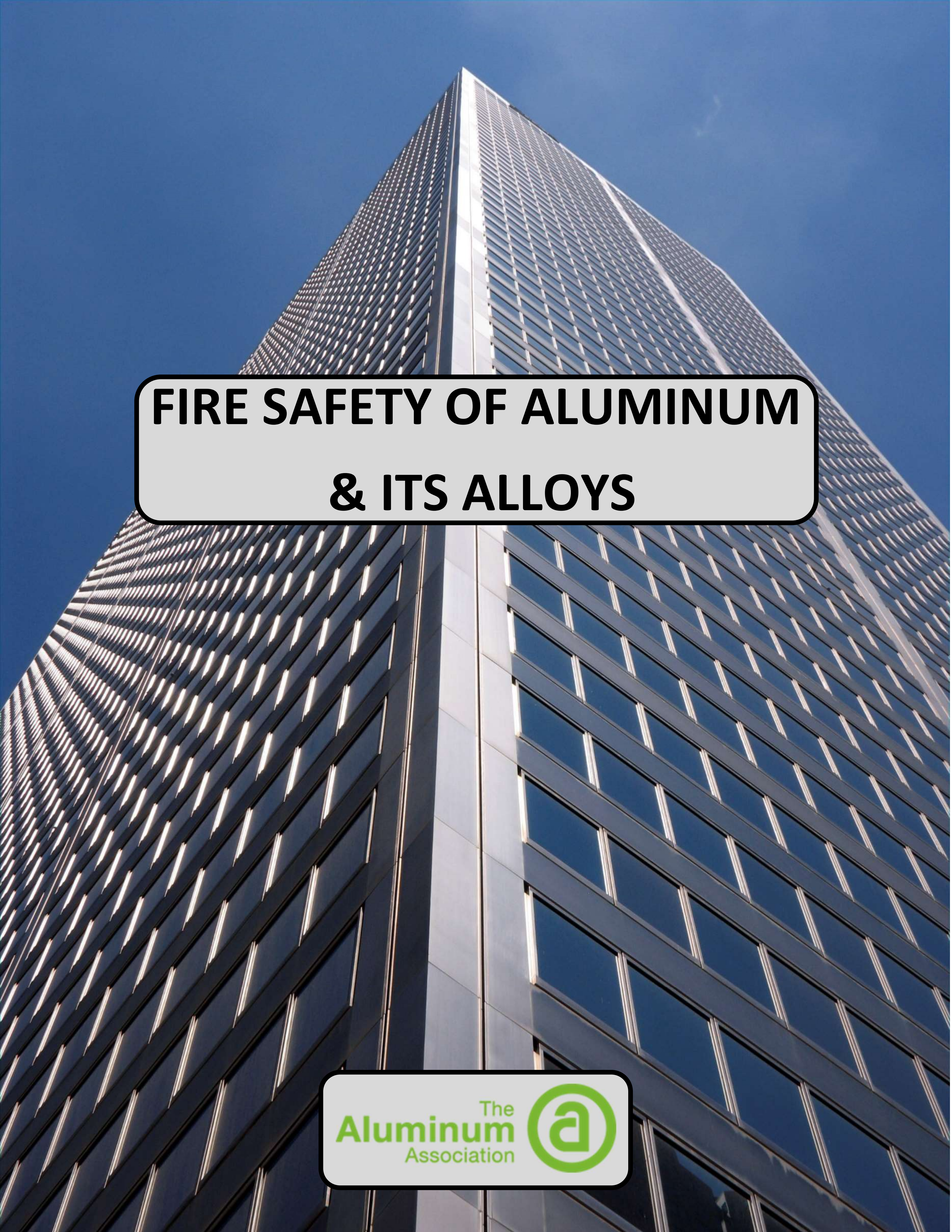

FIRE SAFETY OF ALUMINUM & ITS ALLOYS

The Aluminum Association

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Introduction

As one of the most abundant elements on Earth, aluminum can be found in nearly every industry in our modern world. It is light, inexpensive, and easy to work with, making it ideal for a wide variety of applications ranging from electronics and machinery to aircraft structures and tableware. Aluminum is easily combined with several different elements to produce hundreds of alloys with a dizzying array of properties, making aluminum one of the most versatile materials in industry. Depending on the alloying elements, it can be soft and malleable, or exceedingly strong and rigid. It is also prized for its excellent thermal and electrical properties as well as corrosion resistance.

As aluminum is increasingly used in construction, concerns have arisen regarding its potential combustibility, usually fueled by media reports and speculation. These perceptions are mistaken and are often the result of rushed judgements by individuals unfamiliar with the relevant science. Unfortunately, this has resulted in erroneous information spreading among both the general public and professional circles to the point where the notion that aluminum burns has become a sort of mistaken common knowledge that is more often than not taken for granted without due reference or investigation. This paper aims to provide the reader with scientifically backed information dispelling this misconception within the context of building construction, though the information presented herein may certainly be of use in other contexts.

Properties of Aluminum

Aluminum as a material has a number of properties relevant to its behavior in a fire. Unalloyed aluminum will melt at around 660°C, or 1220°F, but most of its alloys will begin to lose strength at temperatures above 150°C, or 300°F. These relatively low numbers may at first raise concerns about aluminum's performance at high temperatures, but aluminum's high specific heat, thermal conductivity, and reflectivity all help to give the metal some interesting characteristics and make it viable for construction applications.

The specific heat of a material, also referred to as the specific heat capacity, is the amount of heat energy required to raise the temperature of that material by one unit. This is calculated by dividing the required energy at a unit of temperature by the mass of the material. The specific heat of aluminum alloys ranges from 816 to 1050 J/(kg·K) in SI units, or 0.195 to 0.258 Btu/(lb·°F). This is approximately twice that of steel, meaning that a given mass of aluminum will take twice as much energy to heat up by one degree as the same mass of steel. Put another way, aluminum furniture and structural elements will take twice as long to heat up as an equivalent mass of steel, the material to last longer before it loses its strength or melts.

The thermal conductivity of a material is a measure of its ability to transfer heat. For aluminum alloys, this ranges from 88 to 251 W/(m·K) or 51 to 164 Btu(h·ft·°F), 3-6 times higher than normal steel and 10-17 times higher than stainless steel. The advantages this provides include the ability to remove heat from a source area and distribute it to the rest of the material. This slows the rate at which the entire mass heats up while also allowing some of the heat to radiate off the material due to it being spread out across a larger surface area. This can even allow sufficiently large aluminum structures to act as a heat sink by moving heat away from a fire and slow the buildup of heat, allowing both the aluminum and other objects or structures in contact with it to last longer in a blaze.

Lastly, aluminum benefits from having a relatively high reflectivity. A bare aluminum surface will reflect 80-90 percent of heat radiation, many times more than steel, meaning that only a fraction of radiated heat will actually be transferred to the aluminum. This property alone significantly lengthens the amount of time aluminum can withstand high temperatures when not in direct contact with a source of heat, and even more so when combined with the aforementioned properties.

Each of these properties alone increase the reliability of aluminum in a fire, but together they greatly mitigate the drawbacks of its relatively low melting point by increasing the time it takes the material to reach that melting point, all while allowing designers to take advantage of its utilitarian benefits to better manage heat, intentional or otherwise.

Aluminum at High Temperatures

Due to these properties, certain aluminum alloys are currently used in high temperature applications where the material is either able to maintain strength at the given operating temperatures, or it is able to reliably recover from exceeding the temperature threshold at which it would normally lose strength. An excellent example of this is the use of aluminum in high-performance engine parts such as pistons, which are exposed to high temperatures and pressures but then cool quickly by conducting the heat to the cylinder walls and into the oil at the bottom of the piston. Closer to home, aluminum is an increasingly common material found in cookware that comes in direct contact with flames or conductive heating elements. None of these applications would be possible if aluminum burned.

Additionally, aluminum is regularly melted and remelted during the recycling process. Aluminum is famously recyclable, and all manner of aluminum products which include the metal in various forms, thicknesses, and treatments are melted down to be recast. It is common for a given batch of aluminum to have multiple lifetimes as part of several different products which have been recycled. Once again, none of this would be possible if aluminum were a combustible material, as the extreme temperatures involved would be bound to ignite it. The same is true for the very processes that extract aluminum from bauxite ore in the first place.

The only exception to this is when aluminum is in powdered form. Most metals will oxidize rapidly or burn when finely divided into a powder, and aluminum is no different. Aluminum powder is an ingredient in solid rocket motors used in space launch vehicles and missiles, as well as a prominent component of thermite. In all of these cases, it is important to note that the aluminum is not burning on its own or with the atmosphere; rather, it is undergoing a chemical reaction with an oxidizer with which it is mixed. Pure aluminum powder, no matter how fine, will not ignite in air at any temperature. In the case of thermite, the most common oxidizer used is iron oxide, commonly known as rust. Neither rust nor the steel it comes from will burn on their own unless they are chemically reacting with something else, or they are supplied with extremely high levels of oxygen and have a very high surface area (steel wool is a good example of this, especially when used for light painting by quickly swinging a burning clump of it on a string in the dark). Aluminum is a common ingredient in thermite not only because of its low cost, but because it makes the resulting mixture slightly safer to handle than some alternatives. Even aluminum foil does not have a sufficient surface area to volume ratio to burn in air and will simply melt like solid bulk aluminum.

A separate safety consideration concerns the possibility of rust particles reacting with aluminum slivers or powder when uncoated aluminum is struck by rusty steel, such as a nail. Both materials in isolation present no problems, but if the two are mixed in finely divided form, such as the particles formed from an impact or gouge, there is a slight possibility of inadvertently creating a minute amount of thermite which may in turn ignite from the heat generated by the impact. There is no risk of a reaction with the rest of the solid aluminum, or the rusty steel for that matter, but it may pose a risk if other combustible material is present. This is a very specific niche issue but has been a documented concern in certain high-risk environments, such as oil rigs. The simplest way to avoid this scenario is to apply a coat of paint to exposed aluminum if the presence of rusty objects is expected and cannot be avoided.(1)

The takeaway from these examples is that all metals and other seemingly safe materials such as wheat flour, sugar, non-dairy creamer, or polyethylene plastic will burn rapidly as a powder under the right circumstances, but that those conditions are extreme and not applicable to the standard form of those metals. Apart from aluminum, other metals frequently used in thermites include iron, copper, and lead, none of which are combustible in normal form. That metals have a melting point is common knowledge, but the public rarely considers that metals can also boil and vaporize because the conditions and temperatures required are so extreme as to be irrelevant for the vast majority of applications.

Origins of Common Misconceptions

Misinformation surrounding aluminum's combustibility is persistent and their origins deserve to be addressed. Over the years, several highly-publicized events contributed to the erroneous belief that aluminum burns, mainly due to a lack of understanding of the events themselves.

Beginning in the 1960s, aluminum was used as a substitute for copper for electrical wiring in residential construction. Aluminum had long been used in long-distance transmission lines, as it continues to be today due to its low weight and cost combined with excellent electrical conduction, however the new application presented a change for electricians used to working with copper wiring. Unsurprisingly, the two metals have a number of differences in their respective material properties, especially with regards to their coefficients of thermal expansion. As it undergoes changes in temperature, aluminum will expand and contract more than copper does. This has a tendency to loosen connections that are not made with this in mind, and all too often electricians would install aluminum wiring with end connectors designed for use with copper wire. Electrical fires start when certain components get too hot and ignite flammable material they are in contact with, such as plastic insulation around wires or plastic elements in the connectors. This heat can result when the contact area of a connection is too small for the amount of current flowing through it, and the electrical resistance of the material causes it to heat up. When a connection is loosened by the wire repeatedly expanding and contracting, only part of the wire is touching the connector, meaning that the current it is carrying has a fraction of the contact area through which to travel, resulting in a buildup of heat.

Another way this can happen is if the connection uses two dissimilar metals which results in galvanic corrosion, with the same effect.

These problems resulted in a number of house fires in the 1960s and 1970s, and both electricians and the general public became convinced that the aluminum itself was catching fire. The aluminum industry responded with more information and training for technicians and the development of new alloys that wouldn't expand or contract as much with temperature changes, making them easier to install. Unfortunately, the damage was done and public opinion has remain stubbornly skeptical of aluminum wiring ever since.

Several naval incidents involving ships from the US Navy and Royal Navy also contributed to fears surrounding aluminum. The most famous of these is the sinking of the British guided-missile destroyer HMS *Sheffield* during the Falklands War in May, 1982. The ship was hit by an Argentine Exocet missile which detonated inside the ship where its warhead and remaining solid rocket fuel caused extensive damage and started a fire. The crew was unable to effectively fight the fire as the ship's electrical systems and sea water fire main were damaged by the impact and explosion, and eventually abandoned the ship. The *Sheffield* sank several days later while being towed to South Georgia. Media reports were quick to blame aluminum as a possible contributor to the fire, but these reports were incorrect as the *Sheffield* and her sister ships of the Type 42 class were built entirely from steel. The media confusion stemmed from the presence of aluminum on several earlier U.S. Navy and Royal Navy ships which suffered from fires in the 1970s, despite the fact that both navies determined that the use of aluminum in the ships' designs had nothing to do with their loss. In all of those cases, certain aluminum components such as ladders and part of the superstructure had melted in the extreme temperatures but did not combust or otherwise contribute to the fires.

Similar confusion surrounded the use of aluminum in some military vehicles and civilian cars. When they were lost to enemy fire, ammunition detonating prematurely or fuel lines being ruptured, the wrecks would be inspected after the fire had gone out. While the steel frames were often damaged from the heat, little or no aluminum could be found. It was sometimes assumed that the aluminum had burned away, but in reality it had merely melted off of the wreck and pooled on the ground below.

More recently, several building fires in the UK and Australia were blamed on aluminum cladding on the buildings' exteriors. In these cases, the cladding consisted of a composite comprised of two layers of aluminum sheet on either side of a polyethylene core. While aluminum is not combustible, polyethylene will burn slowly when exposed to flame. At higher temperatures, it can depolymerize into a vapor which burns violently and can even explode. Furthermore, this cladding was often placed over various types of insulation which also burned when heated. Cavities separating the insulation from the exterior cladding had the unfortunate effect of acting as chimneys, funneling flames and heat upwards to other floors, allowing other sections of polymer insulation and paneling to ignite, while the aluminum cladding shielded the flames from firefighters' water jets. As with the other examples, aluminum would eventually melt in the fires, depending on where it was located, but the metal itself did not combust or add to the fire in any way. This was confirmed in the investigations following each blaze but lagged far behind the initial media reports and accompanying rumors that claimed otherwise.

Verification Through Testing

The Aluminum Association commissioned a series of tests, first in 2011 and then again in 2020, to provide additional scientific data proving that solid bulk aluminum does not burn. The alloys chosen for testing in 2011 were 3003, 5052, 5083 and 6061. These four alloys were selected as they represent alloys in three alloy groups (3XXX, 5XXX, and 6XXX) and are some of the most commonly produced alloys in the industry. The 2020 tests featured five additional aluminum alloys (5005, 6006/6105, 6005A, 6063, and 6351) along with commercially pure aluminum (P1020A). These alloys were selected for their widespread use in construction. Because it is one of the most commonly used aluminum alloys, 6061 was also retested to further substantiate the results.

The National Fire Protection Association (NFPA) defines a noncombustible material as follows:

"A material that complies with any one of the following shall be considered a noncombustible material:

(1) The material, in the form in which it is used, and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat.

(2) The material is reported as passing ASTM E 136, *Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750 Degrees C*.

(3) The material is reported as complying with the pass/fail criteria of ASTM E 136 when tested in accordance with the test method and procedure in ASTM E 2652, *Standard Test Method for Behavior of Materials in a Tube Furnace with a Cone-shaped Airflow Stabilizer, at 750 Degrees C*."

The test method used followed ASTM E136, "Standard Test Method for Assessing Combustibility of Materials Using a Vertical Tube Furnace at 750°C." This is the widely accepted standard for determining the combustibility of building materials, and materials which pass this test meet the NFPA definition of a noncombustible material as described above. This designation is used to comply with applicable building codes and safety standards.

As the name implies, the test consists of placing a sample of the material inside a furnace and heating it to 750°C, or 1382°F. This temperature is maintained either until the sample has failed, or until 30 minutes have passed, whichever occurs first. Thermocouples are used to monitor the temperature inside the furnace to ensure that there is no spike in temperature resulting from the material burning, and the sample is observed to ensure that no flames are present. To ensure the statistical validity of the test, a minimum of four samples are tested, of which at least three must pass. The criteria for passing are as follows:

1. If the sample loses no more than 50% of its weight:
    a. The temperature of the furnace does not rise more than 30°C or 54°F above the stabilized temperature measured before the test begins.
    b. No flaming is observed after the first 30 seconds.

OR

2. If the sample loses more than 50% of its weight:
    a. The temperature of the furnace does not exceed the stabilized temperature measured before the test begins.
    b. No flaming is observed at any time.

The full test method for ASTM E136 can be found here.

All of the alloys tested met the required criteria for passing the test. Full test results for each alloy can be found at www.aluminum.org/safety.

ASTM maintains several other standards relating to the fire safety of building materials that do not apply to aluminum alloys. Two of these which are commonly referenced for other materials and applications are E84 and E2652. E84 is intended to investigate the surface burning behavior of building materials, which presumes that the material is capable of burning in the first place. The scope of the standard therefore notes that it is unsuitable for determining the combustibility or noncombustibility of a material. E2652 is similar to E136 in that it is intended to determine the combustibility of a material, but it is designed around materials with properties that differ from those of aluminum. The scope of the standards states that this particular test "is not suitable or satisfactory for materials that soften, flow, melt, intumesce or otherwise separate from the measuring thermocouple." The test occurs at a temperature of 750°C (1382°F), which is above the melting point of aluminum. This standard is therefore not applicable to aluminum, as the test cannot be properly conducted. E136 has no such issue, which is why it was the standard used above.

Prior to the Association's testing, the Federal Aviation Administration (FAA) conducted its own test to determine the safety of using aluminum-lithium alloys for primary aircraft structures. Aluminum-lithium alloys contain 1 to 3% lithium, which is a highly combustible element, and FAA needed to ensure that its presence would not make the overall alloy combustible. The test was conducted in accordance with the AC 25.856-2A standard, which "provides guidance for the test method to determine burnthrough resistance of thermal/acoustic insulation materials installed in transport category airplanes." Two different 2xxx series aluminum-lithium alloys of varying tempers and thicknesses were tested. With a flame temperature of approximately 982°C (1800°F), there was no question of the test samples making it through without melting, but the test was intended to measure of burn through time to assess how long an aircraft could survive in the case of a catastrophic fire. The results of the test are in the table below:

Material	Thickness	Burn Through Time (minutes)
2024-T3	0.125"	2:08
2198-T8	0.071"	1:52
2198-T8	0.125"	3:10
2198-T8	0.25"	5:45

The results of this test allowed the FAA to certify aluminum alloys as safe for use as both structural and exterior skin materials for transport category aircraft. It should also be noted that the aluminum-lithium did not burn in spite of the product being a thin sheet with a high surface to volume ratio.

Conclusion

Aluminum in solid bulk form will not combust in air, or in any circumstance found in building construction or industrial practices. Popular misconceptions to the contrary are the result of poorly understood incidents in which subsequent investigations have found that aluminum did not contribute to any fire. The various scientific tests used to conclusively determine aluminum's non-combustibility meet the requirements laid out by the applicable government and non-governmental entities tasked with setting and enforcing public safety standards. As such, aluminum is a perfectly safe material to use from a fire safety perspective for all applications for which the use of aluminum was properly considered in the design.

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