone project. Next, the resulting analysis provides instructors with several “teachable moments”—it brings real-world applications of physics to the classroom; it shows how standardized testing protocols are used; and it demonstrates to students (perhaps for the first time) the field of failure analysis and how a cascade of unlikely events can result in an unpredictable catastrophe. Indeed, far from being a set of agreed upon immutable facts, the historical record is a living, changing thing and is open to revisitation, reexamination, and reinterpretation. However, an interview conducted by Gus Grissom a few weeks before his death provides perhaps the best reason for sharing this case study with our students. During the interview, Grissom was asked about the dangers of spaceflight. He replied: “If we die, we want people to accept it. We’re in a risky business, and we hope that if anything happens to us it will not delay the program. The conquest of space is worth the risk of life.”¹³ Thus, bringing the Apollo 1 fire to the introductory physics classroom uniquely raises the historical awareness of our students by vividly portraying the heroic efforts of those individuals involved in the early days of the exploration of space.

Table I. Horizontal and vertical flame test results.

Samples	Weight per area ($\times 10^{-3}$)	Dripping or melting	Sputtering	Horizontal orientation			Vertical orientation				
				Burn time (over 4-in path)	Burn rate	Burn time*	Afterflame †	Afterglow †	Char length †	Burn rate	Burn time*
	lbs/in ²			s	in/s	min	s	s	in	in/s	min
VELCRO (Hook)	1.13	Yes	Yes	66	0.06	41.4	89	120	12	0.14	16.5
VELCRO (Loop)	1.10	Yes	Yes	79	0.05	49.5	78	139	12	0.15	14.5
Polyethylene	1.31	Yes	Yes	140	0.03	87.8	133	190	12	0.09	24.7

*Burn times were extrapolated to the appropriate dimensions of the Apollo CM—a conically shaped capsule that was 11 ft, 1.5 in high; 12 ft, 6.5 in in diameter; and had approximately 210 ft³ of habitable space.¹²

†These terms were described in our prior work.¹

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