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Explorations in Hybrid Rocket Technology: Arc-Track Ignition in 3D-Printed Rockets

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Abstract

A new rocket ignition mechanism developed at Utah State University, arc-track ignition, is very promising, but its underlying physics are poorly understood. An engineering/physics joint team was formed to investigate the process and suggest avenues for improvement of the technology. The objectives of the team evolved over the course of seven months of research. By the nature of this approach, understanding was extended in many ways, but few results were conclusive.

Two accomplishments overshadow the others: the discovery of a new arc-track ignition method, and cataloguing of materials compatible with arc-track ignition technology. Thin film arc-track ignition has the promise of reducing energy needs many-fold and increasing the range of materials compatible with arc-track ignition. The material properties database will enable organizations to determine which materials they should use in constructing their own arc-ignition systems, based on their facilities' capabilities.

I. Introduction

Historically, two types of rocket technologies have been used almost exclusively, the liquid and solid rocket engine. Both technologies are still used, often in the same applications. There are fundamental trade-offs between the two designs that define much of contemporary rocket science. The hybrid rocket is a class of rocket with desirable characteristics of both designs. In practice, hybrid rockets have fallen short of this goal and remain virtually unused in modern rocketry.

Briefly, the two major classes of rocket: In a solid rocket engine (see Figure 1) the fuel and oxidizing agent are both solids. They're mixed together and packed into the body of the rocket. Upon ignition, the rocket burns until it runs out of fuel/oxidizer mixture. Solid rockets are simple, space-efficient (there are no extra parts in a solid rocket), inherently unstable (the fuel and oxidizer are mixed and ready to detonate), and single-use. In a liquid rocket engine (see Figure 2) the fuel and oxidizer are liquids kept in separate tanks. To ignite the rocket the two liquids are pumped from their tanks to a reaction chamber and ignited. This added complexity (and weight!) makes liquid rocket engines more stable and safe than solid rockets and grants them the ability to turn off the engine and restart it at will. To perform fine maneuvering such capabilities are essential.

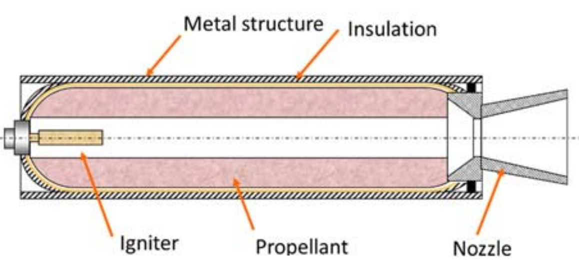

Figure 1: Basic solid rocket design

In hybrid rockets (see Figure 3) the fuel is of one phase and the oxidizer is of another. The reactants are separated, granting them the stability and restartability of liquid rockets, but with less complexity and extra weight, because only one fluid (hybrid rockets often use a gaseous phase oxidizer) has to be moved around, rather than two. True restartability has proven to be very difficult to achieve and has been the subject of a great deal of research.

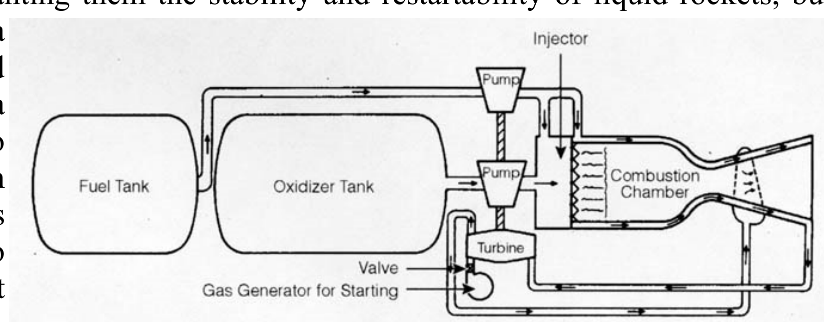

Figure 2: Basic liquid rocket design

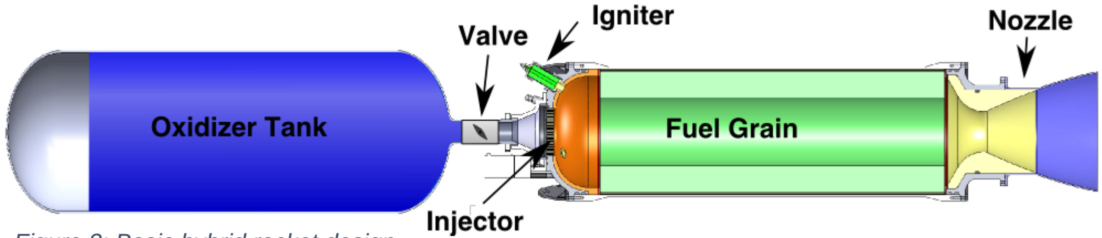

Figure 3: Basic hybrid rocket design

While characterizing the performance of fused deposition modeled (FDM-processed, or 3D-printed) acrylonitrile-butadiene-styrene (ABS) as a potential replacement for conventional hybrid rocket fuels,[1] Whitmore, et al. discovered that the material had unusual electrical breakdown characteristics. When heated by an electrical arc, the surface of FDM-processed ABS is visibly and chemically altered such that it becomes sufficiently conductive to channel a high-voltage, low-amp current, rather than allowing electrical breakdown of the air along its length. In the process of its formation, the arc-track (the region affected by the arc) experiences intense resistive heating, which causes fuel pyrolysis, emitting hot, highly combustible gasses. Combustion occurs when this pyrolysis occurs simultaneously with the introduction of an oxidizing flow. After its formation, only a comparatively small voltage across the arc-track is necessary to cause pyrolysis. The researchers theorized that the arc-track forms because they layered structure of the printed material allows minute electrical charges to concentrate between material layers, drawing the arc to the surface of the material.

The discovery of FDM-processed ABS' unique electrical breakdown characteristics prompted the development of a novel ignition system that takes advantage of the previously described arc track phenomenon. The system has been successfully demonstrated using both gaseous oxygen (GOX)[2] and Nitrous Oxide (N2O)[3] as oxidizers. The arc-ignition system had been developed to an intermediate degree of maturity, with successful prototype systems having thrust levels varying from 5 N to greater than 800 N. Each system demonstrated the capability for multiple on-demand restarts.[4]

In the open-air arc-tracking design used in these systems, two small electrodes are inserted into the top of a printed fuel grain, and metallic conduction paths are routed to "shelves" on opposite ends of the fuel grain (see Figure 4). These shelves stagnate and concentrate the incoming oxidizer flow, increasing local oxidizer concentration, leading to more reliable system ignition. The conducting paths terminate in electrodes flush with the combustion port surface and exposed to the interior of the combustion chamber. When the electrodes are powered electricity flows through a pre-existing arc-track, resulting in pyrolysis and ignition, or an arc forms through the air (or the oxidizing gas, if it is flowing), if there is not yet an arc-track.

Arc-track ignition, and this design in particular, was demonstrably sound, but lacked a fundamental theoretical basis. As repeated studies[5,6] showed, arc-track generation is a

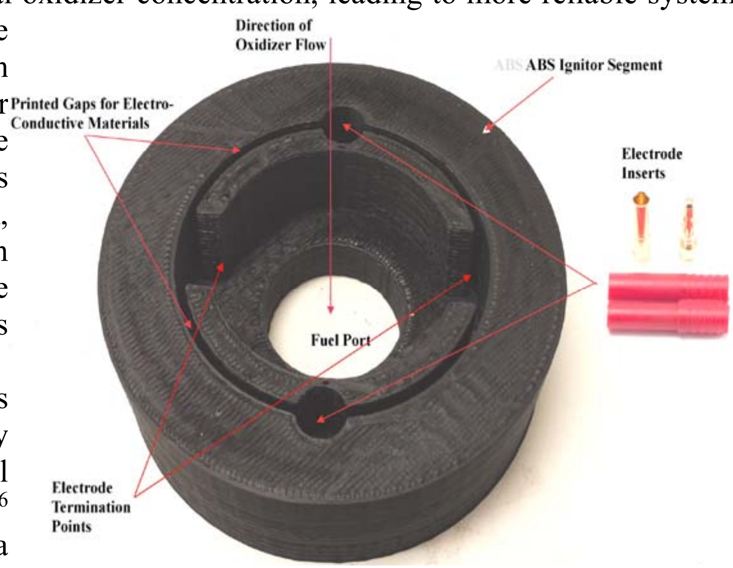

Figure 4: Open-air arc-track ignition system

complex and unruly phenomenon. Some materials never develop a conductive arc-track. ABS doesn't form conductive arc tracks unless it is printed, and the orientation of the arc to the layers of the printed grain has a distinct effect on ignition reliability. In materials that form arc-tracks, the elapsed time to form a track is highly variable. Candidates for arc-track ignition must be printable with FDM technology (as consistent arcing was not achievable with non-printed materials), strong insulators (to enable open-air arc formation at their surface), respond to electrical arcs by breaking down into a less-insulative arc-track, and have sufficient chemical potential energy to be a rocket fuel.

Additional concerns arose from the necessity of arcs in arc-tracking. Electrical arcs emit a great deal of potential interference and charged particles, both of which could compromise nearby electronic devices. This joint physics/aerospace engineering project was formed to develop a model of the electrical and chemical processes of arc-tracking, suggest possible avenues of improvement, and search for new fuel candidates.

Figure 5: Conductive arc-track in wood

II. Methods: A Brief History of Our Research

Due to the highly exploratory nature of overarching objective, our vision for what we could accomplish and our short-term research direction changed many times throughout the research period. This "Methods" section catalogs these changes, along with brief descriptions of the intermediate results which precipitated them. An overview of this evolution follows.

Our focus turned first to the electrical features of open-air arc-tracking in 3D-printed ABS. We developed a three-fold approach to our research: analysis and cataloguing of the electrical properties of ABS, research and testing theories about arc-tracking behavior, and developing a new design that had improved ignition characteristics. Shortly after beginning the project, we added the objective of researching the possibility of using other 3D-printed materials in arc-track ignition systems. Near the end of the research period, we discovered a new arc-tracking ignition method that may eliminate the need for open-air arcs, resolving concerns about potential damage to sensitive onboard electronic components. Because of its potential as a revolutionary innovation, it took priority over most tasks during the final stages of research.

Our first task, analysis of ABS' electrical properties, emphasized printed and solid ABS' different responses to arc exposure. The first property we investigated was resistivity of ABS over a range of voltages (0 to 8 kV), in a range of forms (solid, and printed with a variety of densities), and with different sample/air geometries (the degree to which the most direct path between the electrodes was open to the air). Samples were printed and current-voltage relationships were tracked to determine sample resistance (and, by extension, the material's resistivity) across a large voltage region. Preliminary tests showed resistivities were greater than 100 Gohm/cm, larger than our instruments could reliably measure. We developed a voltage-divider circuit to improve our devices' precision and determined that resistivities were upward of 50 Tohm/cm, still beyond our increased ability to measure. We also observed that arcs would not form *through* the ABS. If there was no short open-air path between the electrodes, the ABS acted as a simple dielectric through the entire voltage range. This demonstrated that arc-track formation could not occur without an open-air arc, which excludes track-first theories of arc-tracking (in which material breakdown occurs before and precipitates arc formation).

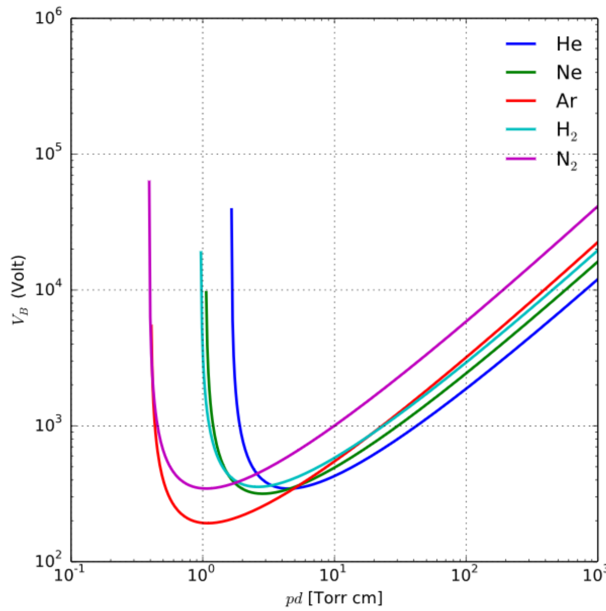

Figure 6: "Paschen curves," showing the relationship between breakdown voltage and the distance-pressure product for five pure gases.

As we approached the voltage at which our voltage divider circuit would melt, we turned to the literature to learn about arc formation. Electrical breakdown of gases into plasma is described by Paschen's law[7], which determines the minimum voltage required to ionize a plasma path in a body of gas (the breakdown voltage) as a function of pressure and distance between the electrodes held at the breakdown voltage. The function has two regions with wildly different behavior (see Figure 6). For appreciable lengths and pressures (more than one centimeter and/or one atmosphere) the breakdown voltage is effectively proportional to the product of the pressure and inter-electrode length. Equivalently, for a given pressure there is a critical electric field strength that will ionize the ambient gas. In the second region, that of low distance-pressure products (around 1 torr*centimeter), the necessary inter-electrode voltage asymptotically approaches infinity. Therefore, at a given pressure there is a minimum distance, below which an electrical arc cannot form, and other electrical phenomena begin to dominate.

Our theoretical starting point was that the printed surface had an essential role in arc formation; something about the layered structure caused the arc to form at its surface and allowed the arc to "move into" the material in the process of arc-tracking. Paschen's law disproved all justifying theories for this process that we could imagine.

The repetitive structure of the surface could, by subdividing the length into smaller lengths, potentiate arcing between peaks on the surface. However, these sub-lengths were within the linear range of Paschen's law, in which only electric field strength matters for arc formation. The electric field is constant across the region, so smaller arcs would be no more probable than large arcs. In a related theory, we considered that small air pockets *inside* (rather than on the surface) the fuel grain may ionize before a large arc would be able to form. This is prohibited by the same line of reasoning as earlier in the case of large air pockets, and in the case of small air pockets, arc will not form at all.

In light Paschen's law and ABS' extremely high resistivity and resistance to electrical breakdown, we abandoned our track-first theories, and adopted an arc-first theory of open-air arc-tracking. In this model, a pre-existing arc occurring near a sample's surface changes a small region of the surface into a conductive char, which then begins conducting electricity better than the arc. The arc reconfigures to take advantage of this conductive region, creating smaller arcs terminating on the ends of the conductive region. Consequently, these arcs are drawn toward the surface that the conductive region is a part of. The layered structure of printed ABS enhances this char formation, perhaps through impeding thermal flow away from the charring region or increasing the surface area exposed to the arc.

Upon developing this reasonably compelling (though obviously incomplete) theory of open-air arc-track formation, we turned to the question of whether there are other 3D-printable materials that could be reasonably used as rocket fuel. Initially, our intention was to print samples from many different materials and measure relevant material properties ourselves. However, many printable materials require equipment significantly more advanced than that which was available to us, forcing us to take a more theoretical approach to our feasibility research.

Material selection for feasibility research was driven primarily by whether the material is currently used in FDM applications. Essentially all materials used in FDM are thermoplastics: hydrocarbon polymers that are solid at normal temperatures and, when heated, become malleable before they combust. Materials suited for our application need to be energy-dense (that's the point of rocket fuel), structurally suitable, and "sparkable"—ignitable with arc-track ignition technology. The structural properties of thermoplastics are well-documented; nearly all applications of thermoplastics hinge on their structural characteristics. The other two considerations were not so simple to look up.

"Energy density" is not a simple property. Fortunately, it is a very valuable property to quantify, and much of rocket science is devoted to this type of question. Of particular value is the quantity "characteristic velocity" (C*), essentially the exhaust velocity that a particular engine design/fuel combination is capable of sustaining. From Newton's third law ("an equal and opposite reaction"), it is clearly seen that high-velocity exhaust translates to a high-efficiency engine. NASA has free software to calculate the C* of rocket fuels, given parameters about the engine design and the chemical properties of the fuel. What we are interested in is the maximum effective C* for a fuel candidate, given basic assumptions about the range of possible engine designs. My role in this process was studying polymer chemistry and finding values for the relevant chemical properties of our material candidates, the chemical formulae and their "enthalpies of formation," the energy required to form the material from its constituent elements in their most stable form (at standard temperature and pressure). Given this information, my partner can determine what engine design gives the highest possible C* for a material. The general result is that compounds high in nitrogen and hydrogen have high potential yields, and materials high in oxygen have low potential yields.

Sparkability is the hardest property to quantify. Essentially no research on arc-track ignition has been done outside of Utah State University. From our earlier research, we had some idea of what properties were important in open-air arc-track ignition. The material has to have a high dielectric strength (breakdown voltage/length) so that the surrounding gas will break down before the material does, or an arc won't be able to form. It needs to form an arc-track when exposed to an arc. It needs to have a high resistivity, so the arc-track will have sufficient current to heat up and cause pyrolysis. Resistivity and dielectric strength are relatively easy to look up for most materials. Arc-track resistance, however, is a less-researched and poorly-quantified property. Much of the latter half of the research period focused on understanding and quantifying arc-track formation.

In the course of our investigations, we concluded that the arc-tracks are composed of a thin char layer with a very high carbon content. We reasoned that adding carbon (in the form of graphite powder) to a thermoplastic could improve its arc-track formation qualities. Results were mixed. The resistivity of ABS doped with carbon, even at very low concentrations (one part carbon to two hundred parts ABS), fell by a factor of 10^{10} or more. The low resistance would make it impossible to maintain a high enough voltage across the electrodes to generate an arc, making open-air arc-track ignition impossible. It may be that far lower concentrations of carbon powder do not reduce the resistivity so drastically, but such low concentrations would almost certainly confer no benefit to arc-track formation.

Carbon-doped ABS is probably useless for open-air arc-track ignition, but we made a very exciting discovery during our experiments with the material. Thin films of the material will spontaneously form arc-tracks when exposed to moderately low voltages, around 200 volts, as contrasted with the 10,000 volts necessary to establish an open-air arc. The material exhibits this property in a highly consistent fashion. This thin film arc-tracking behavior may be able to replace the inconsistent and complicated open-air arc-tracking ignition system. Our current research aims to determine whether the material follows traditional laws of electrical breakdown, whether its properties are consistent between samples, and if it has repeat-firing potential as great as that of open-air arc-track ignition.

III. Results

Our most exciting result is almost certainly the new thin film arc-track ignition mechanism. If it can replicate the performance of open-air arc-track ignition, it will probably be able to do so at much lower voltages, reducing the size of on-board electrical systems. The lack of an electrical arc also reduces the risk of the ignition system damaging on-board electronics. The thin film ignition method can form arc-tracks on solid ABS, a feat not achieved with the open-air arc system.

We collected a database of the properties of many FDM-compatible materials. This database will allow organizations of all scales, from hobbyists to NASA, to determine which materials are best to meet the particular design challenges of their projects. After developing the thin film ignition system, we will incorporate any additional properties necessary to help organizations choose between open-air arc-track and thin film arc-track ignition systems.

IV. Future Research

Thin film arc-track ignition has great promise, and a long way to go before it is ready for wide deployment. The heterogeneity of plastic/graphite mixes may give rise to atypical resistivity characteristics. Carbon-doping may work for many different materials, or it may only be feasible in an ABS matrix. If ABS is an integral part of thin film arc-track ignition, can this ignition mechanism be used with non-ABS fuel? Repeatable ignition is a serious concern. If the thin film is damaged in the first firing, can the rocket fire again?

We have a database of good fuel candidates and a well-developed ignition system. Open-air arc-track ignition needs to be tested for suitability with other promising fuels, such as polyethylene and polypropylene.

Printed ABS responds to open-air arcs very differently than does solid ABS. We have a number of hypotheses to explain this performance difference, but no real data to support them. A good explanation could suggest printing methods that confer significant performance gains.

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