DOT/FAA/TC-13/52

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Development of a Laboratory-Scale Flammability Test for Magnesium Alloys Used in Aircraft Seat Construction

Timothy R. Marker

February 2014

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-13/52		

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF A LABORATORY-SCALE FLAMMABILITY TEST FOR MAGNESIUM ALLOYS USED IN AIRCRAFT SEAT CONSTRUCTION	February 2014
	6. Performing Organization Code ANG-E212
7. Author(s) Timothy R. Marker	8. Performing Organization Report No.
9. Performing Organization Name and Address Federal Aviation Administration William J. Hughes Technical Center Airport and Aircraft Research and Development Division Fire Safety Branch Atlantic City International Airport, NJ 08405	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Northwest Mountain Region—Transport Airplane Directorate 1601 Lind Ave., SW Renton, WA 98057	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code ANM-115

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was Timothy R. Marker.

16. Abstract

This report summarizes the research effort undertaken by the Federal Aviation Administration to develop a laboratory-scale flammability test for magnesium alloys used in the fabrication of aircraft seat structure. During the initial phase, a laboratory-scale test rig was constructed to allow flame exposure to various magnesium alloy bars as they were suspended over a small steel pan. An oil-fired burner configured in accordance with Title 14 Code of Federal Regulations Part 25.853(c) Appendix F Part II was used to simulate the fire. Test samples representing a variety of magnesium alloy combinations were evaluated, including two new-generation alloys containing rare earth elements. The test samples were subjected to the burner flames for various durations. In most cases, the alloys melted, depositing pieces of molten material into the catch pan below. Subsequent to the melting event, the materials would typically ignite, emitting an intense light during ignition. Measurements were made of the flaming duration and the amount of material consumed during each test. From the initial tests, it was determined that several rare-earth-containing alloys showed increased flammability resistance when compared to a legacy magnesium alloy, such as AZ31. Two new generation alloy materials, Elektron®WE43 and Elektron®21, self-extinguished shortly after removing the fire source. By comparison, the AZ31 magnesium alloy configurations did not self-extinguish and continued to burn, sometimes until completely consumed.

Subsequent full-scale tests were conducted with a large external fuel fire adjacent to an aircraft fuselage, simulating a severe, but survivable, accident in which the fire entered the cabin through a s imulated fuselage rupture. The tests determined that no significant change to survivability (based on the survivability model) resulted when using seat frames constructed of the new generation WE43 magnesium alloy in the primary components, when compared to identical tests in which the standard aluminum alloys were used. The primary seat frame components included the legs, the cross tubes, and the spreaders. Two types of magnesium alloys were used in separate tests: a well-performing alloy (WE43) and a poor-performing alloy (AZ31).

During the final phase of work, a flammability test for magnesium alloys was developed based on the findings of the realistic full-scale tests. The intent was to expose an appropriately-sized test sample to the flames of an oil-fired burner for a period of time that allowed the test sample to melt, as initial tests had indicated the magnesium alloys would not ignite until melting had occurred. Numerous test sample shapes, sizes, and exposure levels were trialed in an effort to replicate the outcome of the full-scale tests, namely, the amount of time required to melt and ignite a sample and the approximate amount of time required for the sample to self-extinguish. The final configuration used a 0.25-inch-thick by 1.5-inch-wide by 20-inch-long horizontally-oriented bar test sample that was exposed to the oil burner for a period of 4 minutes. A passing sample is not permitted to ignite prior to 2 minutes and must also self-extinguish within 3 minutes of the burner being turned off (7 minutes from the start of the test). In addition, the sample must not lose more than 10% of its initial weight.

17. Key Words	18. Distribution Statement
Magnesium alloy, Rare earth element-containing alloys, WE43, AZ31, Elektron 21, Oil burner, Postcrash, Survivability	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	228	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ACRONYMS

%RSD	Percent relative standard deviation
3D	Three-dimensional
AFFF	Aqueous film-forming foam
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
IAMFTWG	International Aircraft Materials Fire Test Working Group
ID	Inside diameter
MAPP	Methylacetylene-propadiene propane
ME	Magnesium Elektron
OD	Outside diameter
OEM	Original equipment manufacturer
TSO	Technical Standard Order

EXECUTIVE SUMMARY

In recent years, magnesium alloys have been suggested as substitutes for aluminum alloys in aircraft seat structure, as well as other applications, because of the potential weight savings. The Federal Aviation Administration (FAA) has had several inquiries regarding the policy for using magnesium alloys in airplane cabins. Although magnesium alloys are routinely used in the construction of noncabin aircraft components, they are currently prohibited from use in aircraft seats, according to an FAA Technical Standard Order (TSO) that references an SAE International standard. The FAA TSO-C127, "Rotorcraft and Transport Airplane Seating Systems," prescribes the minimum performance standards that rotorcraft and transport airplane seating must meet, including the qualification requirements and minimum documentation set forth in various sections of SAE AS8049, "Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft." Within AS8049, revision A, paragraph 3.3.3 states, "Magnesium alloys shall not be used." These criteria have blocked the use of magnesium alloys in seat structure for decades.

The FAA's central concern regarding the use of magnesium and its many alloys in the cabin is flammability. The current regulations do not address the potential for a flammable metal to be used in large quantities in the cabin. Therefore, if such a material were introduced into the cabin, the FAA must be assured that the level of safety would not be reduced. Recent developments in materials technology have shown that different magnesium alloys have different susceptibility to ignition. However, magnesium remains a material that, once ignited, is very challenging to cope with using fire extinguishers currently available on aircraft.

To better evaluate the potential risks of using magnesium alloys in the cabin, a task group was formed under the auspices of the International Aircraft Materials Fire Test Working Group, which is chaired and administered by the FAA. The FAA agreed to support additional research in this area to the extent industry could supply materials. This included laboratory- and full-scale tests to determine the level of hazard associated with magnesium use in an aircraft cabin under realistic conditions, including postcrash and in-flight fire scenarios.

A preliminary assessment of magnesium alloy flammability was conducted using a laboratory-scale test apparatus. The test apparatus consisted of an oil-fired burner to simulate the fuel fire and a frame to mount and expose representative test samples. Test samples consisting of various magnesium alloys were evaluated. The laboratory-scale tests indicated a large difference in flammability between the various samples tested. New generation magnesium alloys Elektron®WE43 and Elektron®21[1] both showed greatly improved resistance to ignition compared to a more conventional legacy alloy, such as AZ31.

Subsequent full-scale aircraft fire tests of these alloy systems provided useful information concerning the feasibility of using such materials in the construction of the primary components of aircraft coach seating. During the tests, it was determined that the new generation WE43

[1] Elektron®WE43, Elektron®43, and Elektron®21 are registered trademarks of Magnesium Elektron, which supplied all magnesium alloys discussed in this report. For the purposes of brevity, all Magnesium Elektron registered alloys will be abbreviated as WE43, EL43, and EL21, respectively, throughout the report.

material would not impact postcrash fire survivability, producing minimal quantities of toxic and flammable gases during a 5-minute fire exposure.

During the final phase of the program, a laboratory-scale test was developed, based on information obtained in both the preliminary laboratory and the realistic full-scale tests. Various test sample shapes, sizes, and exposure conditions were trialed in an effort to achieve the appropriate test condition. The proposed test calls for a 0.25-inch-thick by 1.5-inch-wide by 20-inch-long sample, which is exposed to the flames of an oil-fired burner for 4 minutes. To meet the requirement, the sample must not ignite before 2 minutes and must self-extinguish within 3 minutes of the burner flames being removed (7 minutes from the start of the exposure). Additionally, samples must not lose more than 10% of their initial weight.

1. INTRODUCTION.

1.1 PURPOSE.

This report describes the research undertaken by the Federal Aviation Administration (FAA) to develop a laboratory-scale flammability test for magnesium alloy components used in aircraft seating structure. The proposed test was developed based on preliminary laboratory-scale flammability tests and subsequent full-scale tests using an intact fuselage adjacent to a large jet fuel fire. During the full-scale tests, it was determined that no increase in hazard resulted when using a well-performing, new generation magnesium alloy in the construction of the primary seat components. A laboratory-scale flammability test was developed using an oil burner as the fire source. New generation alloys Elektron®WE43, Elektron®43, and Elektron®21[1] meet the requirements of the new test method, whereas legacy alloys such as AZ31 and AZ80 do not. It is anticipated that the test will be used by industry to certify magnesium alloys for use in aircraft seat structure.

1.2 BACKGROUND.

In a majority of survivable accidents accompanied by fire, ignition of the interior of the aircraft is caused by burning jet fuel external to the aircraft as a result of fuel tank damage during impact. One important factor to occupant survivability is the integrity of the fuselage during an accident. Two possibilities usually exist in a survivable aircraft accident: an intact fuselage and a compromised fuselage from either a crash rupture or an open emergency exit, which allows direct impingement of external fuel fire flames on the cabin materials. Based on a consideration of past accidents, experimental studies, and fuselage design, it is apparent that the fuselage rupture or opening represents the worst-case condition and provides the most significant opportunity for fire to enter the cabin [1]. Past FAA regulatory actions governing interior material flammability were based on full-scale tests that employed a fuel fire adjacent to a fuselage opening in an otherwise intact fuselage. This scenario, in which the cabin materials were directly exposed to the intense thermal radiation emitted by the fuel fire, represented a severe, but survivable, fire condition and was used to develop improved material flammability test standards.

To meet these new requirements, aircraft designers had to compromise between material performance, weight, and cost. Material performance is not confined to flammability alone; other parameters are equally important, including corrosion, strength-to-weight ratio, water absorption, and environmental concerns during manufacture. Designers continuously strive to increase performance, while reducing the overall weight of transport category aircraft. The amount of fuel required to operate an aircraft is corollary to the weight of the aircraft; considerable savings in fuel consumption are obtained by reducing the weight of the aircraft. To help save weight, designers review advancements made with new materials, their properties, and the associated costs of using these materials in the fabrication of aircraft.

[1] Elektron®WE43, Elektron®43, and Elektron®21 are registered trademarks of Magnesium Elektron, which supplied all magnesium alloys discussed in this report. For the purposes of brevity, all Magnesium Elektron registered alloys will be abbreviated as WE43, EL43, and EL21, respectively throughout the report.

Magnesium has become popular as a potential replacement or supplement to the standard aluminum alloys used in aircraft construction. Although it is not as strong as aluminum on a weight basis, magnesium is approximately 30% lighter. Creative new designs in specific applications can result in structures of equal strength at a weight savings of approximately 20% over aluminum.

Although magnesium offers the potential for considerable weight savings, it does not come without some drawbacks, namely corrosion and flammability [2]. In recent years, the corrosion aspect has been addressed and largely solved via alloy development, electroplating, powder-coating, and other related surface-treating processes. Recent advancements in the area of flammability have increased the appeal of magnesium and magnesium alloys for use in certain aircraft cabin applications. Despite this attractiveness, obstacles still exist that prevent magnesium from being used in the aircraft cabin; specifically, an outright ban on its use in seat construction. This ban on magnesium use in aircraft seats is facilitated by FAA Technical Standard Order (TSO) C127, "Rotorcraft and Transport Airplane Seating Systems" [3]. The TSO prescribes the minimum performance standards that rotorcraft and transport airplane seating must meet, including the qualification requirements and minimum documentation set forth in various sections of Society of Automotive Engineers (SAE) AS8049. As stated in the TSO:

> "Seating systems…that are manufactured on or after the date of this TSO (dated 3/30/1992) must meet:
>
> (i) the minimum performance standards, qualification requirements, and minimum documentation requirements set forth in Sections 3.2, 3.3, 3.4, 3.5, 4.1, 4.2, 5, 5.1, 5.2, 5.3, and 5.4 of Society of Automotive Engineers, Inc. (SAE), Aerospace Standard AS8049, "Performance Standard for Seats in Civil Rotorcraft and Transport Airplanes," dated July 1990.

Within SAE AS8049, revision A (revised September 1997), paragraph 3.3.3 states, "Magnesium alloys shall not be used" [4]. As a result, these two standards have effectively blocked the use of magnesium in aircraft seat construction.

The SAE Aircraft SEAT Committee is a working group within the SAE that addresses all facets of aircraft seats—design, maintenance, in-service experience, and performance standards development. Participants in the SAE SEAT Committee include original equipment manufacturers (OEM), suppliers, aircraft seat equipment companies, consulting firms, government entities, and other interested parties across the aerospace and defense industries. The SAE Aircraft SEAT Committee is presently the custodian of AS8049.

Because of the recent interest in using magnesium for weight-saving applications, the FAA has had several inquiries regarding its policy for using magnesium in airplane cabins. Specifically, industry groups have lobbied to have the FAA revisit the current policy (TSO-C127) on banning magnesium use in the construction of aircraft seats, as well as other cabin components. Whereas the FAA's central concern regarding the use of magnesium in the cabin is flammability, the current regulations do not address the potential for a flammable metal to be used in large quantities in the cabin. Therefore, if such a material were introduced into the cabin, the FAA

would have to be assured that the level of safety was not reduced. Although different magnesium alloys have different susceptibility to ignition, magnesium remains a material that, once ignited, is very challenging to manage using fire extinguishers currently available on aircraft. An earlier study [5] by the FAA provided only limited information on the ignitability and flammability of a narrow range of legacy-type magnesium alloys.

Despite initial concerns over the potential use of magnesium in cabin components, there was enough interest to initiate a more formal discussion. As a result, a task group to investigate magnesium flammability was formed under the auspices of the International Aircraft Materials Fire Test Working Group (IAMFTWG), which is chaired and administered by the FAA Fire Safety Branch.[2] Although the potential for weight savings is undeniable, the FAA proceeded with caution to ensure the level of cabin safety was not compromised or that an additional hazard was not introduced.

The task group initially solicited industry on prospective areas within the cabin where magnesium use would be beneficial and discussed potential hazards associated with these. Industry had identified aircraft seat structure as the single, most likely area of the cabin interior to benefit from the use of magnesium alloy components in place of existing aluminum. Additional discussions led to a more formal testing program undertaken by the FAA Fire Safety Branch at the FAA William J. Hughes Technical Center in Atlantic City, NJ. The test program included initial investigative laboratory-scale flammability tests as well as realistic, full-scale tests on magnesium alloy seat structure. The goal of the research was to first determine the feasibility of using magnesium alloys in the construction of seat components from a flammability safety standpoint. Because the full-scale tests indicated no additional hazard existed within the cabin, the next phase was to develop an appropriate laboratory-scale flammability test for seat structural components. This flammability test may also be required for structural seat components fabricated from other potentially flammable materials, such as composites.

2. EXPERIMENTS.

2.1 PRELIMINARY OIL-FIRED BURNER TESTS OF MAGNESIUM ALLOY BARS.

A preliminary assessment of magnesium alloy flammability was conducted using a laboratory-scale test apparatus. The test apparatus consisted of an oil-fired burner to simulate a fuel-fed cabin fire, and a mechanism used to mount rectangular cross-section bar stock test samples. The burner was configured according to Title 14 Code of Federal Regulations (CFR) Part 25.853 (c) Appendix F Part II. This is the test standard for evaluating the flammability of aircraft seat-cushion materials. Although there is no current requirement for the flammability resistance of aircraft seat structure, this test was suitable for generating initial test data on the flammability of various magnesium alloys. Test samples consisting of several magnesium alloy bar stock were evaluated. The samples tested were of two different cross sections, approximately 0.39 inch by 1.6 inches, and 0.59 inch by 1.6 inches, with bare-metal band-sawn surfaces. Each bar sample measured 19.7 inches in length and was securely mounted in the test fixture at a distance of 4 inches from the end of the burner cone (figures 1 and 2). The center of the bar sample face

[2] As defined by the Materials Fire Test Working Group Charter.

exposed to the burner was positioned 1 inch above the horizontal centerline of the oil-burner cone.

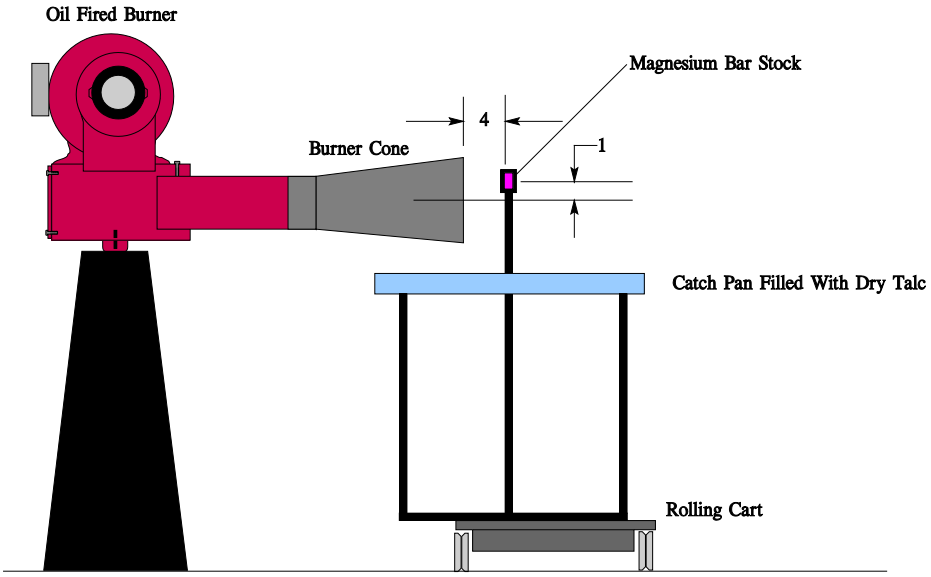


Figure 1. Oil-Fired Burner Test Apparatus Used for Preliminary Study of Magnesium Flammability

Figure 2. Magnesium Alloy Bar Sample Mounted in Test Apparatus Prior to Test

During a typical test, the burner was turned on and allowed to warm for a period of 2 minutes. Following this step, the rolling cart assembly holding the magnesium alloy bar sample was moved in front of the burner (figure 3). The samples were exposed to the burner for 3, 4, or

5 minutes, depending on the thickness of the bar sample being tested. Within this exposure period, the bar samples typically slumped or distorted just prior to melting, and often a large center section of the bar sample fell into a catch pan mounted below (figures 4 and 5). In these instances, the molten pieces in the catch pan continued to burn for varying periods of time. Once the bar sample melted and a portion of it fell into the catch pan, the remaining pieces attached to the sample holder either ignited and continued to burn (figure 6) or, depending on the type of alloy, quickly self-extinguished.

Figure 3. Magnesium Alloy Bar Sample Exposed to Burner Flames

Figure 4. Magnesium Alloy Bar Sample Immersed in Flames, Just Prior to Melting

Figure 5. Center Section of WE43 Bar Sample Falling Into Catch Pan After Melting

Figure 6. Ignition of Magnesium Alloy AZ31 Following Burner Flame Exposure

The catch pan was filled with dry talc to prevent any splattering of molten materials and to aid in the safe extinguishment of burning samples. After the burner was shut off and all burning had subsided, the sample pieces were cooled and removed for inspection (figure 7). Various parameters were measured and recorded during the test, including the sample dimensions, the time the sample melted, the time the burner flame was turned off, the time the sample self-extinguished, and whether any melted pieces that fell into the catch pan were still burning.

Figure 7. Post-Test Inspection Showing Molten Center Section Removed From Catch Pan

Numerous types of magnesium alloy samples were tested. The designation system used to identify the various elements in the magnesium alloy employs a combination of letters and numbers. The first two letters indicate the major alloying elements, according to the following codes:

A—Aluminum (Al)
B—Bismuth (Bi)
C—Copper (Cu)
D—Cadmium (Cd)
E—Rare earth elements
F—Iron (Fe)
G—Magnesium (Mg)
H—Thorium (Th)
K—Zirconium (Zi)
L—Lithium (Li)
M—Manganese (Mn)
N—Nickel (Ni)

P—Lead (Pb)
Q—Silver (Ag)
R—Chromium (Cr)
S—Silicon (Si)
T—Tin (Sn)
W—Yttrium (Y)
Y—Antimony (Sb)
Z—Zinc (Zn)

The two letters are followed by two numbers, indicating the percent concentration of the major alloying elements. In some cases, a fifth letter symbol signifies alloy modification (A through Z, excluding I and O), which distinguishes between different alloys with the same percentages of the two principle alloying elements. This alloy code is followed by a designation of temper. The temper designation system is similar to that for aluminum alloys, as follows:

F—As fabricated
O—Annealed
H—Cold worked
T4—Solution treatment
T5—Artificial aging
T6—Solution treatment followed by artificial aging

For example, an alloy designated as ZE63A-T6 is a magnesium alloy containing 6% zinc (Z), and 3% rare earth elements (E), is the first type (A) of a series of similar alloys, and carries a solution treatment followed by an artificial aging process (T6).

The magnesium alloys tested in the preliminary evaluation ranged from the conventional types of sand and die casting alloys, such as AZ31, to the other end of the spectrum, which contains rare earth elements, including many that have only recently been invented (table 1).

None of the tested sample bars melted before 2 minutes, which was not surprising given the relative thickness of the samples tested. When the exposure time was increased beyond 2 minutes, the samples melted, typically between 3 and 4 minutes for the 0.59-inch-thick samples and approximately 2 to 3 minutes for the thinner 0.39-inch-thick samples. The type of alloy also played a role in the time to reach the melting point. As shown in figure 8, the alloys with higher melting points typically required longer periods of time to melt. The chart shows the time required to melt six different alloys at a thickness of 0.59 inch. Also shown are the lower and upper melting ranges of each of the alloys. With the exception of ZE10, there is a direct correlation with the alloys' upper melting range and the time required to melt the samples.

Table 1. Initial Laboratory-Scale Test Results

Test No.	Alloy	Width (inches)	Height (inches)	Length (inches)	Burner Duration (min:sec)	Sample Melted (min:sec)	Sample Continued to Burn	Sample Self-Extinguished (min:sec)	After Flame Duration (min:sec)	Residue Burning	Comments
1	WE43	0.6	1.6	19.7	4:00	3:45	No	4:00	0:00	No	Height face exposed to flames
2	AZ80	0.6	1.6	19.7	3:30	3:07	Yes	9:21	5:51	Yes	Height face exposed to flames
3	EL21	0.6	1.6	19.7	5:00	3:47	Yes	6:07	1:07	No	Height face exposed to flames
4	ZE41	0.6	1.5	19.7	4:00	3:06	Yes	5:45	1:45	No	Height face exposed to flames
5	ZE10	0.6	1.6	19.7	4:00	3:35	Yes	7:29	3:29	Yes	Height face exposed to flames
6	AZ31	0.5	1.6	19.7	4:00	3:19	Yes	Kept burning	n/a	Yes	Height face exposed to flames
7	WE43	0.6	1.6	19.7	5:00	3:35	No	5:00	0:00	No	Height face exposed to flames
8	EL21	0.6	1.6	19.7	4:00	3:35	No	4:00	0:00	No	Height face exposed to flames
9	AZ80	0.6	1.6	19.7	5:00	3:00	Yes	6:15	1:15	Yes	Height face exposed to flames
10	AZ31	0.6	1.6	19.7	5:00	3:01	Yes	6:12	1:12	Yes	Height face exposed to flames
11	WE43	0.4	1.6	19.7	4:00	2:26	Yes	6:12	2:12	Yes	Height face exposed to flames
12	EL21	0.4	1.6	19.7	4:00	2:08	Yes	6:08	2:08	No	Height face exposed to flames
13	WE43	0.4	1.6	19.7	4:00	2:30	Yes	5:43	1:43	No	Height face exposed to flames
14	AZ80	0.4	1.6	19.7	4:00	2:09	Yes	8:10	4:10	Yes	Height face exposed to flames
15	AZ80	0.4	1.6	19.7	3:00	1:58	Yes	5:00	2:00	Yes	Height face exposed to flames
16	EL21	0.4	1.6	19.7	3:00	2:12	Yes	4:08	1:08	No	Height face exposed to flames
17	WE43	0.4	1.6	19.7	11:45	10:37	Yes	13:42	1:57	No	Intumescent paint coating
18	ZE41	0.6	1.6	19.7	5:00	3:51	Yes	6:31	1:31	No	Width face exposed to flames
19	ZE10	0.6	1.6	19.7	4:00	No melting	No	4:00	0:00	n/a	Width face exposed to flames
20	AZ31	0.4	1.6	19.7	4:00	3:37	Yes	Kept burning	n/a	Yes	Bar orientation vertical
21	Elektron 675	0.4	1.6	19.7	5:20	5:00	Yes	6:35	1:15	No	Height face exposed to flames
22	Elektron 675	0.4	1.6	19.7	5:15	4:50	Yes	6:00	0:45	No	Height face exposed to flames
23	Elektron 675	0.4	1.6	19.7	5:15	5:00	Yes	5:20	0:05	No	Height face exposed to flames

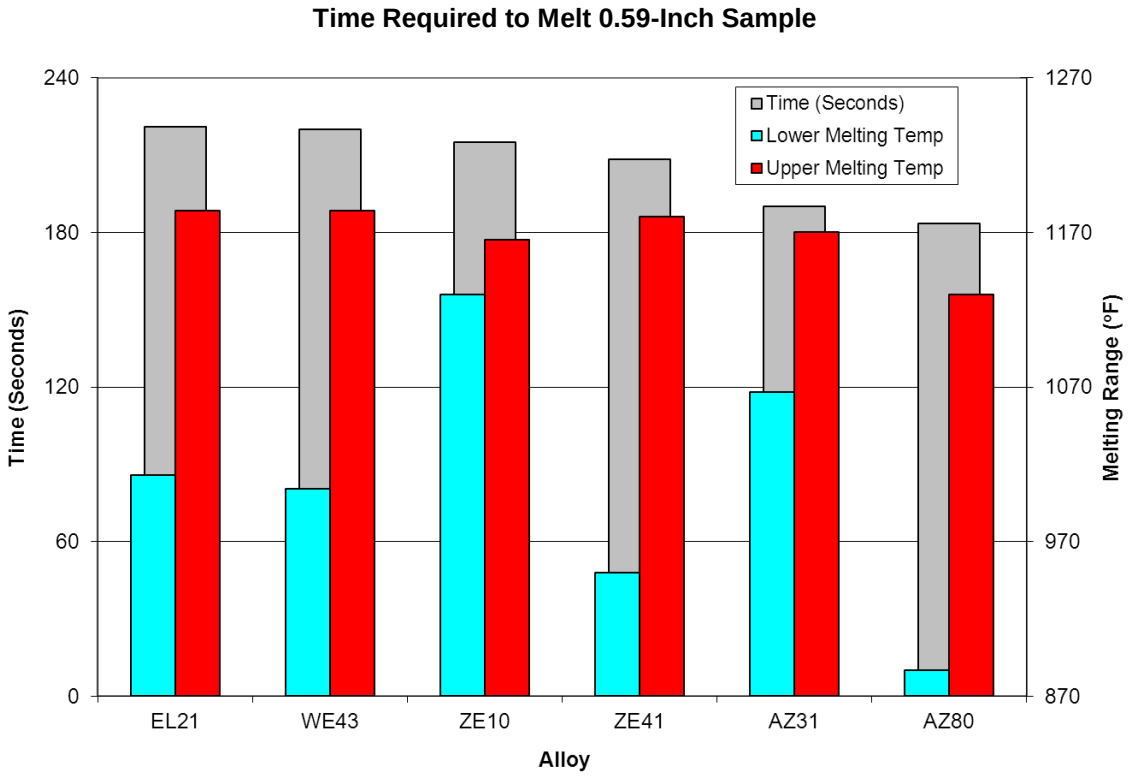


Figure 8. Various 0.59-Inch-Thick Samples and Respective Time to Reach Melting

In many cases, once the samples were subjected to the burner for a time period adequate to cause melting, the alloys ignited. Several samples were new generation alloys specifically designed to minimize flammability. As a result, a large difference in flammability was observed between the various samples tested. For example, the alloys WE43 and EL21 both showed outstanding resistance to ignition compared to the legacy alloys, such as AZ31. In two of the three AZ31 tests, the sample did not self-extinguish, regardless of time, and burned indefinitely.

Of the 23 tests conducted, 18 resulted in continued burning of the sample, the molten remnants, or both. In 5 of the 23 tests, there was no ignition or the materials self-extinguished within 5 seconds. The sample performance seemed to be largely dependent on the alloy type and, in some cases, the section thickness. For example, WE43 self-extinguished in tests 1 and 7, in which the section thickness was measured to be close to 0.6 inch. However, in tests 11 and 13, with a section thickness of only 0.4 inch, both WE43 samples continued to burn for at least 90 seconds after the burner was switched off.

With the exception of two tests (18 and 19), all tests were run with the wide face of the sample (1.6-inch face) exposed to the burner flames. In these two tests, the orientation of the bar was changed so that the narrow face (0.6-inch face) was exposed to the burner to determine the effect. When considering the ZE10 alloy, the orientation appears to have made a significant impact on the results. In test 5, the burner was switched off at 4 minutes, and the sample continued to burn for an additional 3 minutes and 29 seconds. However, in test 19, with the

narrow face exposed, the burner was switched off at 4 minutes; the bar did not melt, and there was no ignition. This indicated less heat from the burner was being transferred to the sample in this orientation. The results confirmed that sample orientation plays a critical role in the results.

A slightly different approach was investigated in test 20, in which the sample bar was shortened and oriented vertically rather than horizontally (figure 9). It was difficult to determine the exact impact of orienting the sample in this manner because this test was performed on a sample of AZ31, which had burned consistently after burner removal. It was clear that this orientation prevented the separation of a large mass of the test sample during the melting process, which was common when mounting the samples horizontally. By mounting vertically, the molten section of sample ran down the unmolten section like a candle. This tendency kept the sample hotter, because the molten mass was still in contact with the sample.

Figure 9. Magnesium Alloy Sample Mounted Vertically

After conducting a number of tests on a variety of alloys, it was suggested that a protective coating or barrier be investigated as a potential method of protection. Intumescent coatings and paints had proven their usefulness in certain fire applications, so a test sample of WE43 was coated with a 500-micron layer of intumescent paint manufactured by Indestructible Paint Ltd., Sparkhill, Birmingham, UK [6]. The intumescent layer was then top-coated with a 25-micron layer of flame-resistant enamel. This protective layer had a pronounced effect on the test result; the sample did not melt until 10 minutes 37 seconds. This was approximately four times the typical 2-minute and 30-second melting time of a WE43 sample of this thickness. The burner was not switched off until 11 minutes and 45 seconds. Although the sample continued to burn for nearly 2 minutes after the burner was switched off, the test demonstrated the effectiveness of the intumescent coating at extending the melting time.

Three final tests were run on Elektron®675, a high-strength wrought alloy designed for elevated temperature applications. The samples melted consistently between 4 minutes and 50 seconds and 5 minutes. The molten residue did not ignite during any of the three tests, and the sample self-extinguished immediately on burner removal during one of the three tests.

2.2 ADDITIONAL LABORATORY-SCALE FLAMMABILITY TESTS USING VARIOUS IGNITION SOURCES.

Following the initial laboratory-scale tests using the oil burner, a better understanding of the flammability performance of the various magnesium alloys was achieved. It was clear that melting the material was required before any burning would take place. The ability to get the samples to melt was largely a function of sample thickness; the thicker samples required more time to heat to reach the melting point. Although the initial tests using the solid, rectangular cross-section bar samples were good starting points to assess material flammability, the sample thickness and shape did not represent a typical seat-frame member. Informal discussions with airframe manufacturers and seat suppliers indicated the primary components of a typical aircraft seat would be the target of future magnesium alloy substitution if permissible. The primary components included the leg assemblies, the spreaders, and the cross tubes. The leg assemblies and spreaders were typically machined from plates and the cross tubes were hollow, circular extrusions. In each of these three component designs, thin sections of material existed that could potentially heat up and melt more readily.

To create a more realistic test condition mimicking a machined leg or spreader, one of the thinner WE43 test sample bars was modified using a milling machine. Two 10-inch-long longitudinal channels were milled into the test sample bar to create a thinner cross-sectional area where the heat from the burner was concentrated (figures 10 and 11). The longitudinal channels were square and approximately 0.25-inch wide by 0.25-inch deep.

Figure 10. Magnesium Alloy Test Sample Bar With a Milled Cross Section

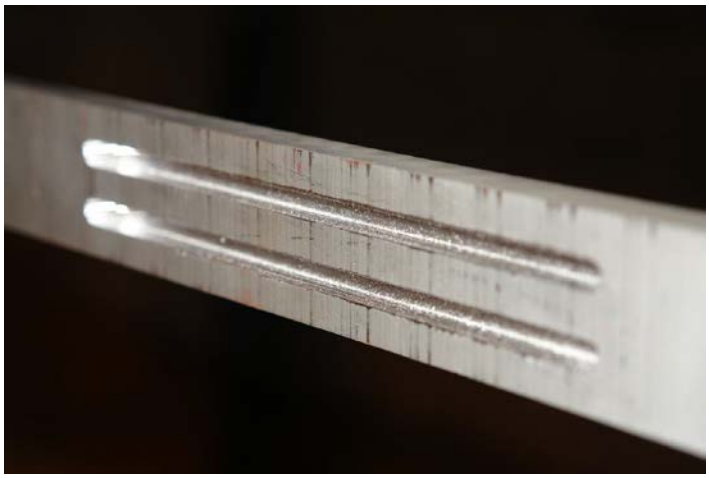


Figure 11. Close-up of Test Sample Bar With a Milled Cross Section

Following burner warmup, the test samples were exposed for a period of 4 minutes, then the burner was switched off. Melting occurred at approximately 2 minutes and 30 seconds. The machining did not appear to cause the test sample to become more flammable, as the melting process was similar to previous tests of nonmilled samples (figure 12).

Figure 12. Post-Test Photograph of Milled Bar Test Sample

One additional test was conducted using a vertically mounted, milled test bar sample (figure 13). A remnant piece from the previously milled sample was used for this test. The milled sample was clamped into place and exposed to the burner until melting was observed. The orientation had no effect on the flammability of the sample, because the burning subsided within 10 seconds of removing the burner.

Figure 13. Post-Test Photograph of Milled Sample Mounted Vertically

To supplement the laboratory-scale flammability tests using the oil burner, several additional small-scale tests were conducted. These were simple, investigative tests intended to develop a better understanding of the overall flammability of the magnesium alloys. During the first test, the magnesium alloy millings captured from the milling process in the previous test were piled into a small mound in the catch pan (figure 14). A handheld methylacetylene-propadiene propane (MAPP) gas torch was used to ignite the pile of material. The millings were relatively easy to ignite with the torch because of their high surface area-to-volume ratio (figure 15). This high ratio allowed the millings to heat quickly and melt rapidly, providing the proper conditions for ignition. A second test was run in which a pile of millings was placed on top of a piece of aircraft-grade carpeting in the catch pan. As in the previous test, the millings were ignited with the torch. Despite the intense light given off by the material, the resulting fire did not spread beyond the diameter of the pile of millings.

Figure 14. Torch Used to Ignite a Small Pile of Magnesium Alloy Millings

Figure 15. Small Pile of Magnesium Alloy Millings on Fire

Another test series was run using small slivers of magnesium alloy sawn from a bar sample. An industrial band saw was used to produce the thin slivers, in both crosswise and lengthwise fashion. It was difficult to obtain uniformly sawn samples, as they measured approximately 0.0625 to 0.125 inch in thickness. The slivers were held using a pair of pliers and were heated using the MAPP gas torch (figure 16). Similar to the pile of millings, the sliced samples had high surface-area-to-volume ratios, making them easy to ignite. Once ignited, the samples continued to burn until nearly or completely consumed (figure 17).

Figure 16. Thin Sliver of Magnesium Alloy Being Heated With Torch

Figure 17. Thin Sliver of Magnesium Alloy on Fire After Being Heated With Torch

A longitudinal slice of the magnesium alloy was sawn from the length of a sample bar and clamped vertically in front of the oil burner (figure 18). Following burner warmup, the sample was exposed until melting began (approximately 1 minute). The melting caused the sample to slump downward, at which point the burner was turned off (figure 19). Although a significant percentage of the sample had melted during exposure, it did not ignite.

Figure 18. Longitudinal Slice of Magnesium Alloy Positioned Vertically in Front of the Burner

Figure 19. Vertically Mounted Slice After Self-Extinguishment

A final laboratory test was conducted on a modified bar sample. The sample was sliced lengthwise and sectioned, removing approximately 25% of the bar length (figure 20). The sample was clamped in place horizontally, with the sectioned area positioned in front of the burner. The sectioned area was approximately 0.125 to 0.1875 inch in thickness. Following burner warm-up, the sample was exposed for approximately 2 minutes, at which point it melted and ignited (figure 21). The burner was subsequently turned off.

Figure 20. Sectioned Bar Sample Positioned Horizontally in Front of the Burner

Figure 21. Sectioned Magnesium Alloy Bar Sample Ignited Using Oil Burner

The sample continued to burn for several minutes, with molten pieces of the sample falling into the catch pan. This was an unexpected result, as the previous test series using the vertically mounted slice did not ignite following melting.

2.3 FULL-SCALE TESTS OF SEATS CONSTRUCTED OF MAGNESIUM ALLOY COMPONENTS.

To evaluate potential hazards associated with the ignition of magnesium alloy components under more realistic conditions, a full-scale test series was conducted. Based on input from industry regarding the potential use of magnesium alloy inside a passenger cabin, it was clear that the seat structure was a primary target area. In particular, the large, machined primary components, such as the legs, spreaders, and cross tubes, were ideal for retrofitting. These aluminum components were substantial in mass and would benefit the most from substitution using a magnesium alloy. Other less massive seat components, such as the seat bottom and back pans, would not be ideal for magnesium alloy substitution and, therefore, were not considered in the full-scale study. To conduct the tests, a narrow-body test fuselage was used. Using this test fuselage was the most practical approach for repetitive tests and systematic evaluation of the various magnesium alloys. The test fuselage consisted of a 20-foot-long steel cylinder section fabricated from curved steel channels, which was then inserted between two halves of a Boeing 707 fuselage (figure 22). This test fuselage was configured with a standard-sized opening, 40 by 80 inches, representing a break in the fuselage. In this configuration, flames from an external fuel fire impinged directly on one of the seats positioned in the opening. An 8- by 10-foot fuel pan was situated adjacent to the test fuselage. The fire was produced from 55 gallons of JP-8 fuel ignited in the fuel pan. The mocked up section of the test fuselage included seats and other cabin materials, such as paneling and carpet (figure 23).

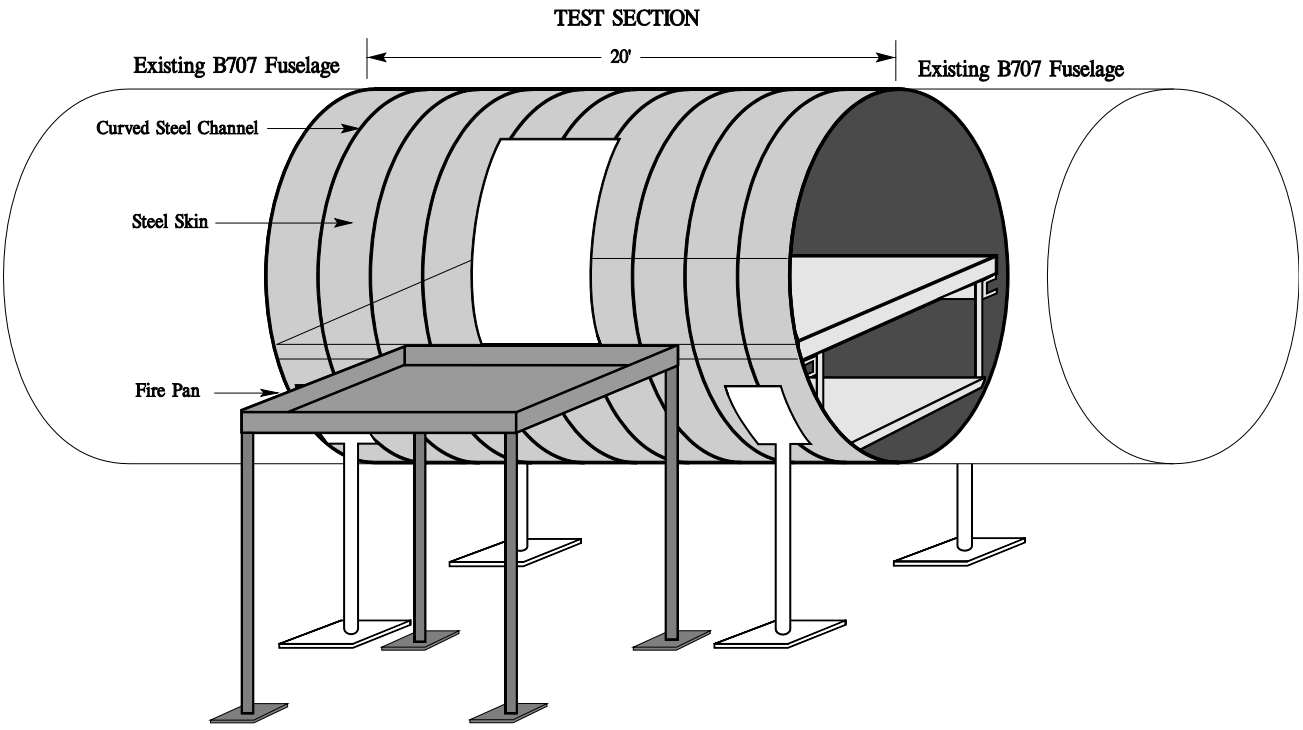


Figure 22. Full-Scale Test Fuselage

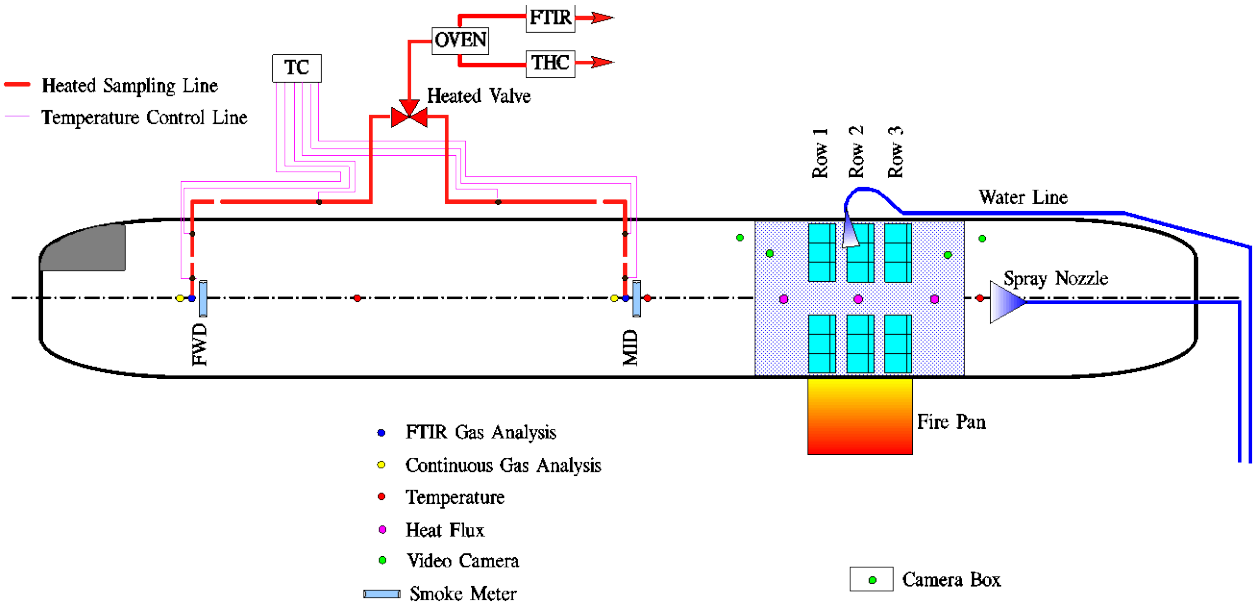


Figure 23. Test Fuselage Showing Fire Pan and Seats

The main objective of the full-scale tests was to determine if an additional hazard was created during a cabin fire when magnesium alloy was used in the primary seat components [7]. A baseline test was conducted to establish a basis by which any increased hazards could be measured. The baseline test used standard aircraft triple-coach seats with aluminum primary components. Following the baseline test, the plan agreed on between the FAA and industry was

to conduct a test using seat components machined from a well-performing magnesium alloy, such as WE43. If the results of this test indicated no obvious increase in hazard, a third test would be conducted using seat components machined from a poor-performing magnesium alloy, AZ31, for contrast. A fourth, optional test was discussed in which the primary and additional secondary seat components would be machined using the well-performing magnesium alloy. This would provide another data point to help verify the overall performance of the magnesium alloy in increased quantities during realistic conditions. To maintain control, all other materials would remain identical throughout the tests. This would enable an accurate assessment of only the magnesium alloys' impact on the test outcome.

The initial baseline test resulted in excessive burning of the seat-cushion materials, which caused cabin conditions to rapidly deteriorate. A flashover[3] condition began at approximately 90 seconds, which was unanticipated because all of the cabin materials met current FAA flammability requirements. Because rapid flashover occurred in the initial baseline test, it was agreed that this test condition was too severe to draw distinctions between materials, and that a second baseline test was necessary. Adjustments were made to the test fuselage to reduce the onset of flashover. An exhaust fan used in the first baseline test was not used, and different seat bottom and back cushion materials were substituted. Despite these changes, the second baseline test also resulted in a rapid flashover condition. Although the survivable conditions were extended an approximate 30 seconds because of the material substitutions and adjustments, the test condition remained too severe. A post-test inspection focused on the seat-back frames, which were fabricated from carbon tape impregnated with epoxy resin. It was possible that the flammable seat-back structure contributed to the fire load and allowed the burning seat back to collapse onto the bottom cushion and the floor, promoting additional fire spread. The many thermoplastic parts in the seat-back headrest area were also considered as contributory given the rapid ignition and spread of fire along the seat-back assemblies. Considering these elements and the relatively short time periods to reach incapacitation, a decision was made to conduct a third baseline test with the intent of maintaining survivable conditions for a greater duration. By extending the time to reach incapacitation, a more complete and accurate assessment of the magnesium alloy performance could be made during subsequent tests. To prevent the rapid ignition and spread of fire along the seat-back assemblies, a new seat back was designed and constructed of known materials with good, fire-resistant qualities. An aluminum frame with accompanying fire-hardened foam was outfitted to the standard aircraft triple seats and the test was repeated. The revised seat back performed well, allowing the test to progress for several minutes before flashover conditions began at 3 minutes and 40 seconds. For simplicity, it was agreed prior to the test that extinguishment of the external fuel fire would begin at 5 minutes. It was also agreed that the internal cabin fire would be permitted to progress unabated for 5 additional minutes and water spray would be applied to these materials at the 10-minute mark. This test sequence would be repeated for subsequent tests using magnesium alloys in the seat frames.

A post-test inspection indicated that the newly designed seat backs had prevented extensive flame spread and that the 5-minute test duration appeared sufficient because there was thorough

[3] Flashover is a condition in which the combustion gases generated from the burning materials suddenly ignite, producing extreme temperatures and simultaneously consuming a large quantity of the oxygen. During flashover, the cabin conditions change from survivable to nonsurvivable in a very short time period.

melting of the seat frame near the fire opening, which was the desired result. An inspection of the seat structure revealed that both cross tubes were melted, as were the outboard leg component and outermost spreader assembly. The next inboard spreader assembly had partially melted and was lying on the fuselage floor. Although they were not primary components, the seat-back frames and most of the lower baggage bar on this triple seat were also completely melted. These results indicated a successful baseline test condition had been created. The conditions resulted in thorough melting of the primary components, but the overall atmospheric conditions were not severe enough to prevent subsequent magnesium alloy materials from being effectively evaluated.

With the appropriate baseline test condition established, a test was conducted using seat-structure components machined from the well-performing magnesium alloy WE43. This alloy had shown excellent resistance to ignition during the preliminary laboratory-scale tests. Following fuel pan ignition, the test progressed similarly to the baseline test, with flashover developing at approximately 3 minutes and 45 seconds. As agreed, extinguishment of the external fuel fire with aqueous film-forming foam (AFFF) began at 5 minutes. The interior cabin fire was allowed to progress without intervention until the 10-minute mark, when water was sprayed into the cabin. The application of water was completed by 12 minutes and 20 seconds, when all cabin materials were extinguished. A post-test inspection revealed that a number of the portside seat backs, including the aluminum frames, were consumed. A closer look at the portside seats indicated considerable melting of the row 2 seat assembly's primary components. The two outer spreaders (both cross tubes) and the outer leg experienced melting during the test. This result was similar to the baseline test, in which several primary seat components had also melted. This and the results from the baseline test confirmed that the test conditions were ideal, with thorough melting of the primary components while survivable conditions remained for approximately 4 minutes. The seats were carefully removed from the test fuselage and inspected. The inspection revealed clear indications that the magnesium alloy was involved in the fire because several pieces showed evidence of ignition.

As originally planned, a subsequent test was conducted using a poor-performing alloy (AZ31) in the construction of the seat's primary components. Following fuel pan fire ignition, the test proceeded according to plan for several minutes. The beginning of flashover conditions was observed at 3 minutes 15 seconds. Between 3 minutes 15 seconds and 3 minutes 30 seconds, the flashover condition grew in intensity. Fuel pan fire extinguishment began at 5 minutes with AFFF and appeared to be completed by 5 minutes and 25 seconds. During this initial extinguishment period, there were clear indications of a magnesium alloy fire inside the fuselage, as viewed from an externally mounted camera, beginning at 5 minutes and 15 seconds. The external fuel fire reignited and was not fully extinguished until 6 minutes and 20 seconds. The interior fire was allowed to continue without interruption once the external fire was fully extinguished. Brief periods of intense light emission, indicative of magnesium burning, were observed from several areas within the immediate area of the seats. These observations were viewed by the external camera aimed through the fuselage opening. The interior fire continued to consume the row 2 seat structure and collapsing was observed as the structure melted and burned. Other more remote sections within the viewing area of the camera showed brief bursts of intense light. As pieces of the seat structure collapsed, minor sparking was observed from the burning sections of magnesium alloy. The fire continued to consume the seat structure, causing

a mass of molten and burning magnesium to begin to form near the floor under the seat structure. By 10 minutes, this mass of burning magnesium was significant.

At 10 minutes, the interior water nozzles were activated, which caused a violent intensification of the burning mass of magnesium alloy. By 11 minutes, the fire diminished in size, but there was still clear evidence of burning magnesium. By 12 minutes, the camera was completely obscured, but the water spray continued. Between 12 and 14 minutes, periodic flashes of light were observed, indicating the fire was still active, which required the water nozzles to remain activated. Between 14 minutes 30 seconds and 15 minutes, there was a steady flickering of light from the active magnesium fire. Because the fuel pan was overflowing with water, the water nozzles were shut off at 15 minutes. A precautionary spray of water was released at 19 minutes 45 seconds for 1 minute, at which point the test was deemed successfully completed, with no additional signs of fire in the fuselage.

A post-test inspection revealed that a number of the portside seat backs were totally consumed, including the aluminum frames. The portside row 2 seat assembly sustained the most damage, as expected, with no visible evidence of any remaining seat-back frames. It was difficult to determine how much of the row 2 seat assembly damage was from the initial fuel fire and how much was from the subsequent magnesium fire during the observation period. The starboard-side seat backs were largely intact, with only surface burning and charring of the fabric dress cover and aisle-side arm rests. The thermoplastic tray table assemblies from all starboard-side seats were still intact, with no other damage observed.

2.3.1 Comparison of Baseline (Aluminum) Test to Magnesium Alloy Tests.

Several comparative charts are presented in this section to effectively evaluate the performance of the two magnesium alloys. These charts compare the fuselage interior conditions for the baseline test, the well-performing WE43, and the poor-performing AZ31 magnesium alloy tests.

The forward cabin temperatures, measured at heights between 4 and 5 feet above the floor, showed similar results for the three tests. The baseline test reached the highest temperature at this station, and WE43 maintained the lowest temperature (figure 24). Whereas there were subtle differences in the peak temperatures, the data indicated that all three tests progressed similarly, with the temperature rise beginning between 150 and 180 seconds into the test. A similar trend was observed at the mid-cabin temperature tree, which was located close to the burning materials (figure 25). The temperature ranking was the same at this location as at the forward cabin station, with the baseline test reaching the highest temperatures and WE43 producing the lowest temperatures.

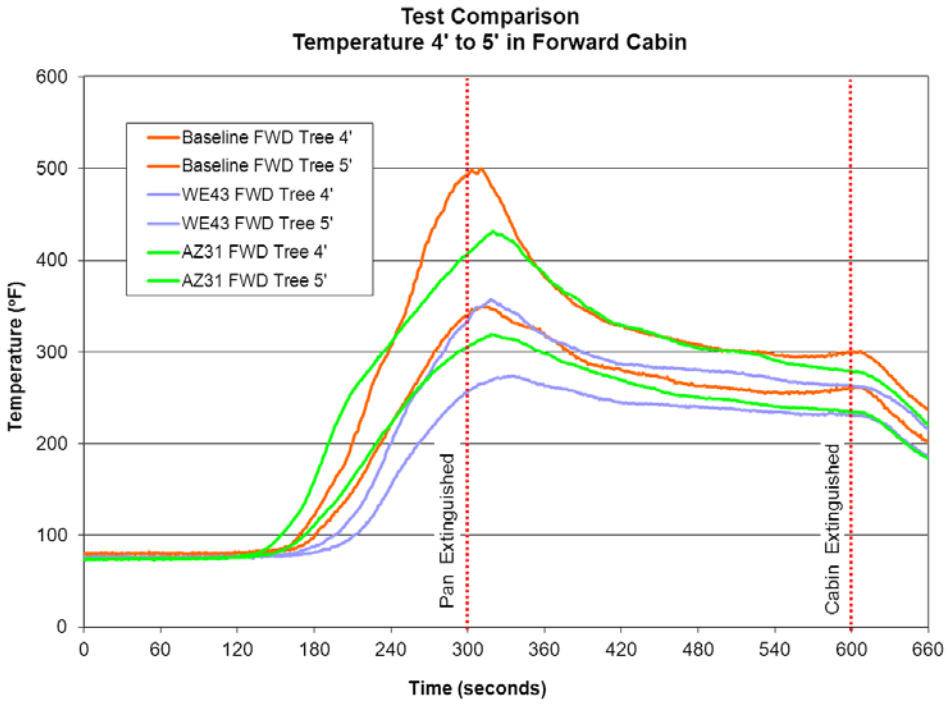


Figure 24. Temperature Comparison at the Forward Cabin Area

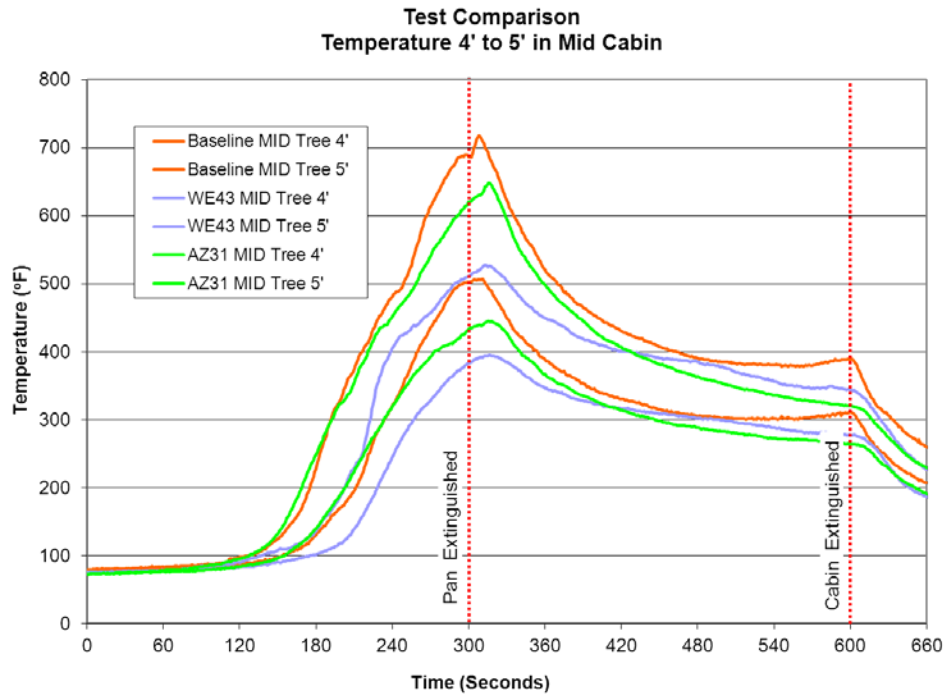


Figure 25. Temperature Comparison at the Mid-Cabin Area

The data obtained for the CO levels followed the same trend as the temperature data. The forward cabin area CO levels (measured at 3 feet 6 inches and 5 feet 6 inches) began to increase above trace levels between 140 and 200 seconds into the test, with the baseline and AZ31 test levels rising slightly before the WE43 test level (figure 26). Although there was a slight delay shown with the WE43 test, all test levels were nearly identical at the point of external fuel fire extinguishment, approximately 0.8% to 0.9%. During the 5-minute observation period, the baseline and AZ31 test levels continued to climb for a short period, peaking at 1.2% before diminishing. All test levels were again similar at the 10-minute mark when the water spray was activated, reaching approximately 0.4% to 0.5%. The mid-cabin area CO levels (measured at 3 feet 6 inches to 5 feet 6 inches) showed a much more erratic behavior, indicating greater turbulence in the cabin air at this location (figure 27). This was not unexpected because there is typically more air movement closer to the fire. Although less clear than the forward cabin station, the CO levels obtained for all tests were relatively similar, with the AZ31 test levels rising before the baseline or WE43 test levels. At the 10-minute mark, when the water spray was activated, all levels diminished to 0.3% to 0.5%.

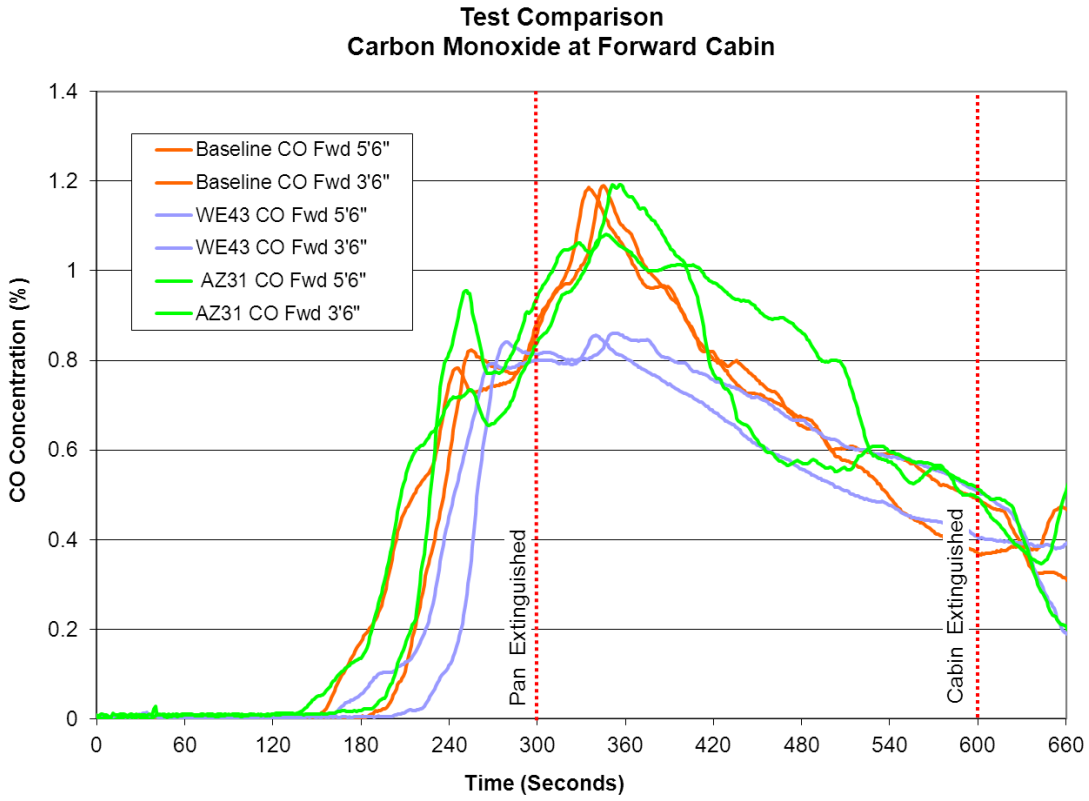


Figure 26. The CO Level Comparison at Forward Cabin Area

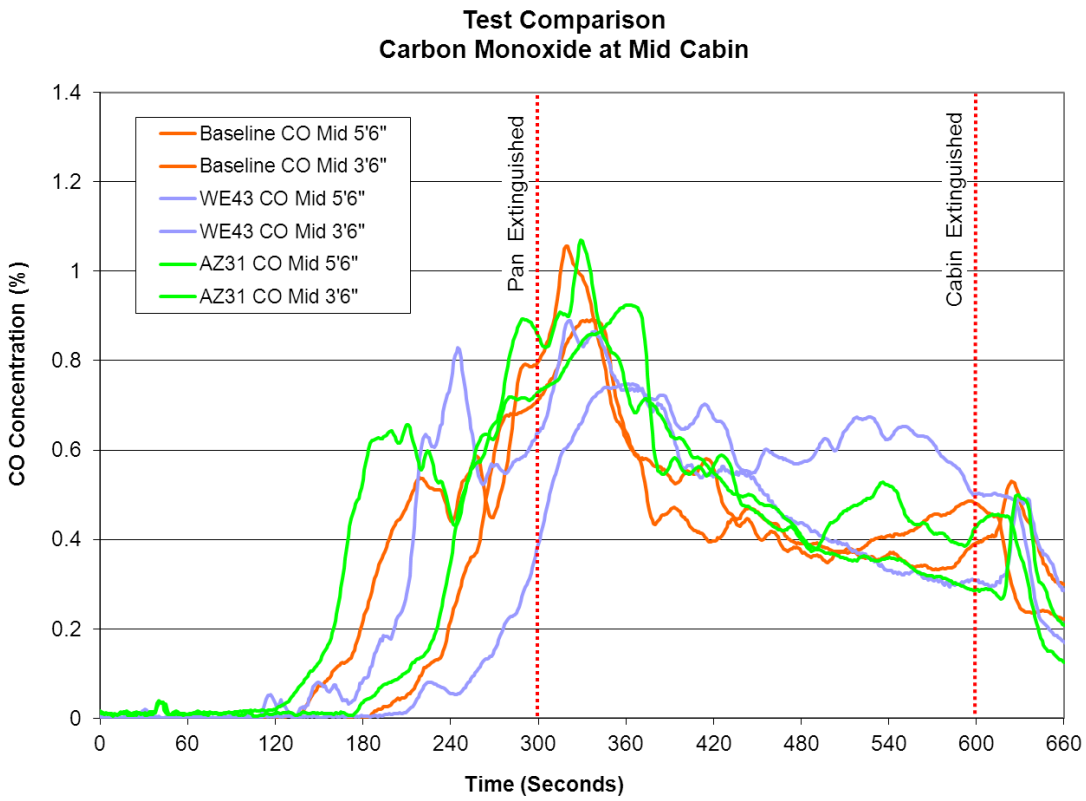


Figure 27. The CO Level Comparison at Mid-Cabin Area

Oxygen depletion was also recorded and showed much the same delay and trending when the three tests were compared (figures 28 and 29). At the forward cabin area, the oxygen levels dropped to between 13% and 14% at the point where the external fuel fire was being extinguished (figure 28). The levels all began to rise from their lowest points at approximately 330 seconds into the test. They increased fairly linearly until the 10-minute mark, at which point all levels were nearly the same at 16% to 17%. Although not as uniform as the forward-cabin levels, the mid-cabin oxygen levels also showed a similar trend (figure 29).

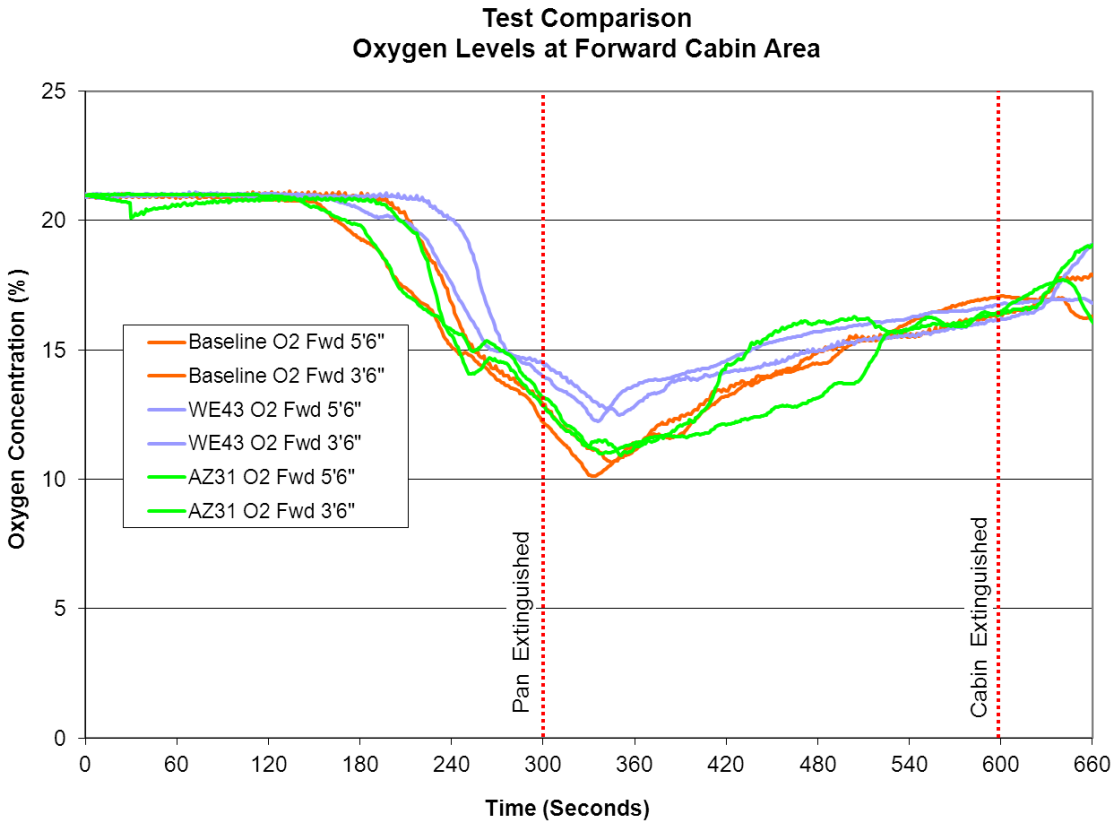


Figure 28. Oxygen Level Comparison at Forward-Cabin Area

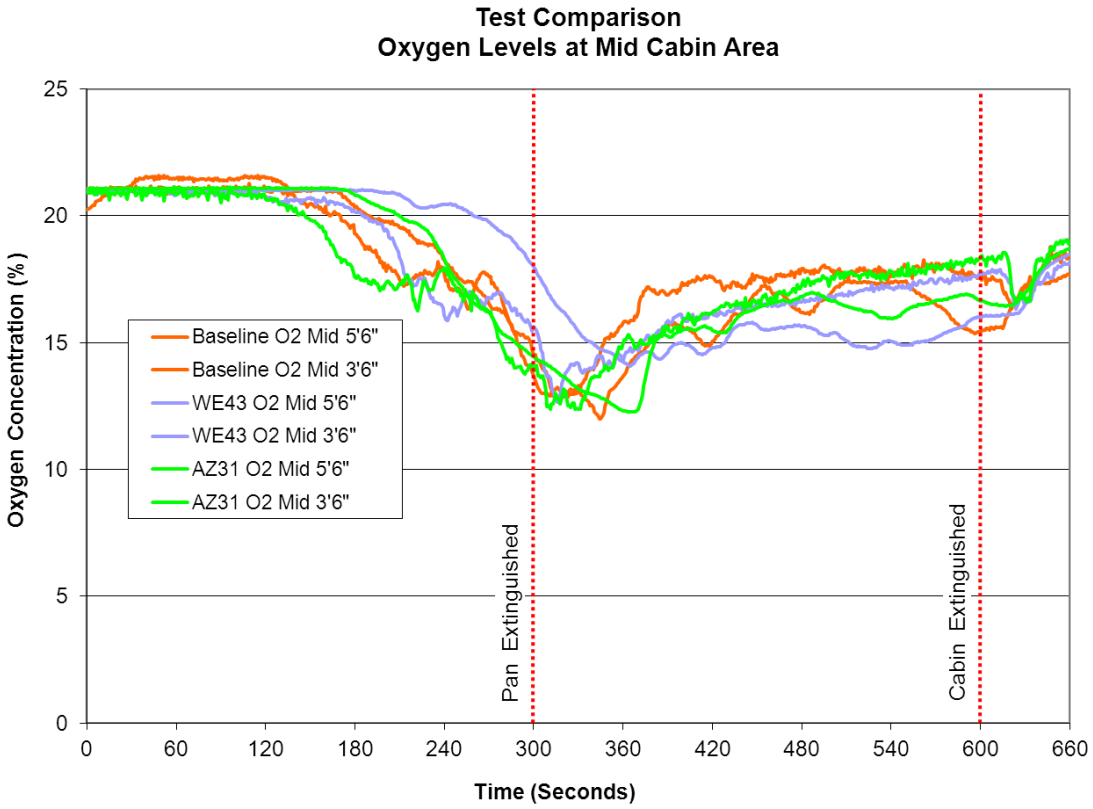


Figure 29. Oxygen Level Comparison at Mid-Cabin Area

A survivability model was used to predict the theoretical time at which a person would become incapacitated, based on the levels of temperature and gases measured during the test. After inputting all the temperature- and gas-measurement data from the tests, the model generated fractional effective dose survivability curves [8]. The results from this three-test comparison were very similar; the test results showed comparable levels of temperature and gases measured. At the forward cabin area, the time to reach incapacitation for the three tests was within 28 seconds of each other (figure 30). This separation was likely within normal experimental errors for a test of this nature and scale. Likewise, the incapacitation results were within 21 seconds of each other at the mid-cabin area (figure 31). The results also showed that whereas the WE43 magnesium alloy material provided marginally better results at the forward cabin area, the baseline test provided a better result at the mid-cabin area, which highlighted the close similarity in performance of these materials during this study.

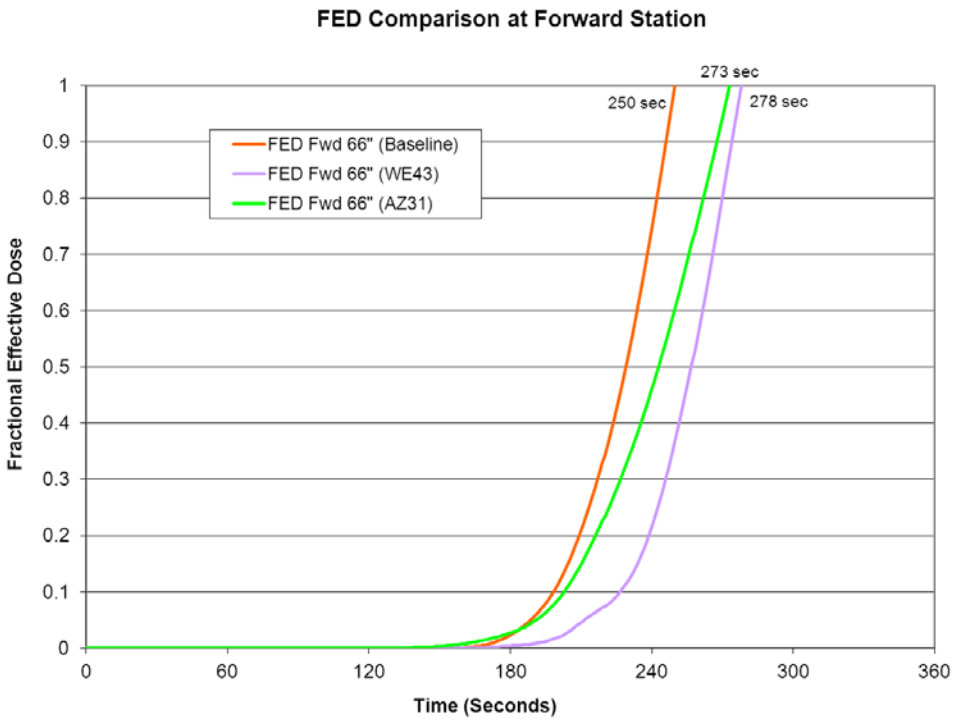


Figure 30. Survivability Comparison for Baseline and Magnesium Alloy Tests at the Forward Cabin Area

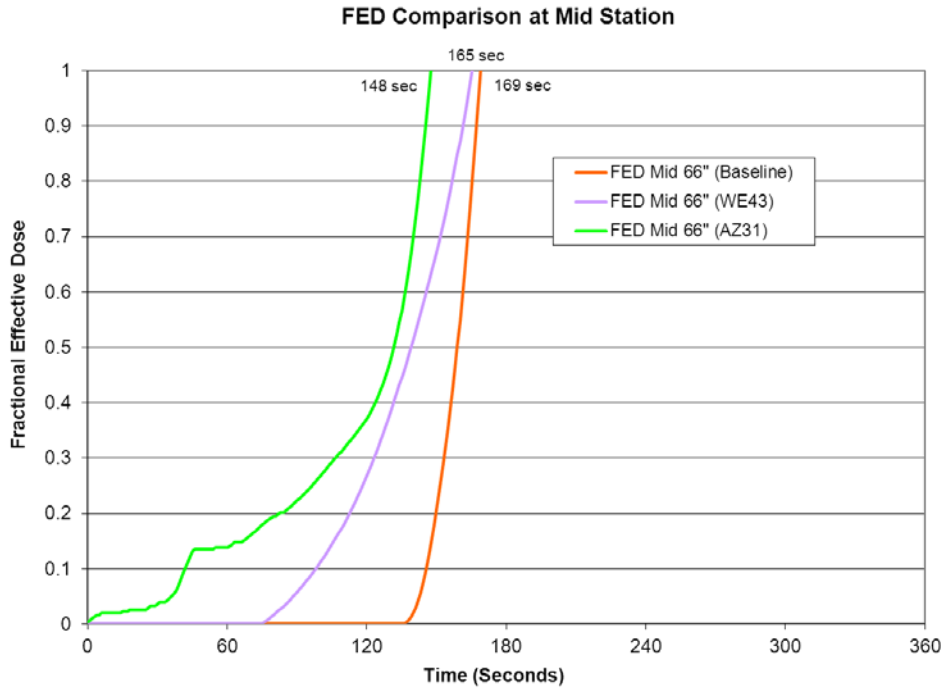


Figure 31. Survivability Comparison for Baseline and Magnesium Alloy Tests at the Mid-Cabin Area

2.3.2 Additional Tests Using Magnesium Alloy in the Primary and Secondary Seat Components.

One final test was planned in which additional magnesium alloy components would be used in the seat structure. The purpose of the test was to determine if additional quantities of magnesium alloy used in the fabrication of less massive seat-frame components would have an influence on the overall test results during realistic cabin fire conditions. Aside from the primary leg, spreader, and cross-tube components, the magnesium alloy would also be used to fabricate the box section seat-back frames and lower box-section baggage bar (both composed of aluminum in the preceding tests). Because of the relatively good performance displayed by the WE43 alloy, it was chosen for this final evaluation. The seat structures were assembled using the machined WE43 primary components along with the fabricated seat-back frames and baggage bars. The newly fabricated WE43 seat-back assemblies were identical in size to those used in the baseline test and previous magnesium alloy tests. The completed assemblies were then mounted inside the test fuselage and the thermocouples were installed on the leg frames, as in the previous tests.

Following pan fire ignition, it became apparent that the fire was entering the cabin more aggressively than in the previous three tests. Although this was noted by the test director and other witnesses, no immediate explanation could be offered for this perceived difference because all pre-test conditions and settings had been repeatedly checked prior to ignition of the fuel fire. The test continued until the 5-minute mark, even though all internal cameras were completely obscured and there were no visible means of determining the severity of the conditions inside the test fuselage. Pan fire extinguishment began at 5 minutes with AFFF, lasting approximately 30 seconds. After the majority of the fuel fire was extinguished, the AFFF was deactivated. This allowed the fire to reflame, requiring a final application of AFFF, which completely extinguished the fire by 6 minutes.

Because of the observed increase in fire severity entering the cabin during this test, it was agreed that a repeat test would be conducted. However, during the repeat test, a similar, more aggressive fire appeared to develop in comparison to the baseline, WE43, and AZ31 tests. Despite the efforts of the researchers at determining the reason for the increased fire severity, none could be found. However, researchers and interested parties witnessing the test were in unanimous agreement that this increase in fire severity at the start of the test was not a result of the additional magnesium alloy used in the seat backs or baggage bars. It was clear that the more aggressive fire during these final two tests developed immediately, prior to any involvement of magnesium components. Although this was observed by those witnessing the test, there was no option other than to allow the test to progress as it had during the previous trial, once the fuel pan was ignited. The pre-test conditions and settings were again discussed as the test proceeded, but all parties agreed these parameters had been repeatedly checked prior to ignition of the fuel fire.

Within 20 seconds, the fire was rolling into the upper area of the fire opening and along the ceiling panel in 1-second pulses, which typically did not happen until approximately 90 seconds during the baseline and two magnesium alloy tests. By 1 minute, there was a thick, heat-filled layer of smoke from the fuselage ceiling down to approximately 5 feet above floor level. The aft upper camera became obscured by 1 minute and 40 seconds. Visibility on the aft lower camera was still good at this point and showed vigorous burning of all portside seat backs. This burning continued and grew in intensity until 2 minutes and 10 seconds, at which point the camera was largely obscured. The fire had not progressed across the aisle and involved the starboard side

seats at this point. By 3 minutes, the forward lower camera was completely obscured. Throughout the 3 minutes of visible conditions inside the fuselage, at no point was there localized intense light indicative of burning magnesium alloy.

As planned prior to the start of the test, the external fuel fire continued for 2 additional minutes until the 5-minute mark, even though all internal cameras were completely obscured and there were no visible means of determining the severity of the conditions inside the fuselage. Pan fire extinguishment began at 5 minutes with AFFF, lasting approximately 30 seconds. Minor pan flare-ups were addressed with short bursts of AFFF, and the pan fire was completely extinguished by 6 minutes. The interior fire could be monitored clearly from the externally mounted camera. The row 2 seat and fallen panels on top of the seat were observed burning vigorously from 6 minutes until 8 minutes into the test. At 8 minutes, the increased burning reignited the fuel fire in the pan, which was quickly extinguished within 20 seconds. The interior materials continued to burn, with a noticeable collapse of the row 2 seat structure at approximately 9 minutes. Between 9 and 10 minutes, two small, barely noticeable areas of higher intensity light, most likely small magnesium alloy fires, were observed at the floor level just inside the fire opening. The water spray nozzles were activated at 10 minutes and the interior fire appeared to be extinguished instantly, but this was not the case. The water spray caused significant turbulence and smoke/steam, obscuring visibility. Following a brief period, the fire was visible again at 10 minutes and 30 seconds. The water spray continued; by 11 minutes and 30 seconds all visible signs of the internal fire were extinguished. Water spray was deactivated at 12 minutes and 30 seconds. The smoke/steam lifted and visibility returned at 13 minutes, confirming that all burning had ceased.

A post-test inspection revealed a number of the portside seat backs were totally consumed. As in the previous test, the portside row 2 seat assembly sustained extensive fire damage with evidence of substantial melting of the row 2 and row 3 magnesium alloy seat-back frames. The remaining portions of these assemblies had fallen backward onto the row 3 seat. It appeared that the cross tubes on both the row 2 and row 3 seats had melted, allowing a collapse of a majority of the seat structure. Although the fire had severely impacted these seat assemblies, the portside row 1 assembly still contained a visible seat back and a partial seat-back frame in the middle-seat place. This result was nearly identical to the previous test. During the observation period, it was again difficult to determine how much of the row 2 and row 3 seat assembly damage was from the initial fuel fire and how much was from the subsequent interior fire.

As in the previous comparison, a survivability model was used to predict the theoretical time at which a person would become incapacitated. This was based on the levels of temperature and gases measured during the test. The results from these two additional tests using magnesium alloy in the secondary seat components is shown along with prior test survivability calculations (figure 32). As expected from visual observations made during the tests, the two tests using additional magnesium alloy resulted in slightly shorter periods of time to reach theoretical incapacitation.

As shown, the incapacitation results were 38 seconds and 12 seconds quicker than the baseline test for each test performed at the mid-cabin area. This result was expected, given the observed increase in severity of the fire entering the cabin during the start of each of these two final tests.

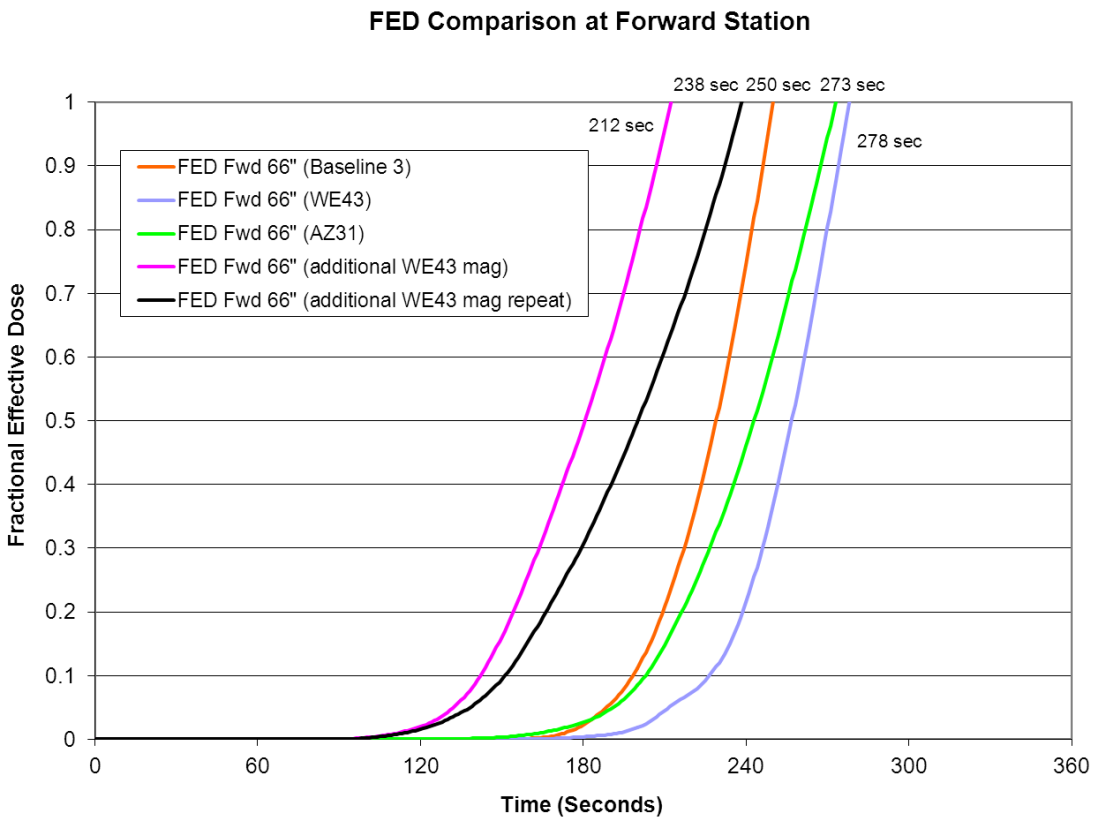


Figure 32. Survivability Comparison for Baseline and All Magnesium Alloy Tests at the Forward Cabin Area

2.4 REFINEMENT OF LABORATORY-SCALE FLAMMABILITY TEST.

The purpose of the full-scale tests was to determine if an additional hazard was created during a cabin fire when magnesium alloy was used in the primary seat components. The testing indicated no significant change to survivability (based on the survivability model) when using either a well-performing or poor-performing alloy. Although no change in survivability was noted, the performance of the poor-performing alloy was deemed unacceptable because of extinguishment difficulties. For this reason, the next phase of the program was initiated—developing an appropriate laboratory-scale flammability test for magnesium alloy seat structure.

To develop an appropriate laboratory-scale flammability test for magnesium components, consideration was first given to the initial tests done using the oil burner. A certain level of success was obtained using horizontally oriented bar samples that were placed approximately 4 inches from the burner cone. Although these initial tests were able to separate poorly performing magnesium alloy materials from more fire-resistant types, the basic test consisted of melting the center section bar sample, which typically collapsed and fell into the catch pan below. In many instances, the molten-alloy material falling into the catch pan had either already ignited or was in the process of igniting as it was falling. Conversely, the bar sample remaining in the sample holder either did not ignite or quickly extinguished once the majority of the molten section had fallen away. Thus, this configuration often resulted in two entirely different results

(significant ignition/burning of the droppings, but little or no burning of the remaining sample). In an attempt to overcome this situation during the test development phase, the concept of orienting the sample vertically was raised, with the expectation that a sample could be ignited near its top. Once ignited, the sample could continue to burn vertically, similar to a candle, thus enabling sustained ignition for a period of time after the ignition source was removed. This burn progression could possibly eliminate the previous result, for which a large segment of the test sample melted and fell away from the ignition source (burner flames). To facilitate easy ignition of the vertical sample, it was theorized that the upper portion could be minimized in mass/size compared to the lower portion. This resulted in the concept of a cone-shaped sample in which a more massive base at the bottom formed into a less massive pinnacle near the top, where the ignition source was concentrated. The first truncated cone-shaped prototype samples were machined using AZ31 and WE43 alloys, because these materials were used in the full-scale test demonstrations and typically yielded substantially different results. Initially, two truncated cone sample configurations were produced. The samples measured approximately 10 inches in height with a base diameter of approximately 1.6 inches and a truncated top measuring either 0.4 inches or 0.6 inches in diameter (figure 33).

Figure 33. Initial 10-Inch-Long Truncated Cone Test Sample

2.4.1 Vertically Oriented Solid Cone Tests.

An oil-fired burner configured in accordance with Title 14 CFR Part 25.853 (c) Appendix F Part II was used to simulate the fire threat. The test configuration was nearly identical to the configuration used during preliminary laboratory-scale tests conducted previously. The face of

the top of the sample was situated 4 inches from the exit plane of the burner cone, with the top of the sample approximately level with the upper surface of the burner cone (figures 34, 35, and 36).

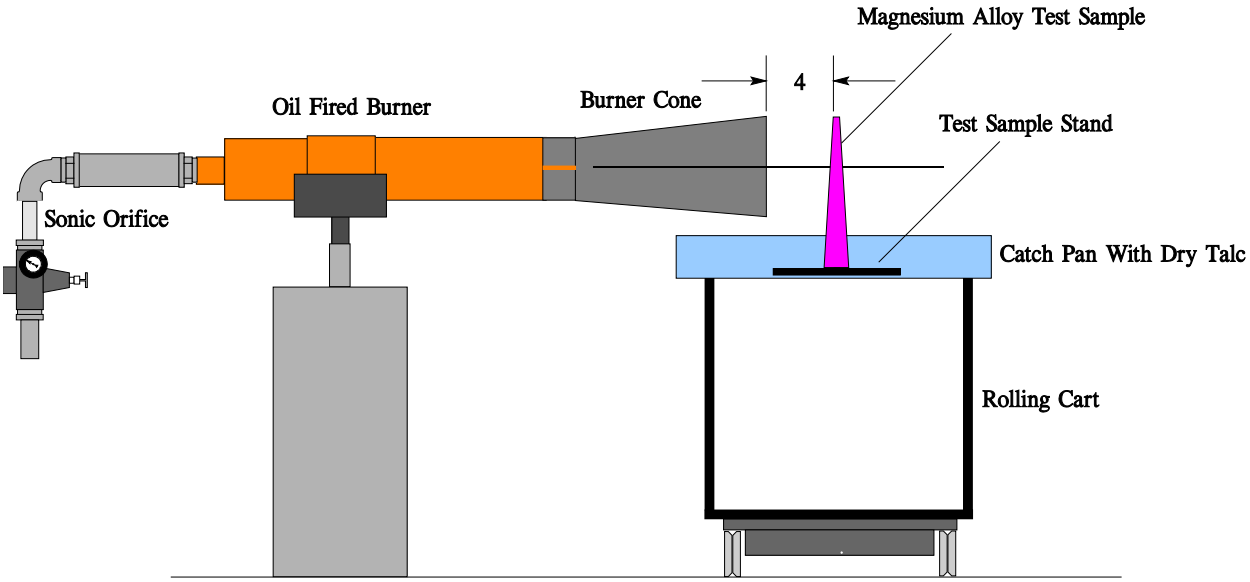


Figure 34. Initial Truncated Cone Sample Test Configuration

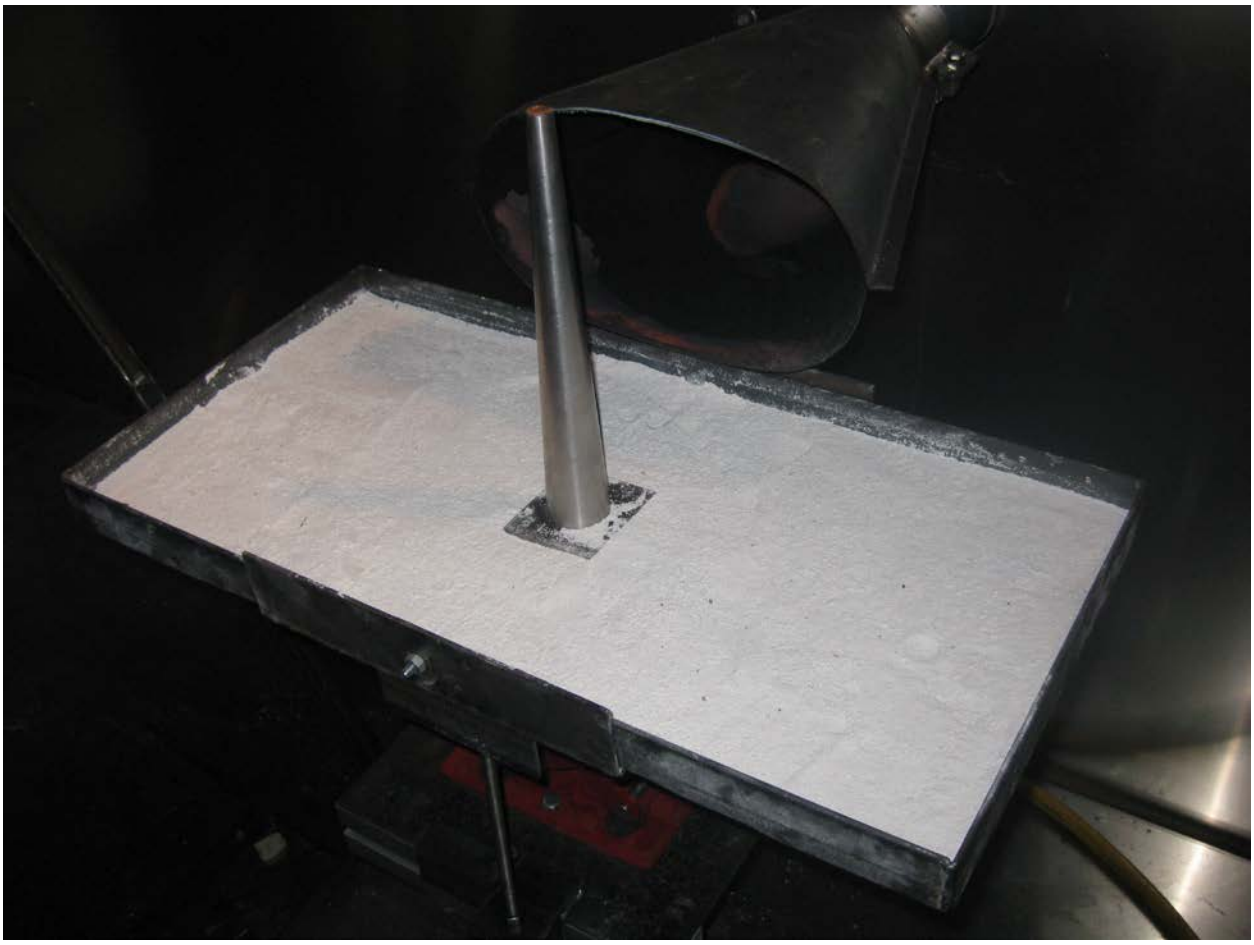


Figure 35. Truncated Cone-Shaped Test Sample Affixed in Talc-Filled Catch Pan, With Burner Shown in Background (2/8/2011)

Figure 36. Truncated Cone-Shaped Test Sample Affixed in Talc-Filled Catch Pan (2/8/2011)

Five tests were initially run using this sample configuration. During the first test, the WE43 alloy sample melted in 2 minutes and 30 seconds, with ignition beginning at 3 minutes and 40 seconds. The burner flames were terminated at 4 minutes and the sample continued to burn until 5 minutes and 40 seconds, at which point it self-extinguished. The exposed sample melted near the top, which was expected because this area had the least mass and was also centered in the burner flames. When the melting occurred, the upper portion of the sample slumped quickly with some of the molten material dripping into the catch pan and the remaining material forming a thin, irregularly-shaped appendage that partially resolidified. It was this appendage that ignited and burned during the test (figures 37 and 38). During the second test, an AZ31 sample was exposed, which melted at 1 minute and 38 seconds and ignited at 1 minute and 50 seconds. The burner flames were terminated at 3 minutes, but the sample continued to burn until it was completely consumed, roughly 27 minutes later. During this test, although similar to the WE43 test, the melting sequence occurred much sooner. The appendage that was formed during the melting process ignited more quickly and continued to burn into the main body of the unmelted sample, resulting in a lengthy period of burning. Three additional WE43 samples were then tested with results similar to the initial WE43 test. Melting typically occurred near the 2-minute mark, with ignition occurring approximately 30 seconds later. Two of these samples self-

extinguished in slightly more than 1 minute, whereas the last sample self-extinguished immediately following burner flame removal.

Figure 37. Typical Ignition of Truncated Cone-Shaped Test Sample (2/8/2011)

Figure 38. Post-Test Inspection of Truncated Cone-Shaped Test Sample (2/8/2011)

In an effort to prevent the formation of the thin, irregular-shaped appendages during the melting process, a sixth test was conducted on an inverted, truncated, cone-shaped sample (figure 39). Because the larger mass of the conical base was now positioned in the midst of the burner flames, it was theorized that this could slow down the melting sequence, resulting in a more gradual and possibly more regular-shaped melting area.

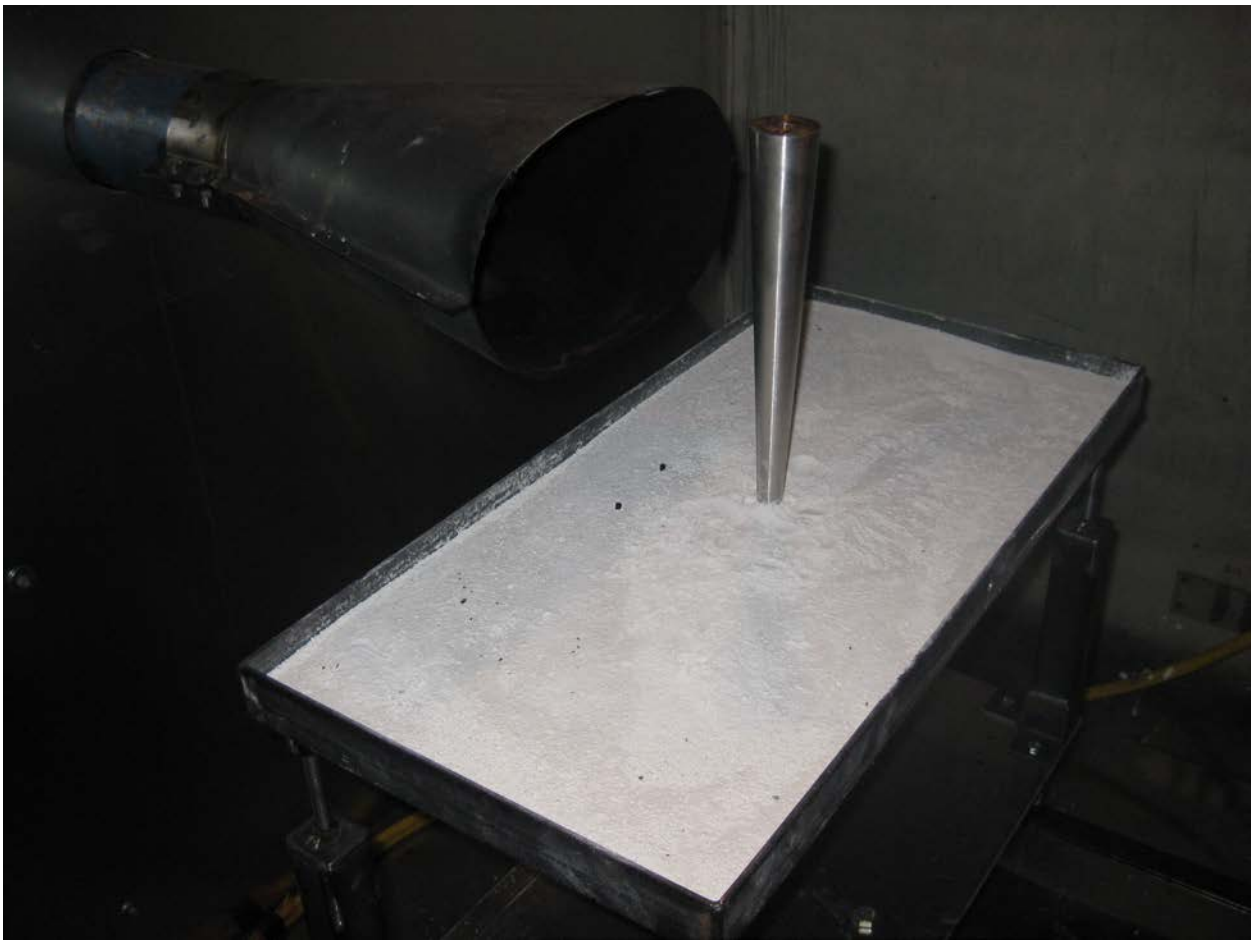


Figure 39. Inverted, Truncated Cone-Shaped Test Sample (2/16/2011)

Although this configuration resulted in a much greater time to reach the melting point of the alloy (5 minutes), it did not result in any increase in the regularity of the molten and resolidified mass of material that ignited. The sample ignited at 6 minutes and 45 seconds and the burner flames were terminated 30 seconds later. The sample continued to burn for an additional 2 minutes and 30 seconds before self-extinguishing at 9 minutes and 45 seconds.

To evaluate another sample configuration, one of the original WE43 truncated cone samples was machined down on a lathe to produce a thin, upright cylinder for testing (figure 40). As expected, because of the reduction in mass, the cylindrical sample melted after 1 minute and 40 seconds of exposure to the burner flames. During the melting, a fairly large portion of the alloy separated from the sample and fell into the catch pan, igniting simultaneously. At approximately 2 minutes and 40 seconds, the remaining upright sample ignited while the molten material in the catch pan continued to burn. The burner flames were terminated 30 seconds later at 3 minutes and 10 seconds. The upright sample self-extinguished on burner flame removal, but the molten material in the catch pan continued to burn for an additional period of time (figure 41).

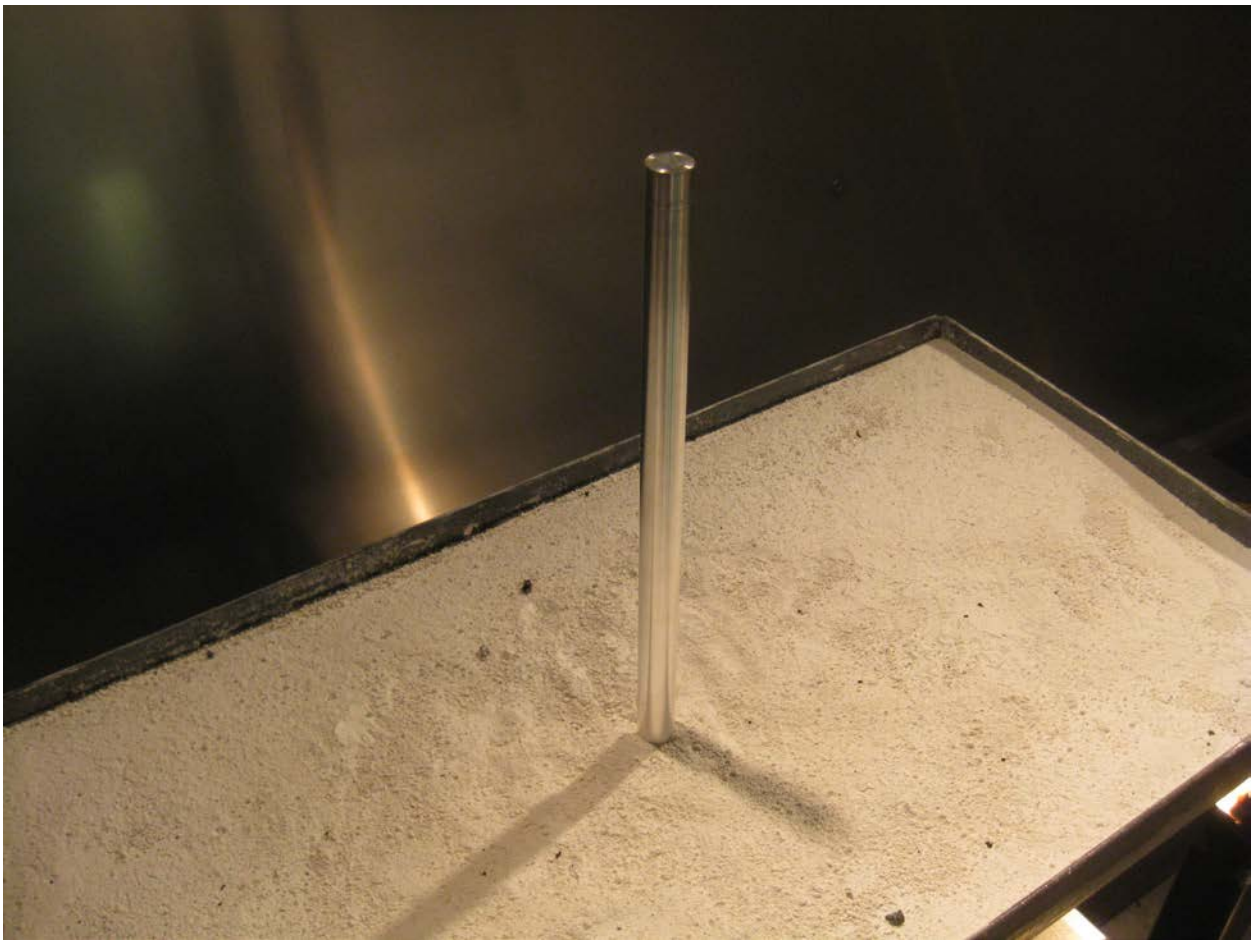


Figure 40. Cylinder-Shaped Test Sample Affixed in Talc-Filled Catch Pan (2/24/2011)

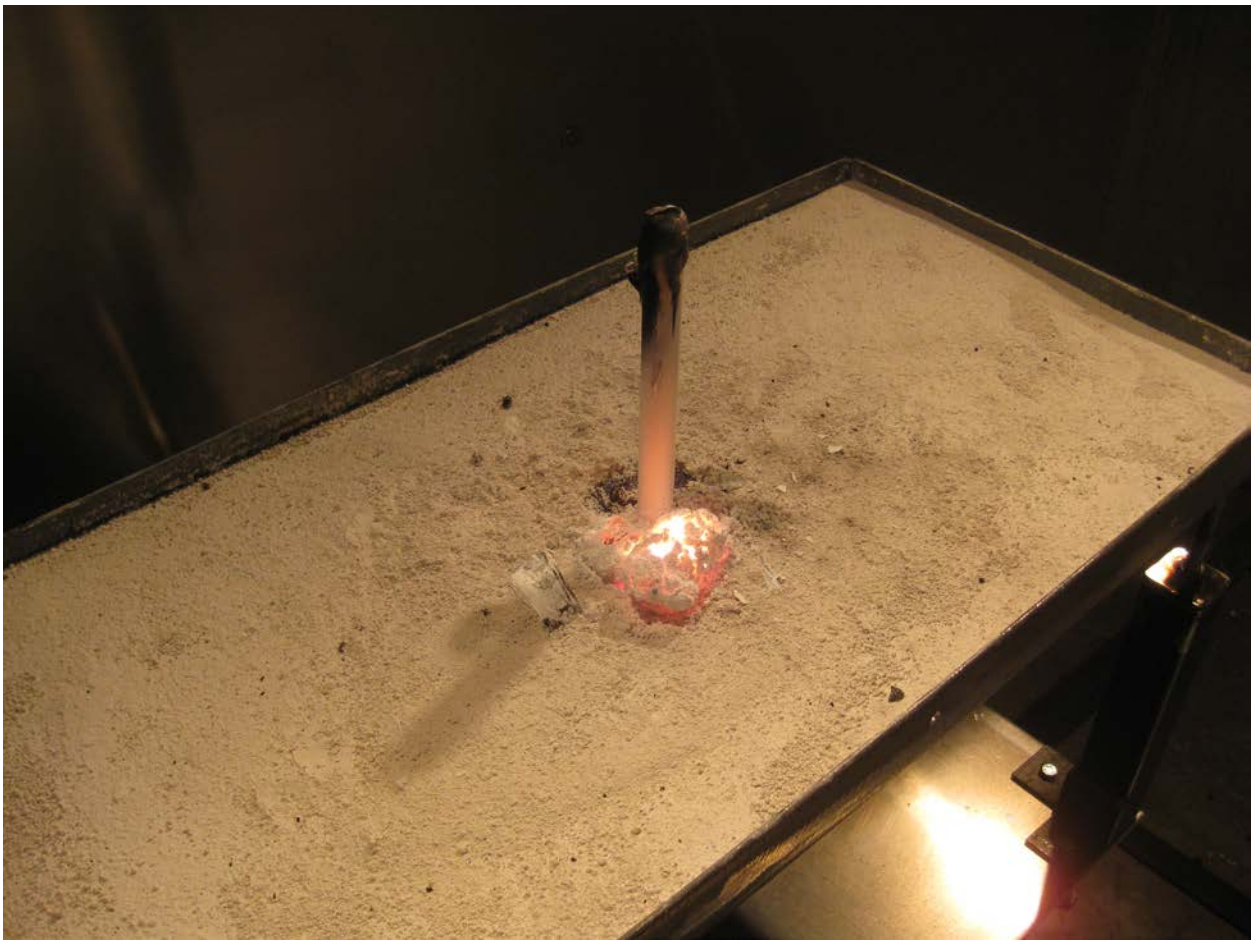


Figure 41. Cylinder-Shaped Test Sample Showing Large Segment Separating and Falling Into Talc-Filled Catch Pan (2/24/2011)

The level of difficulty in determining when a burning sample was declared as no longer burning was of note with respect to the initial seven tests. In the case of the truncated cones, in which the ignition and subsequent burning were confined to the appendage of molten and resolidified material, it was relatively easy to determine when the burning ceased. However, during tests in which material melted and separated (with the separated clump of material igniting and burning), it was much more difficult to determine an exact time to declare when the burning had ceased. These difficulties led to the suggestion of monitoring the time of self-extinguishment of both the remaining sample and the separated material, as these two events were essentially independent of each other.

One final test was run on an AZ31 truncated cone sample in its typical configuration. The sample melted at 2 m inutes and simultaneously began to burn. The burner flames were terminated at 4 minutes, but the sample continued to burn for approximately 26 additional minutes, resulting in total consumption of the material. The details of this test and the previous cone tests are summarized in table 2.

Table 2. Summary of Initial Cone-Shaped Magnesium Alloy Flammability Tests

Test Date	Alloy Type	Base Dia (in)	Head Dia (in)	Length (in)	Surface Area (in2)	Vol (in3)	Surface to Volume Ratio	Time to Melt (Min:Sec)	Melting Rate (in^3/min)	Time to Ignition (Min:Sec)	Burner Exposure (Min:Sec)	Time Ignition Ends (Min:Sec)	Duration of Ignition (Min:Sec)	Comments
2/8/11	WE43	1.58	0.59	10.1875	36.9784	10.058	3.68	02:30	4.02	03:40	04:00	05:40	01:40	Self-extinguished
2/8/11	AZ31	1.58	0.40	10.1563	33.7190	8.750	3.85	01:38	5.36	01:50	03:00	30:00	27:00	Completely consumed
2/8/11	WE43	1.57	0.39	10.0000	32.8965	8.454	3.89	01:42	4.97	02:30	03:00	04:20	01:20	Self-extinguished
2/8/11	WE43	1.58	0.60	10.2500	37.3829	10.209	3.66	02:22	4.31	02:54	03:30	04:35	01:05	Self-extinguished
2/8/11	WE43	1.57	0.39	9.8125	32.3203	8.296	3.90	02:05	3.98	02:25	03:10	03:10	00:00	Immediate self-extinguish
2/16/11	WE43	1.58	0.59	10.1875	37.0004	10.073	3.67	05:00	2.01	06:45	07:15	09:45	02:30	Inverted sample
2/24/11	WE43	0.60	0.60	10.1875	19.7685	2.880	6.86	01:40	1.73	02:40	03:10	03:10	00:00	Cylindrical sample
2/24/11	AZ31	1.57	0.40	10.0000	33.0592	8.516	3.88	02:00	4.26	02:00	04:00	30:00	26:00	Completely consumed

A quick review of the truncated cone-shaped sample test results indicated the melting and resolidification of material was highly random, with no set appendage formation pattern being observed. As a result, it was likely the extinguishment outcomes would not be as repeatable as desired. Furthermore, these initial tests showed that a fairly large percentage of the material continued to fall into the catch pan on melting, which was not the objective of the cone configuration. The initial intent was to have a very small mass of the sample melt at the top, ignite, and burn like a candle. In an attempt to force this condition, one of the original truncated cone samples was machined down into a thinner cone at the top, while retaining the original cone base near the bottom (figure 42). The concept of this stepped cone configuration was to allow easy ignition at the pointed tip of the cone, then subsequent ignition of the greater sample mass below. After warming up the test burner, the stepped cone was placed in front of the flames. As expected, the upper, thin portion of the sample melted in 1 minute and 24 seconds. The molten material dripped down onto the remaining sample, but did not ignite. The test progressed without ignition until 4 minutes and 37 seconds, at which point additional melting of the upper segment occurred. Immediately following this event, the sample ignited at 4 minutes and 40 seconds. The burner flames were not terminated until 1 minute later at 5 minutes and 40 seconds. The sample self-extinguished 10 seconds later at 5 minutes and 50 seconds (figure 43).

Figure 42. Conical Step-Shaped Test Sample Affixed in Talc-Filled Catch Pan (3/22/2011)

Figure 43. Post-Test Inspection of Conical Step-Shaped Test Sample (3/22/2011)

Although the stepped-cone sample did not burn continuously as was expected, it did show the ability of the thinner tip of the cone to melt more quickly. For this reason, one of the truncated cones was next machined down to a point, resembling a true conical shape (figure 44).

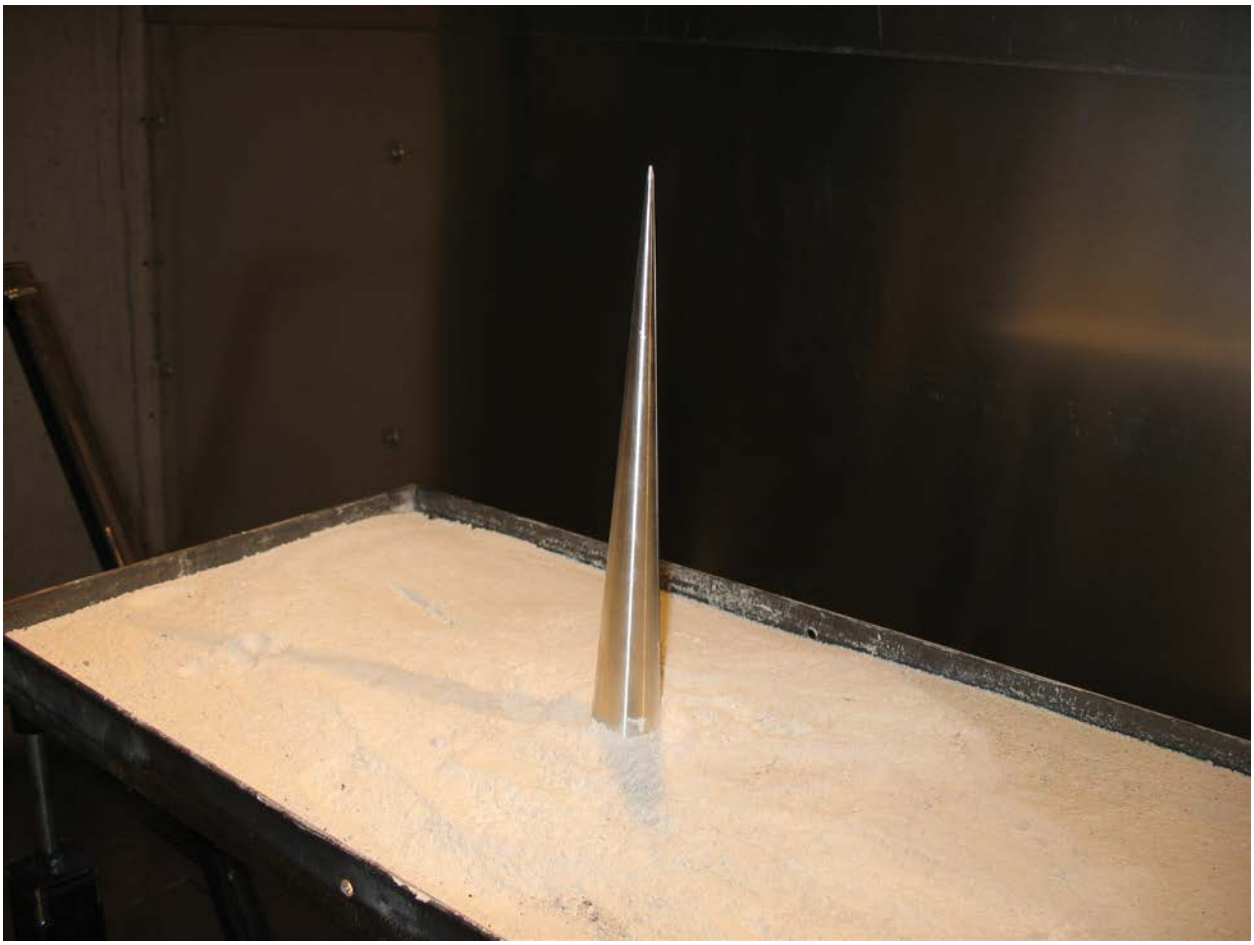


Figure 44. Cone-Shaped Test Sample Affixed in Talc-Filled Catch Pan (3/23/2011)

As with previous tests, the face of the top of the sample was situated 4 inches from the exit plane of the burner cone. During this particular test, the height of the top of the sample was lowered so that it was level with the horizontal centerline of the burner cone. Following the normal 2-minute burner warmup, the sample was translated into test position. As a result of the lowered test sample position with respect to the burner, the sample did not melt and the burner flames were terminated at 10 minutes. This was not a typical result; previous cone-shaped samples had melted in the 2-minute timeframe. The sample was allowed to cool and was then repositioned so the top of the sample was 1 inch above the horizontal centerline of the burner cone. During this test, an identical result occurred with no melting of the sample; the burner flames were terminated at 10 minutes and 30 seconds. It was evident that this position was also too low for sufficient heat transfer to melt the sample, so it was allowed to cool, and was then again raised so the top of the sample was 2 inches above the horizontal centerline of the burner. During this test, the top third of the sample melted at 8 minutes, with the molten material slumping down the surface of the unmelted sample remaining. The sample did not ignite and the burner flames terminated at 12 minutes. A repeat test was conducted with a fresh cone-shaped WE43 sample of approximately the same dimensions. The sample melted at 2 minutes and 32 seconds (similar to most of the truncated cone melt times), but did not ignite. The burner flames were terminated at 10 minutes. It appeared that during the tests that used the pointed cone samples, a significant

portion of the sample height melted and fell away from the burner flames, resulting in no ignition. In an attempt to keep more of the sample mass in front of the flames, the next several tests were conducted using the upper 6 inches of the original approximately 10-inch-high truncated cone samples. Essentially, the lower 4 inches of the samples were removed, resulting in a slightly smaller base diameter (figures 45 and 46).

Figure 45. Shortened Truncated Cone Sample With Burner Shown in Background (3/28/2011)

Figure 46. Shortened Truncated Cone Sample (3/28/2011)

During the initial test of this configuration, the top of the sample was situated at 2 inches above the horizontal centerline of the burner. Following burner application, the first sample melted at 3 minutes and 55 seconds, at which point it simultaneously ignited and continued to burn. The burner flames were terminated 1 minute later at 4 minutes and 55 seconds and the sample continued to burn until 6 minutes and 20 seconds, at which point the sample self-extinguished (figure 47). The test was repeated, with melting of a small portion of the top of the sample at 2 minutes and 15 seconds. Despite the melting, the sample did not ignite, so the test was continued. At 3 minutes and 30 seconds, an additional mass of material melted; ignition occurred simultaneously. The burner flames were terminated at 4 minutes and the sample continued to burn for an additional 9 minutes and 30 seconds. As mentioned previously in this section, it was difficult to determine the exact point in time when the sample self-extinguished, because the burning was concentrated on the mass of material that separated from the sample. This accumulated mass near the base of the sample was initially burning intensely, then gradually cooled and oxidized over a period of more than 9 minutes.

Figure 47. Post-Test Examination of Shortened Truncated Cone Sample (3/28/2011)

An additional test of a shortened WE43 sample was performed. Similar to the previous test, a small mass of the sample melted at 2 minutes and 30 seconds without ignition, then an additional mass melted at 3 minutes and 30 seconds, with ignition occurring simultaneously. The burner flames were terminated at 4 minutes, with sample self-extinguishment at 5 minutes and 30 seconds. Because the burning was not as extensive as in the previous test, the determination of the extinguishment point was much more evident. As a test check, a shortened, truncated cone sample of AZ31 was conducted. As expected, the sample melted at 2 minutes and 20 seconds, at which point it ignited. The burner flames were terminated at 3 minutes and the sample continued to burn until it was completely consumed.

Additional experimentation was necessary because the testing completed so far did not produce consistent results. As stated previously, the goal was to develop a repeatable test method in which the WE43 magnesium alloy would ignite, burn for a target period of approximately 90 seconds after burner flame termination, and then self-extinguish in a relatively short period.

During the next test, the diameter of the head of the truncated cone was increased, whereas the length remained at 6 inches (figure 48). This configuration yielded favorable results, with the initial melting occurring at 3 minutes and 52 seconds. This lengthier period of time for the initial

melt was expected because of the greater mass of the sample. At 4 minutes and 47 seconds, an additional mass of the sample melted and ignition occurred simultaneously. The burner flames were terminated at 6 minutes and 52 seconds and the sample continued to burn for a short duration, self-extinguishing at 8 minutes and 5 seconds.

Figure 48. Truncated Cone Sample With Larger Head Diameter (4/1/2011)

Additional tests were conducted with the smaller diameter head for comparison, with no unexpected change in results. Each sample burned for 25 seconds and 1 minute and 10 seconds, respectively, before self-extinguishing after the burner flames were removed. A check test was also conducted using AZ31 alloy, with the sample melting and igniting at 2 minutes and 15 seconds, burning until the material was completely consumed. Check tests were conducted to ensure that the test configuration would result in easy ignition of the AZ31 alloy.

Three additional tests were conducted using samples with the larger head diameter, but also with slightly reduced base diameters (figure 49). This resulted in a less conical, more cylindrical sample shape. Because the larger head diameter had produced a favorable result, the premise of slightly reducing the mass in the lower section of the sample was suggested to reduce the amount of time needed to melt the sample without sacrificing the propensity for this head size to burn.

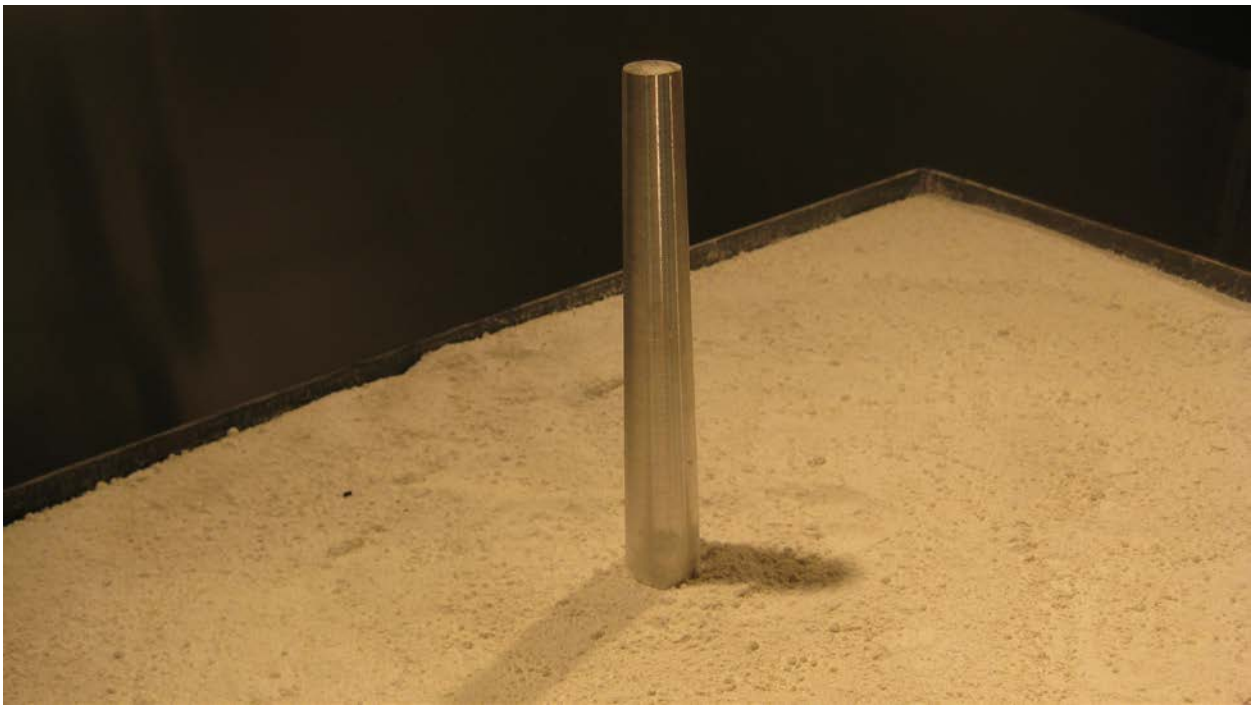


Figure 49. Truncated Cone Sample With Larger Head Diameter, Smaller Base (4/14/2011)

The configuration proved to be consistent, with melt times of 2 minutes and 51 seconds, 2 minutes and 46 seconds, and 2 minutes and 38 seconds. The time of ignition was also very consistent, at 3 minutes and 50 seconds, 3 minutes and 54 seconds, and 4 minutes. Following termination of the burner flames at approximately 5 minutes, all three samples continued to burn for 13 minutes, 15 minutes, and 13 minutes, respectively. Although consistent, the resulting lengthy burn durations were not representative of the results obtained during full-scale tests, in which the WE43 seat structure was able to self-extinguish much more rapidly.

Two additional truncated cone samples fabricated from Elektron®21 were tested. The sample length was increased slightly from 6 inches to approximately 8 inches, with the smaller head diameter, to determine if this configuration yielded a shorter burn duration (figure 50). Although this alloy had not been used in any of the full-scale tests, it exhibited a high level of flame resistance during previous horizontal bar testing. The samples melted at 1 minute and 52 seconds and 1 minute and 55 seconds; secondary melt times and ignition times were comparable. However, after removal of the burner flames, both samples continued to burn for an extended period, with burn durations of over 15 minutes and 8 minutes, respectively. An increasingly large oxidation mass began to form at the top of the sample once the burner flames were removed (figure 51). Although the burning mass was initially small and burned intensely, it began to enlarge as the burning subsided and the mass cooled. This made it difficult to determine the time of extinguishment. The results of the 18 tests described in this section are summarized in table 3.

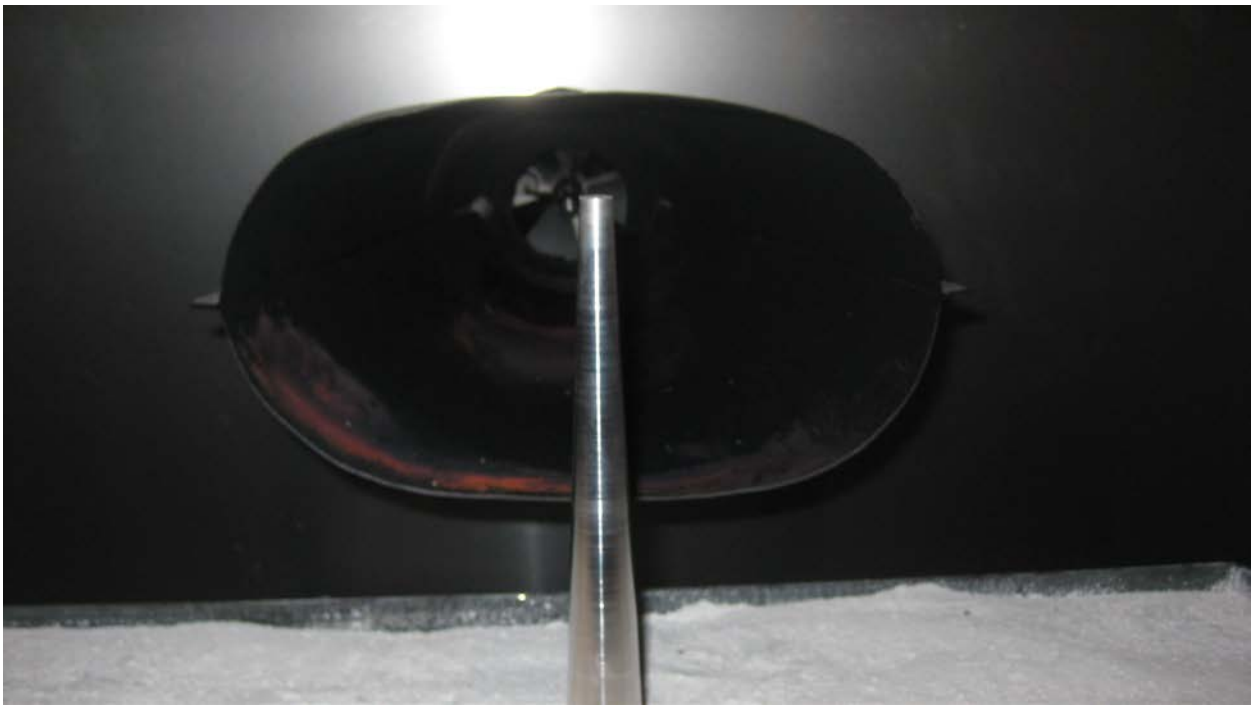


Figure 50. Truncated Cone Sample With Increased, 8-Inch Length (4/14/2011)

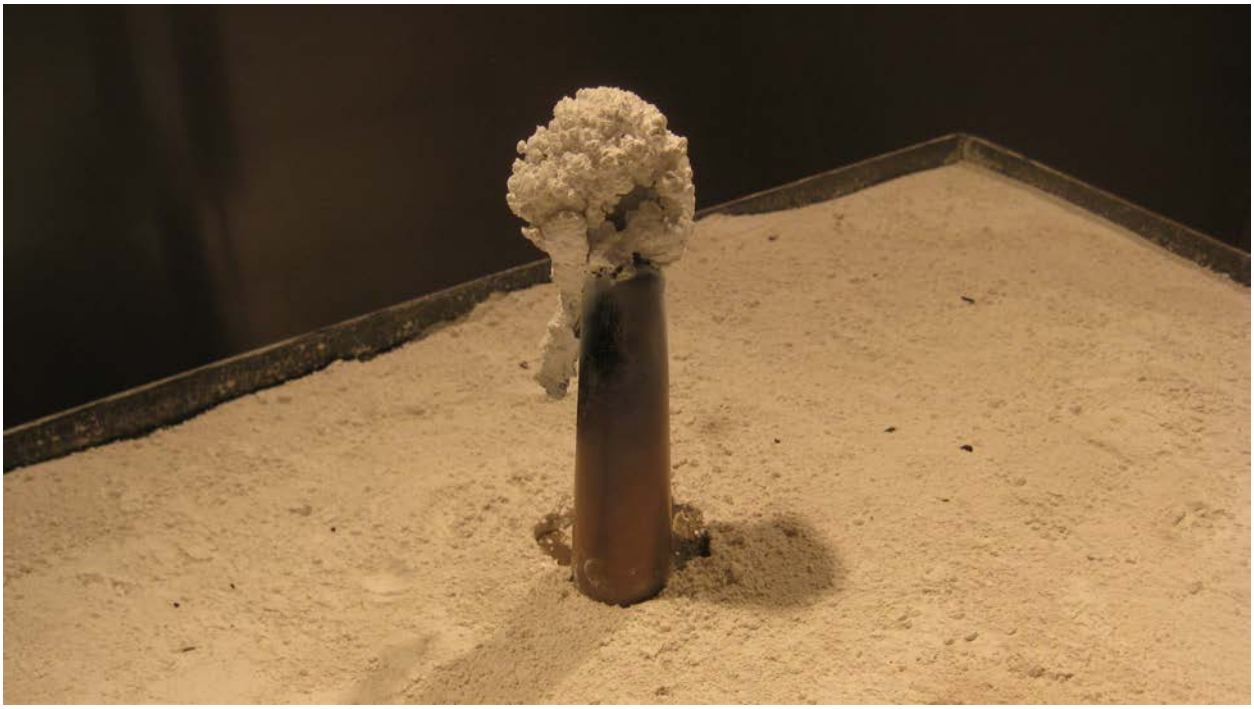


Figure 51. Oxidation Mass Formed at Top of Elektron®21 Sample (4/14/2011)

Table 3. Summary of Results on Various Truncated and Other Cone Configurations

Date Tested	Alloy Type	Base Dia (in)	Head Dia (in)	Length (in)	Surface Area (in2)	Vol (in3)	Surface to Volume Ratio	Time to Melt (Min:Sec)	Melting Rate (in3/min)	Secondary Melting (Min:Sec)	Time to Ignition (Min:Sec)	Burner Exposure (Min:Sec)	Time Ignition Ends (Min:Sec)	Duration of Ignition (Min:Sec)	Comments
3/22/11	WE43	1.58	0	10.2500	27.475	6.699	4.10	01:24	4.78	04:37	04:40	05:40	05:50	00:10	Stepped cone
3/23/11	WE43	1.567	0	9.1875	24.625	5.906	4.17	x	x	x	x	10:00	10:00	00:00	Sample tip at burner centerline; no melting
3/23/11	WE43	1.567	0	9.1875	24.625	5.906	4.17	x	x	x	x	10:30	10:30	00:00	Sample tip 1 inch above burner centerline
3/23/11	WE43	1.567	0	9.1875	24.625	5.906	4.17	08:00	0.74	x	x	12:00	12:00	00:00	Sample tip 2 inch above burner centerline
3/23/11	WE43	1.572	0	10.0625	26.864	6.510	4.13	02:32	2.57	x	x	10:00	10:00	00:00	Sample tip 2 inch above burner centerline
3/28/11	WE43	1.298	0.3965	6.0000	17.456	3.700	4.72	03:55	0.94	x	03:55	04:55	06:20	01:25	Cone shortened to 6 inches; tip 2 inch above CL
3/28/11	WE43	1.075	0.3960	6.0000	14.911	2.728	5.47	02:15	1.21	03:30	03:30	04:00	13:30	09:30	Cone shortened to 6 inches; tip 2 inch above CL
3/29/11	WE43	1.096	0.3915	6.0000	15.102	2.800	5.39	02:30	1.12	03:30	03:42	04:00	05:30	01:30	Repeat previous, sample burned for 1:30
3/29/11	AZ31	1.088	0.3915	6.0000	15.018	2.769	5.42	02:20	1.19	x	02:20	03:00	20:00	17:00	Check method using cone of AZ-31
4/1/11	WE43	1.176	0.5935	6.0000	18.060	3.822	4.73	03:52	0.99	04:47	04:57	06:52	08:05	01:13	Test fatter sample, but still 6 inches tall.
4/1/11	WE43	1.100	0.3950	6.0000	15.187	2.828	5.37	03:08	0.90	04:23	05:15	06:15	06:40	00:25	Sample reignites at 11:16, burns until 26:15
4/1/11	WE43	1.120	0.3940	6.0000	15.402	2.907	5.30	02:37	1.11	03:53	04:50	05:50	07:00	01:10	Self-extinguished
4/1/11	AZ31	1.120	0.400	6.0000	15.462	2.925	5.29	02:15	1.30	x	02:15	03:00	20:00	17:00	Completely consumed
4/14/11	WE43	0.875	0.5850	6.0000	14.629	2.542	5.75	02:51	0.89	03:20	03:50	05:05	18:05	13:00	Bigger head dia, smaller base dia
4/14/11	WE43	0.938	0.5750	6.0000	15.211	2.747	5.54	02:46	0.99	x	03:54	04:54	20:00	15:06	Bigger head dia, smaller base dia
4/14/11	WE43	0.936	0.5895	6.0000	15.345	2.789	5.50	02:38	1.06	03:21	04:00	05:00	18:00	13:00	Bigger head dia, smaller base dia
4/14/11	EL21	1.101	0.3915	8.1250	20.132	3.819	5.27	01:52	2.05	03:20	03:30	04:30	20:00	15:30	Sample length increased
4/14/11	EL21	1.098	0.3915	8.0625	19.942	3.773	5.29	01:55	1.97	02:27	04:14	05:14	14:00	08:46	Sample length increased

Further experimentation continued with lower mass samples, in an effort to reduce the amount of molten mass accumulating at the base of the samples. Initial testing on 10-inch long pointed conical samples resulted in separation of a significant portion, which melted and collapsed away from the main body of the test sample. Because the resulting collapse prevented any of the material from remaining in front of the burner flames, no ignition occurred. This configuration was revisited, with some slight modifications. The sample length was reduced from approximately 10 inches down to 8 inches, and the sample tip was placed 2 inches above the horizontal centerline of the burner cone (figure 52). As with previous tests, the face of the top of the sample was situated 4 inches from the exit plane of the burner cone. Following the normal 2-minute burner warm-up, the sample of AZ31 was translated into test position. This first sample quickly melted at 35 seconds, with ignition occurring at 45 seconds. The burner flames were terminated more quickly during this test at 1 minute and 15 seconds. The sample burned until 3 minutes and 15 seconds, at which point it self-extinguished. This was an unexpected result, as all previous tests of AZ31 alloy had burned until completely consumed. It appeared that the reduction in the exposure duration contributed to this result. The test was repeated with another AZ31 sample, resulting in a very similar outcome—43 second melt, 1 minute and 34 seconds until burning, and 3 minutes of sample burning after the burner flames were terminated before self-extinguishment. These two tests were followed by a test using a WE43 sample with nearly identical dimensions. After being translated in front of the burner, the WE43 sample melted at 1 minute and 33 seconds, with no ignition occurring. The sample remained until 6 minutes and 20 seconds, at which point additional melting occurred, but again no ignition (figure 53). The burner flames were terminated at 7 minutes. A follow-up WE43 test was conducted to determine repeatability. After flame application, the sample melted at 1 minute and 12 seconds, again with no ignition. The sample remained until 2 minutes and 38 seconds, when additional material melted. Shortly thereafter at 2 minutes and 45 seconds, the sample ignited and started to burn.

Figure 52. Pointed Conical Sample of WE43 (5/5/2011)

The burner flames were terminated 1 minute later at 3 minutes and 45 seconds. Unexpectedly, the sample continued to burn for an additional 3 minutes and 45 seconds, which was longer than either of the two AZ31 samples had burned. Because this result was atypical, a check test was run using a 10-inch long truncated cone sample of AZ31. The sample melted at 2 minutes with ignition occurring simultaneously. The burner flames were terminated at 4 minutes and the sample continued to burn for an additional 16 minutes, completely consuming the sample. It appeared that this original truncated cone configuration was consistent in terms of AZ31 igniting and burning completely. For comparison, a final test was run on another 8-inch long WE43 pointed cone sample. During the test, the sample melted at 1 minute and 5 seconds and ignition occurred at 1 minute and 30 seconds. A secondary melting event occurred at 3 minutes and 45 seconds without disruption to the burning. The burner flames were terminated at 4 minutes and the sample self-extinguished at 5 minutes and 35 seconds. This result did not match those of either of the previous two using the pointed WE43 cones (one sample did not ignite and the other ignited and burned for 3 minutes and 45 seconds). The results indicated that this sample configuration produced inconsistent results. The pointed sample results are shown in table 4.

Figure 53. Pointed Conical Sample of WE43, Post-Test (5/5/2011)

Table 4. Summary of Results on Pointed Cone Configurations

Date Tested	Material Type	Base Diameter (in)	Head Diameter (in)	Length (in)	Surface Area (in^2)	Volume (in^3)	Surface-to-Volume Ratio	Time to Melt	Melting Rate (in^3/min)	Secondary Melting	Time to Ignition	Burner Exposure	Time Ignition Ends	Duration of Ignition	Comments
5/5/11	AZ31	1.093	0.113	7.8750	15.895	2.744	5.79	00:35	4.70	x	00:45	01:15	03:15	02:00	Sample tip 2 inches above horizontal CL
5/5/11	AZ31	1.090	0.118	8.1250	16.383	2.829	5.79	00:43	3.95	x	01:34	02:34	05:34	03:00	Sample tip 2 inches above horizontal CL
5/5/11	WE43	1.090	0.115	7.9375	15.990	2.756	5.80	01:33	1.78	06:20	x	07:00	07:00	00:00	Sample tip 2 inches above horizontal CL
5/5/11	WE43	1.093	0.120	8.0000	16.214	2.806	5.78	01:12	2.34	02:38	02:45	03:45	07:30	03:45	Sample tip 2 inches above horizontal CL
5/5/11	AZ31	1.570	0.400	10.0000	33.059	8.516	3.88	2:00	4.26	x	02:00	04:00	20:00	16:00	Sample tip 3 inches above horizontal CL
5/25/11	WE43	1.090	0.115	8.0000	16.114	2.779	5.80	01:05	2.56	03:45	01:30	04:00	05:35	01:35	Sample tip 2 inches above horizontal CL

Up to this point, the experimentation with shortened truncated cones and pointed cones had produced somewhat inconsistent results when compared to the original truncated cone configuration. For this reason, testing continued using the original format of 10 inches in length, a base diameter of approximately 1.6 inches, and a head diameter of approximately 0.4 inches. In an effort to determine the level of repeatability, a total of 30 tests were run using this configuration. The results are summarized in table 5.

Table 5. Results of Truncated Cone Tests (original dimensions)

Date Tested	Material Type	Base Diameter (in)	Head Diameter (in)	Length (in)	Surface Area (in^2)	Volume (in^3)	Surface-to-Volume Ratio	Time to Melt	Melting Rate (in^3/min)	Secondary Melting	Time to Ignition	Burner Exposure	Time Ignition Ends	Duration of Ignition	Comments
5/12/11	WE43	1.573	0.390	9.7500	32.182	8.270	3.89	02:05	3.97	04:14	04:20	05:00	06:15	01:15	Sample tip 2 inches above horizontal CL
5/12/11	WE43	1.568	0.389	10.0625	33.035	8.482	3.89	02:02	4.17	03:40	04:40	05:00	05:08	00:08	Sample tip 2 inches above horizontal CL
5/12/11	WE43	1.567	0.390	10.1250	33.217	8.529	3.89	01:46	4.83	03:08	x	04:00	04:00	00:00	Sample tip 3 inches above horizontal CL
5/12/11	WE43	1.567	0.391	10.1250	33.224	8.530	3.89	02:00	4.27	x	03:50	04:00	05:30	01:30	Sample tip 3 inches above horizontal CL
5/12/11	WE43	1.568	0.390	10.1250	33.244	8.541	3.89	01:52	4.58	02:36	02:58	04:00	04:50	00:50	Sample tip 3 inches above horizontal CL
5/12/11	WE43	1.570	0.390	10.1250	33.272	8.557	3.89	01:55	4.46	02:46	04:04	05:00	09:30	04:30	Sample tip 3 inches above horizontal CL
5/13/11	WE43	1.569	0.390	9.7500	32.110	8.234	3.90	02:22	3.48	04:19	x	05:00	05:08	00:08	Sample tip 2 inches above horizontal CL
5/13/11	WE43	1.563	0.390	10.0625	32.951	8.438	3.91	02:01	4.18	04:05	02:15	05:00	05:10	00:10	Sample tip 2 inches above horizontal CL
6/9/11	WE43	1.568	0.390	10.1875	33.436	8.594	3.89	02:01	4.26	03:27	02:10	05:00	06:20	01:20	Sample tip 2 inches above horizontal CL
6/9/11	WE43	1.571	0.391	10.1250	33.316	8.576	3.88	01:59	4.32	03:27	03:40	04:00	05:05	01:05	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.568	0.391	10.1875	33.452	8.600	3.89	02:21	3.66	x	x	04:00	04:00	00:00	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.569	0.390	10.1250	33.262	8.551	3.89	02:08	4.01	x	x	04:00	04:00	00:00	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.571	0.390	10.0625	33.107	8.516	3.89	02:46	3.08	x	x	05:00	05:00	00:00	Sample tip 2 inches above horizontal CL

Table 5. Results of Truncated Cone Tests (original dimensions) (Continued)

6/10/11	WE43	1.572	0.391	10.1250	33.325	8.580	3.88	02:22	3.63	x	x	05:00	05:00	00:00	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.572	0.390	10.1250	33.308	8.574	3.88	02:18	3.73	04:00	x	04:00	04:00	00:00	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.570	0.390	10.1875	33.473	8.613	3.89	01:51	4.66	02:52	02:10	04:00	04:54	00:54	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.575	0.390	10.0625	33.163	8.546	3.88	02:30	4.62	x	02:55	04:00	04:45	00:45	Sample tip 2 inches above horizontal CL
6/10/11	WE43	1.570	0.392	10.1875	33.498	8.622	3.89	02:08	4.04	04:01	x	04:00	04:00	00:00	Sample tip 2 inches above horizontal CL
8/23/11	WE43	1.575	0.390	10.1250	33.373	8.607	3.88	03:01	2.85	x	02:10	04:00	04:20	00:20	Sample tip 2 inches above horizontal CL
8/23/11	AZ31	1.569	0.390	10.1250	33.262	8.551	3.89	02:45	3.11	x	02:45	04:00	20:00	16:00	Sample tip 2 inches above horizontal CL
8/23/11	ZE41	1.571	0.389	10.0000	32.899	8.457	3.89	04:08	2.05	x	x	05:00	05:00	00:00	Unexpected result
8/23/11	ZK60	1.575	0.389	9.9375	32.779	8.441	3.88	03:20	2.53	x	03:20	04:00	05:50	01:50	Droppings not extinguished until 6:20
8/23/11	EL21	1.575	0.390	9.9375	32.795	8.447	3.88	02:53	2.93	x	x	05:00	05:00	00:00	Unexpected result
8/23/11	WE43	1.575	0.392	10.1250	33.398	8.616	3.88	03:36	2.39	x	03:00	04:00	11:00	07:00	Sample tip 2 inches above horizontal CL
8/30/11	WE43	1.572	0.390	10.1250	33.318	8.579	3.88	04:27	1.93	x	x	05:00	05:00	00:00	Sample tip 2 inches above horizontal CL
8/30/11	WE43	1.571	0.390	10.1250	33.299	8.569	3.89	02:17	3.75	03:54	x	04:00	04:00	00:00	Sample tip 2 inches above horizontal CL
8/30/11	WE43	1.571	0.390	10.1250	33.299	8.569	3.89	02:12	3.90	x	02:28	04:00	04:05	00:05	Sample tip 2 inches above horizontal CL
8/30/11	WE43	1.571	0.390	10.1250	33.299	8.569	3.89	03:01	2.84	x	02:50	04:00	20:00	16:00	Sample tip 2 inches above horizontal CL
8/30/11	AZ80	1.573	0.392	10.0000	32.976	8.491	3.88	01:32	5.54	02:35	02:32	04:00	20:00	16:00	Sample tip 2 inches above horizontal CL
8/30/11	AZ91	1.571	0.390	10.0000	32.915	8.464	3.89	01:32	5.18	03:15	02:14	04:00	12:30	08:30	Sample tip 2 inches above horizontal CL

With the exception of four tests, the samples were positioned with the top of the sample 2 inches above the horizontal centerline of the burner cone. Beginning with test 8 of 30, the sample was positioned slightly closer to the burner so the centerline of the sample was 4 inches away from the exit plane of the burner cone (previously, the face of the sample top had been positioned 4 inches from the burner exit plane). The tests were completed over an approximate 3-month time period during a range of atmospheric conditions (e.g., external temperature, humidity, and atmospheric pressure). A quick survey of the WE43 results indicated a fairly consistent melt time in the 2-minute range with occasional excursions to more than 3 minutes and one test that required 4 minutes and 27 seconds for the sample to melt. In terms of the duration of the ignition of the WE43 samples, the results ranged from no burning (zero ignition) to complete consumption. However, a majority appeared to self-extinguish in less than 2 minutes after the burner flames terminated. Figure 54 shows a collection of post-test samples, some displaying a white, powdery residue near the top of the sample, which is indicative of oxidation/burning.

Figure 54. Post-Test Results of Truncated Cones (6/16/2011)

The WE43 test results were charted in an effort to determine the level of test repeatability (figure 55). The chart depicts three parameters for each of the 24 tests: time to ignition, time of burner flame termination (either 4 or 5 minutes), and time of sample self-extinguishment. A cursory review indicates a lack of consistency in terms of the time required for ignition, which was problematic.

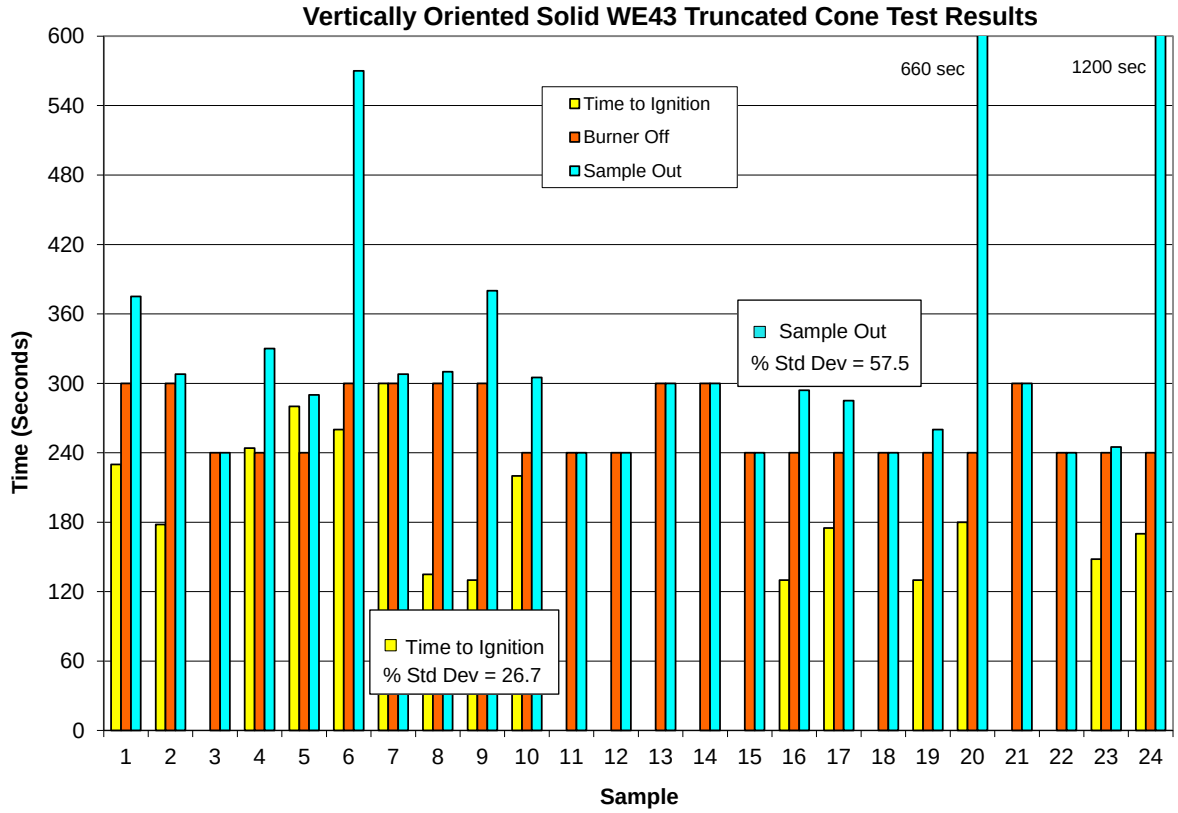


Figure 55. Charted Results of Truncated WE43 Cone Samples

The test results are further summarized in table 6. The average, the standard deviation, and the percent standard deviation for each of three measured parameters of the test are listed. There is a high degree of scatter when considering the time it takes for the WE43 samples to self-extinguish. The average time was calculated at 352.5 seconds, but was accompanied by a high standard deviation of 202.7 seconds. This resulted in a percent standard deviation of 57.5%, which was unacceptable for a laboratory-scale test. The melt time and time to ignition were much more consistent than the extinguishment time, but still unfavorably high. This result was not unexpected, as the melting of the samples was dependent only on the amount of heat transferred from the burner, which was essentially unchanged during the course of testing. However, the time to ignition appeared to result from other factors that were not readily controlled, such as the shape and location of the molten and resolidified material that occurred during the melting process. Similarly, the time for extinguishment appeared to be dependent on such factors as the size, shape, and location of the burning appendage of material.

Table 6. Summary of WE43 Truncated Cone Test Results

	Time to Melt (Seconds)	Time to Ignition (Seconds)	Sample Extinguished (Seconds)
Average	140.9	194.0	352.5
Standard Deviation	36.9	55.8	202.7
% Standard Deviation	26.2	28.8	57.5

Because more than 60 tests had been conducted on vertically oriented cone samples up until this point, it was evident that a more consistent test configuration, sample format, or both were necessary. It would be impossible to establish appropriate pass/fail parameters because of the current level of inconsistency. For this reason, an effort was initiated to evaluate other test sample configurations and shapes.

2.4.2 Testing of Various Sample Shapes and Configurations.

The first concept was to orient one of the standard 10-inch-long truncated cones horizontally, resting on a grooved bed of compressed ceramic Kaowool™ boards (figure 56). The 10-inch-long horizontal sample was situated with a 1-inch section extending beyond the end of the uppermost ceramic board, allowing for this segment to melt and possibly continue to burn into the larger mass of material. An additional shelf was formed by lengthening one of the lower ceramic boards to capture any molten material that could fall below (figure 57). The tip of the sample was located 4 inches from the exit plane of the burner cone, along the horizontal axis of the burner. Following normal warmup, the sample was translated into position in front of the burner. The sample melted at 3 minutes and 25 seconds with no ignition. Additional melting also occurred at 4 minutes and 35 seconds, again without ignition. The burner flames were terminated at 6 minutes. For comparison purposes, an identical test was conducted using an AZ31 alloy sample in place of the WE43 sample. This sample melted at 3 minutes and 55 seconds and simultaneously ignited and began to burn. The burner flames were terminated at 5 minutes and the sample self-extinguished at 7 minutes and 30 seconds. This was somewhat unexpected because nearly all previous samples of AZ31 had resulted in complete consumption once ignited.

Figure 56. Test Configuration Using Grooved Ceramic Board as Sample Holder (9/20/2011)

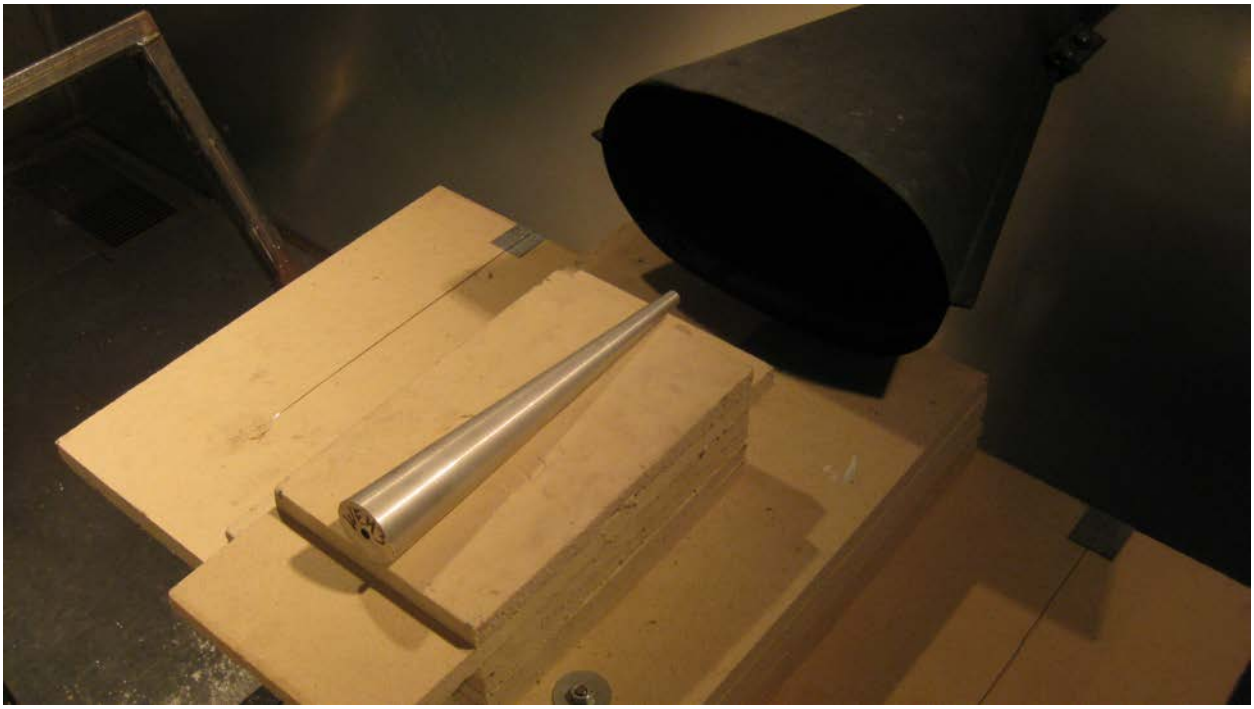


Figure 57. Truncated WE43 Cone Sample Mounted on Grooved Ceramic Board (9/20/2011)

In an attempt to reduce the mass of the sample, a truncated AZ31 cone was turned down on a lathe to produce a cylindrical shape. The shape was then situated in the grooved ceramic board, similar to the two previous tests, with the exception of material not extending beyond the

ceramic boards (figure 58). The end face of the cylinder was situated 4 inches away from the exit plane of the burner cone. After exposing the sample to the burner flames, melting did not occur until 6 minutes and 15 seconds, at which point ignition occurred. The lengthy period of time required for melting was likely due to the small amount of material being directly exposed to the burner flames. The sample was removed from the burner flames at 7 minutes with burning continuing for an additional 15 minutes, essentially consuming the entire amount of material (figure 59).

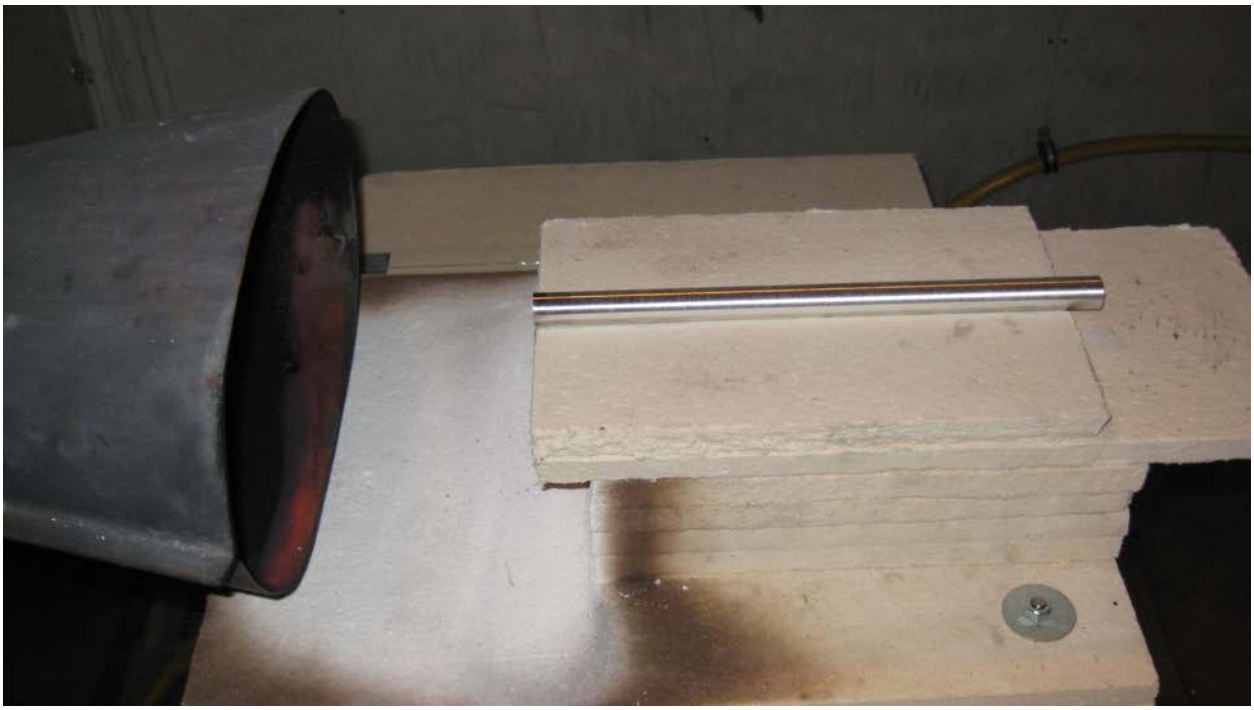


Figure 58. Thin Horizontal AZ31 Cylinder Sample on Grooved Ceramic Boards (9/21/2011)

Figure 59. Thin Horizontal AZ31 Cylinder Sample, Post-Test (9/21/2011)

Until this point, all testing had been conducted on solid samples, regardless of shape (truncated cone, pointed cone, thin cylinders, and various combinations of these). Although aircraft seats generally contain solid leg components machined from plate, there are also many hollow or lower-mass components. Because there were several magnesium components available (salvaged from the previous full-scale tests), it was decided that some experimentation on these would provide additional, useful data.

The seat-back frames used in the full-scale tests were fabricated from extruded rectangular box sections with outside dimensions of approximately 0.75 inch by 1.5 inches and a wall thickness of 0.125 inches. A 12-inch-long section of this component was cut and mounted horizontally in front of the burner with the end of the component located along the centerline of the burner, approximately 4 inches from the burner cone (figures 60 and 61).

Figure 60. Rectangular WE43 Box Section Component Mounted Horizontally, Front View (9/22/2011)

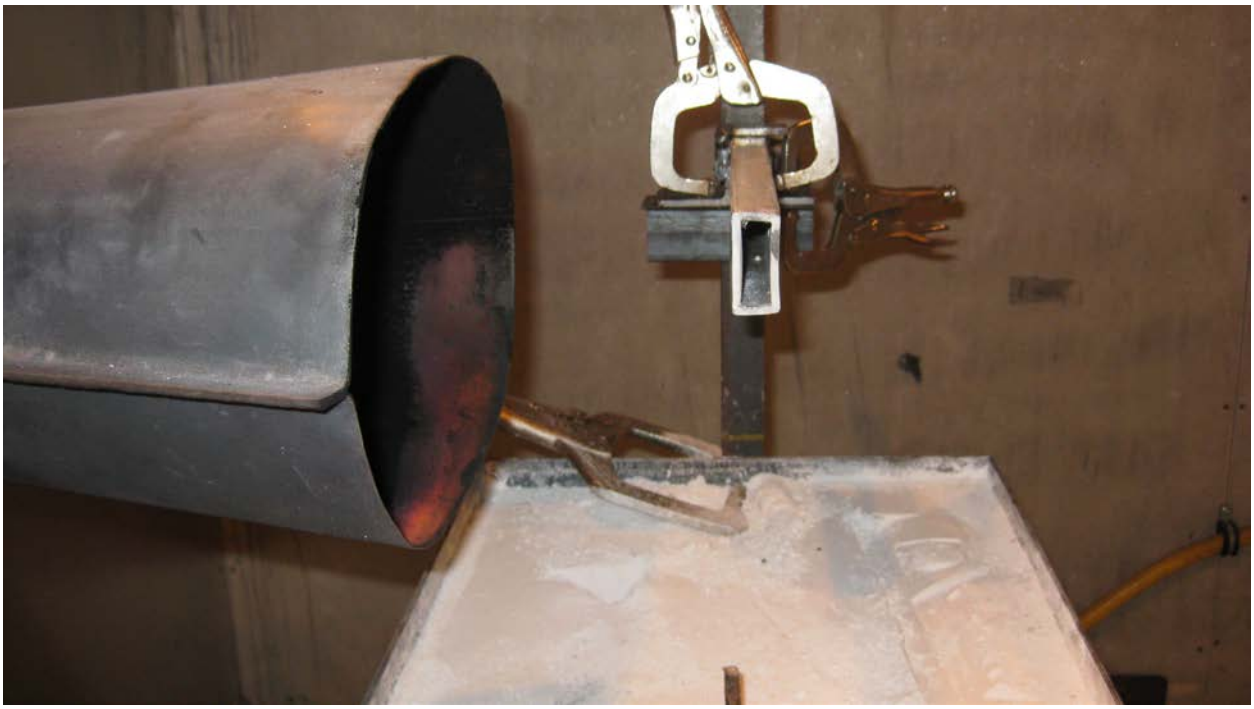


Figure 61. Rectangular WE43 Box Section Component Mounted Horizontally, Side View (9/22/2011)

Following burner warmup, the horizontal sample was placed in front of the burner. As expected, the thin-walled sample began to yield at 2 minutes and 50 seconds, much more quickly than previous solid samples. Ignition of the material occurred simultaneously near the open end of the box sample. As the sample continued to melt and slump downward, the burning intensified. The burner flames were terminated at 5 minutes, and the sample self-extinguished at 6 minutes and 20 seconds (figure 62). This was a promising result because the original target of the project was to develop a WE43 test sample that produced an approximate 90 seconds of burning prior to self-extinguishment.

Figure 62. Rectangular WE43 Box Section Component, Post-Test (9/22/2011)

Because of the favorable result with the horizontally mounted box section, and because of availability, a follow-up test was run in a similar fashion on the smaller baggage bar component of the seat. This component was also a rectangular box section with rounded edges, but smaller and thinner in dimension. These components measured 0.5 inch by 1 inch with a wall thickness of 0.0625 inch. As conducted previously, a 12-inch length of the component was cut and mounted horizontally in front of the burner (figures 63 and 64).

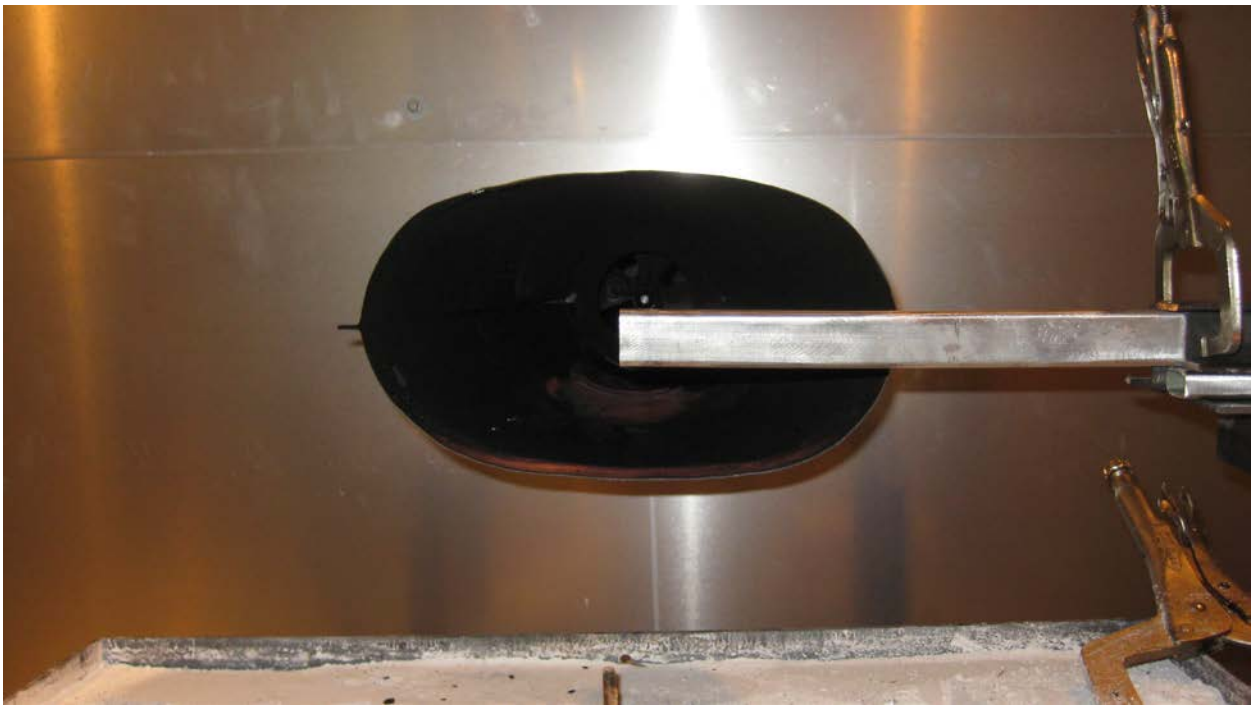


Figure 63. Small Rectangular WE43 Box Section Component Mounted Horizontally, Front View (9/22/2011)

Figure 64. Small Rectangular WE43 Box Section Component Mounted Horizontally, Side View (9/22/2011)

After moving the sample into the test position following burner warmup, the sample quickly began to yield at 1 minute. Although no immediate ignition occurred, the sample continued to collapse downward for the next minute, then ignited at 2 minutes. The burning intensified as the sample continued to slump and the burner flames were terminated at 4 minutes. Burning continued for an additional 20 seconds, at which point the sample self-extinguished (figure 65).

Figure 65. Smaller Rectangular WE43 Box Section Component, Post-Test (9/22/2011)

Although this result was also promising, it appeared there was only a small percentage of material that had ignited and burned. The resulting shape that formed during the melting process was somewhat random, which indicated the potential for repeatability issues.

Because additional WE43 seating components were available, the testing continued. In an effort to produce a rigid configuration that could resist collapse during the melting process, a section of the machined leg component was used. The original component was fabricated by machining out the surfaces of an irregular shape of 1-inch thick plate, which resulted in a component with essentially an I-beam cross section. This component was cut in an area that resulted in the formation of a short length of an I-beam sample that was mounted horizontally (figure 66). Because of the asymmetry of the component, only a short segment of it had a consistent cross section, but there was enough length that the end was situated along the centerline of the burner.

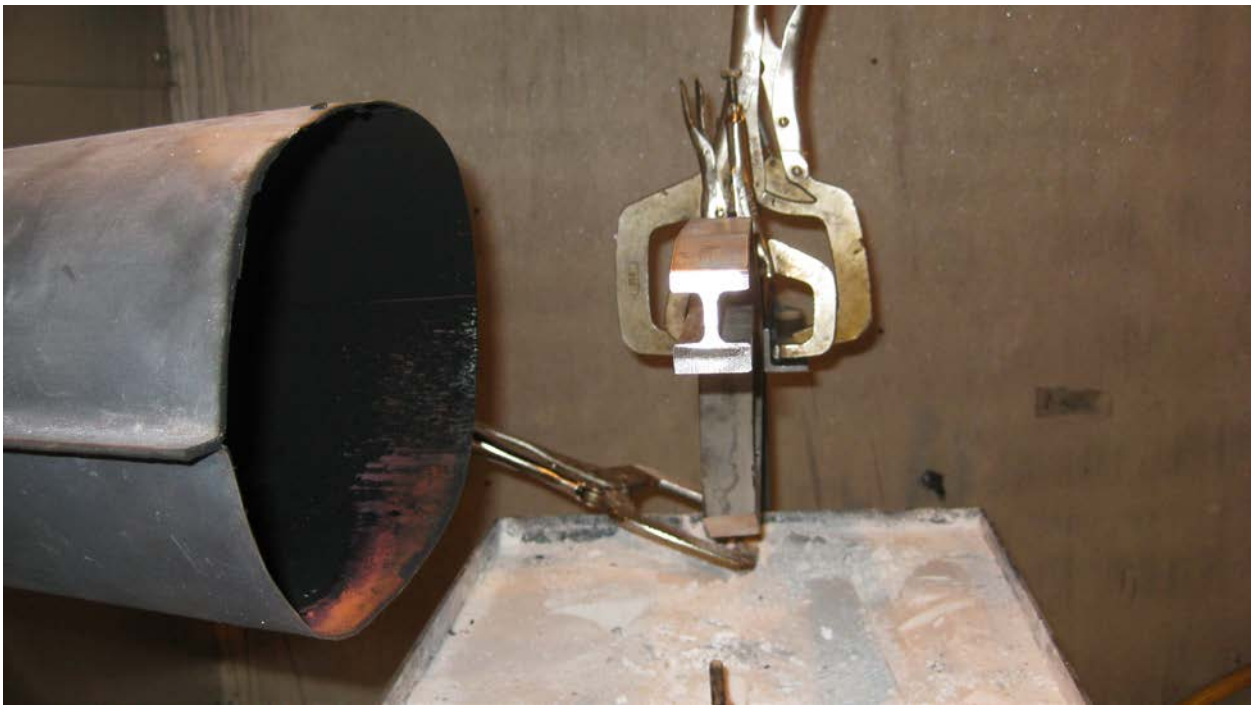


Figure 66. Thin I-Beam Cross-Section Sample From Seat-Leg Component (9/22/2011)

Following normal application of the burner flames, the sample began to melt at 3 minutes and 15 seconds. The melting occurred near the exposed end, which slumped downward. As the melting continued, the sample ignited at 3 minutes and 32 seconds. The burning intensified as the molten material eventually reached the catch pan below, forming a small puddle (figure 67). The burner flames were terminated at 5 minutes and the sample self-extinguished at 6 minutes and 30 seconds. This was a favorable outcome, as the amount of burning after flame removal was at the target amount.

Figure 67. Thin I-Beam Cross-Section Sample, Post-Test (9/22/2011)

Testing continued on a T-Beam cross-section sample that was machined from a 12-inch-long solid square bar leg component. The 1-inch by 1-inch square cross section was machined on two faces, leaving a T formation approximately 6 inches in length, which was mounted horizontally in front of the burner (figure 68). The bottom web was approximately 0.5 inch thick, whereas the vertical flange measured 0.1875-inch thickness by a height of 0.5 inches (figure 69). The front face of the vertical flange was positioned 4 inches from the exit plane of the burner cone.

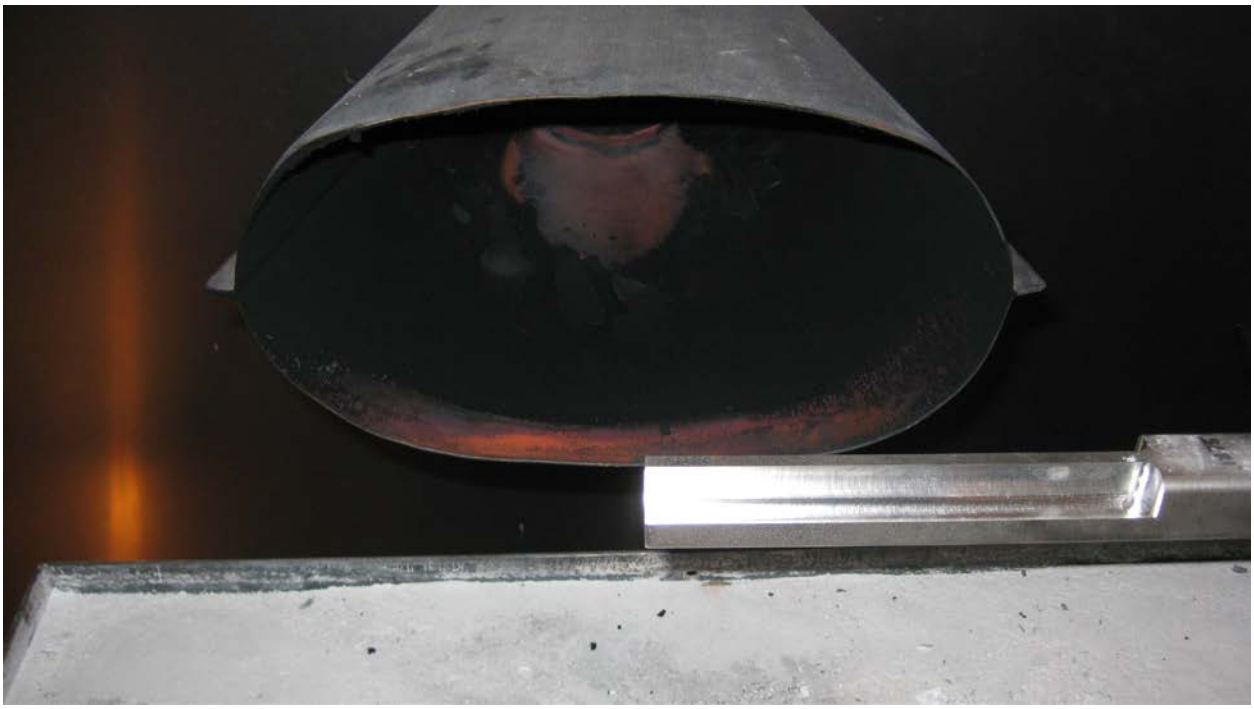


Figure 68. Thin T-Beam Cross-Section Sample Machined From Seat-Leg Component, Front View (9/27/2011)

Figure 69. Thin T-Beam Cross-Section Sample Machined From Seat-Leg Component, Side View (9/27/2011)

Following burner warmup, the sample was placed in front of the burner flames. Similar to the previous test, the sample began to yield at 3 minutes and 20 seconds with the material bending downward. This section of yielding material ignited at 3 minutes and 40 seconds and intensified as the test progressed. A small segment of the yielding material fully melted and separated from the primary sample (unknown time). The burner flames were terminated at 5 minutes and the sample continued to burn until 8 minutes and 30 seconds, then self-extinguished (figure 70). It appeared this T-shaped cross-section configuration assisted the duration of the burning, because the thicker bottom flange remained relatively rigid during the yielding process, whereas the thinner vertical flange ignited and started to burn because of its lower mass.

Figure 70. Thin T-Beam Cross-Section Sample Post-Test (9/27/2011)

To test this theory, a repeat test was performed in which the vertical flange was machined down to a thickness of 0.125 inch, whereas the bottom flange remained at 0.5-inch thickness. This would allow the vertical flange to ignite even more quickly. Other than the thinner web, the other dimensions remained identical to the previous test. Following burner warmup, the sample was placed in front of the flames. As expected, the sample began to yield slightly more quickly at 3 minutes and 12 seconds. The sample ignited at the end of the yielding area of the sample at 4 minutes and 12 seconds, but did not appear to burn as intensely as during the previous test. The burner flames were terminated again at 5 minutes, but the sample self-extinguished at this point also.

Because this result did not follow the anticipated pattern of burning, a final test was run in which the vertical flange was machined to an even thinner measurement of 0.0625 inch. The bottom flange remained at 0.5-inch thickness and all other dimensions remained the same as in the previous test (figure 71).

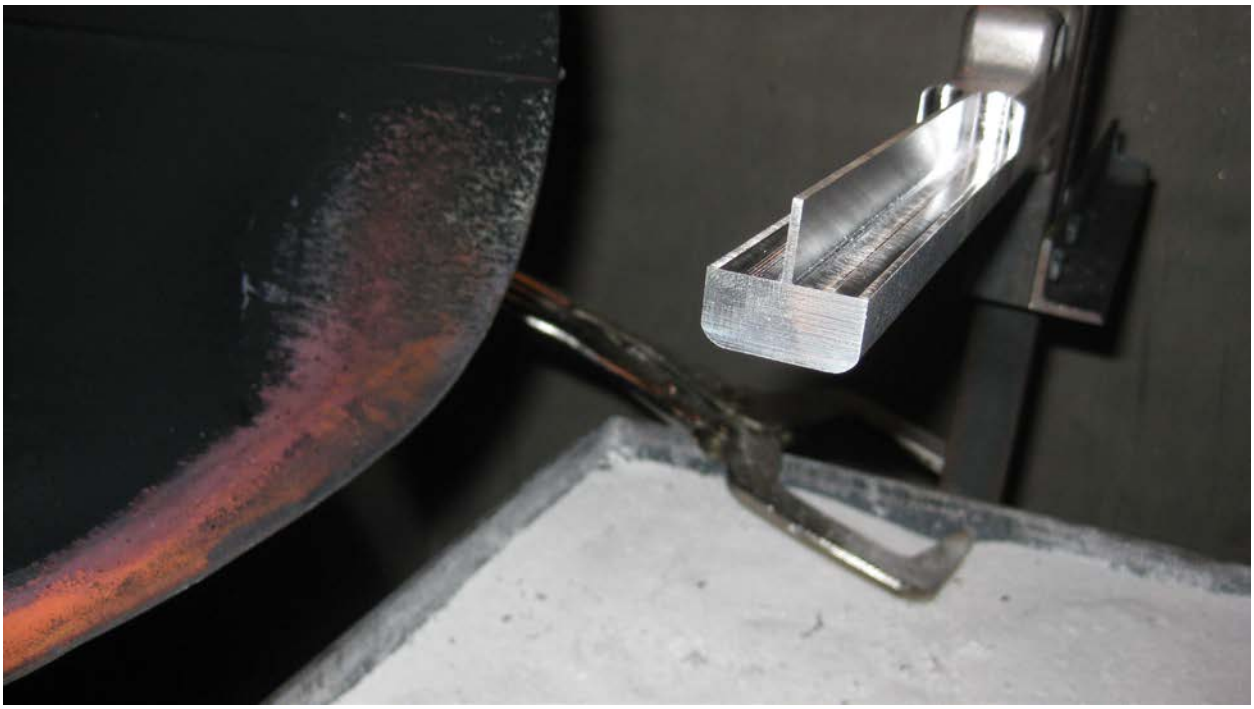


Figure 71. Thin T-Beam Cross-Section Sample Machined From Seat-Leg Component (9/28/2011)

After the burner was warmed up and the sample positioned in place, yielding of the material began at 3 minutes and 5 seconds. This was a consistent and expected result, as the thinner the vertical flange became when machined, the more quickly the yield occurred. The yielding material began to slump down towards the catch pan and began to spark at 4 minutes 24 seconds. The sparking transformed into full burning at approximately 4 minutes and 50 seconds. The burner flames were terminated at 5 minutes, with burning continuing for an additional 50 seconds until it ceased (figure 72).

Although this T-shaped cross section showed initial promise, the results were again inconsistent in terms of the duration of burning following termination of the burner flames. Because the machining process needed to produce these samples was very time consuming, the testing was discontinued in favor of a more realistic and affordable approach. Although the testing performed to that point did not result in the final selection of a particular sample configuration, the experiments were viewed as exploratory, thus providing information for future experiments.

Figure 72. Thin T-Beam Cross-Section Sample, Post-Test (9/28/2011)

During the previous three tests using the horizontal T-web configuration, the yielding material formed an irregularly shaped, vertically oriented mass, which became thinner at the bottom as it approached the catch pan. The mass loosely resembled an inverted cone, with the heavier base of the cone attached to the horizontal sample and the tip of the cone at the bottom. Because numerous truncated cone samples were still available from previous testing, an experiment was conducted using an inverted WE43 truncated cone sample suspended from a steel frame (figure 73). The smaller bottom of the suspended sample was situated along the horizontal axis of the burner cone (figure 74). The intention was to ignite the smaller mass area at the bottom and continue vertical burning after burner removal.

Figure 73. Inverted Truncated WE43 Cone Suspended From Hanger, Front View (9/29/2011)

Figure 74. Inverted Truncated WE43 Cone Suspended From Hanger, Side View (9/29/2011)

After normal burner warmup, the suspended sample was carefully situated in front of the burner flames. The very tip of the bottom of the sample melted at 1 minute and 59 seconds and ignited and began to burn at 2 minutes and 1 second. The burning continued until 3 minutes and 45 seconds, at which point the burning mass separated from the test sample and fell into the catch pan. When this occurred, the suspended (primary) sample was no longer burning. The burner flames were terminated at 4 minutes with no additional burning of the suspended sample (figures 75 and 76). However, the mass of separated material located in the catch pan continued to burn for an additional 2 minutes. Because the separation of material was an undesired result, the test was repeated under identical conditions. During the test, no melting or burning of the WE43 suspended sample occurred and the burner flames were terminated at 5 minutes.

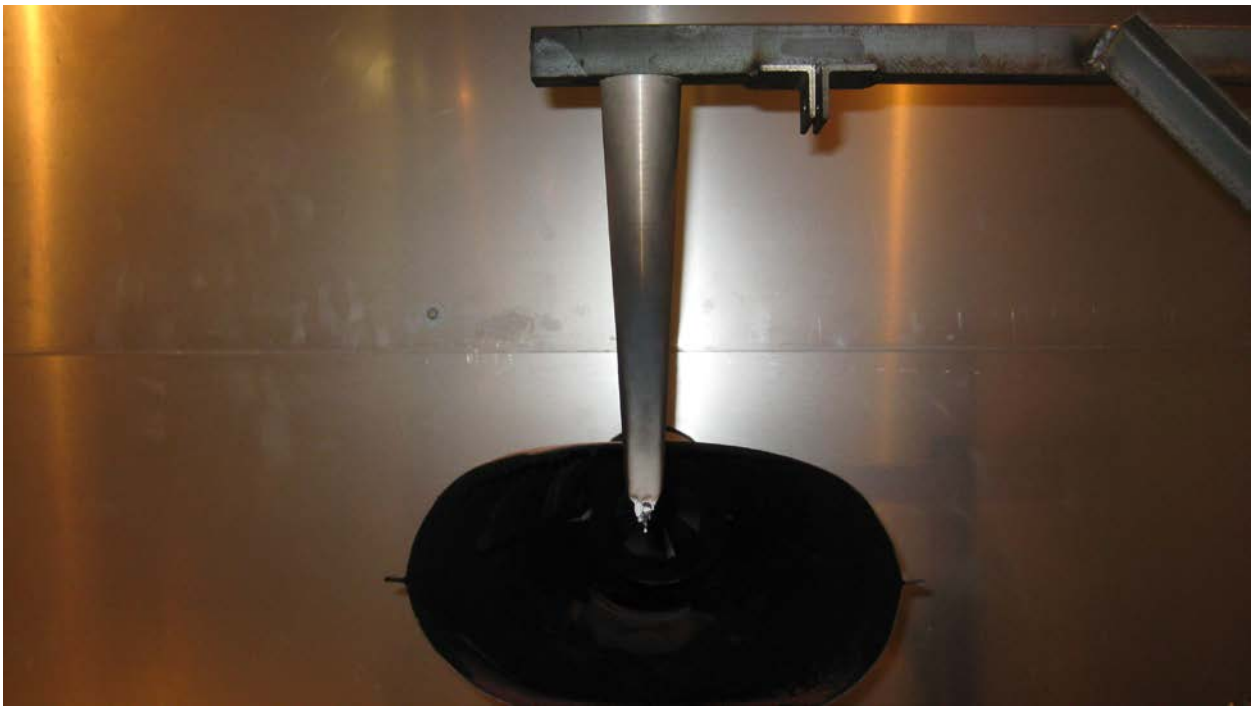


Figure 75. Inverted Truncated WE43 Cone, Post-Test (9/29/2011)

Figure 76. Closeup of Inverted Truncated WE43 Cone, Post-Test (9/29/2011)

For comparative purposes, a pointed AZ31 cone sample was suspended from the test frame, similar to the previous test. Because the pointed sample was considerably shorter than the previous 10-inch-long truncated cone samples, a length of threaded rod was used to facilitate the suspension (figure 77). The sample was situated with the pointed tip approximately 1 inch below the horizontal centerline of the burner cone. The intent was to increase the amount of heat transfer to the sample by lowering it s lightly as compared to the previous test, in which the sample did not melt after 5 minutes of exposure.

Figure 77. Inverted Pointed AZ31 Cone Suspended From Hanger (9/29/2011)

Following burner warmup, the suspended sample was moved into position in front of the burner. At 33 seconds, the tip of the sample melted quickly and instantly started to burn. However, this burning was confined to the very tip of the sample and when the burner flames were terminated at 4 minutes, the sample immediately self-extinguished (figure 78). This was an unexpected result because the AZ31 alloy, once ignited, typically burns until completely consumed. It was theorized that insufficient heat was transferred into the sample to sustain ignition.

Figure 78. Inverted Pointed AZ31 Cone, Post-Test, Side View (9/29/2011)

To confirm this result, the test was repeated with an identical pointed cone sample of AZ31. Following burner warmup, the sample was positioned in front of the burner. Similar to the previous test, the sample melted at 35 seconds and again ignited immediately. The burning continued, but was confined to the very tip of the sample and immediately self-extinguished when the burner flames were terminated at 4 minutes (figure 79). This result confirmed the previous result, indicating the likelihood of insufficient heat being transferred into the sample, thus preventing continued burning. Although the configuration produced repeatable results, these results did not correlate well with previous testing and full-scale results, all of which indicated the AZ31 alloy was difficult to extinguish once ignited.

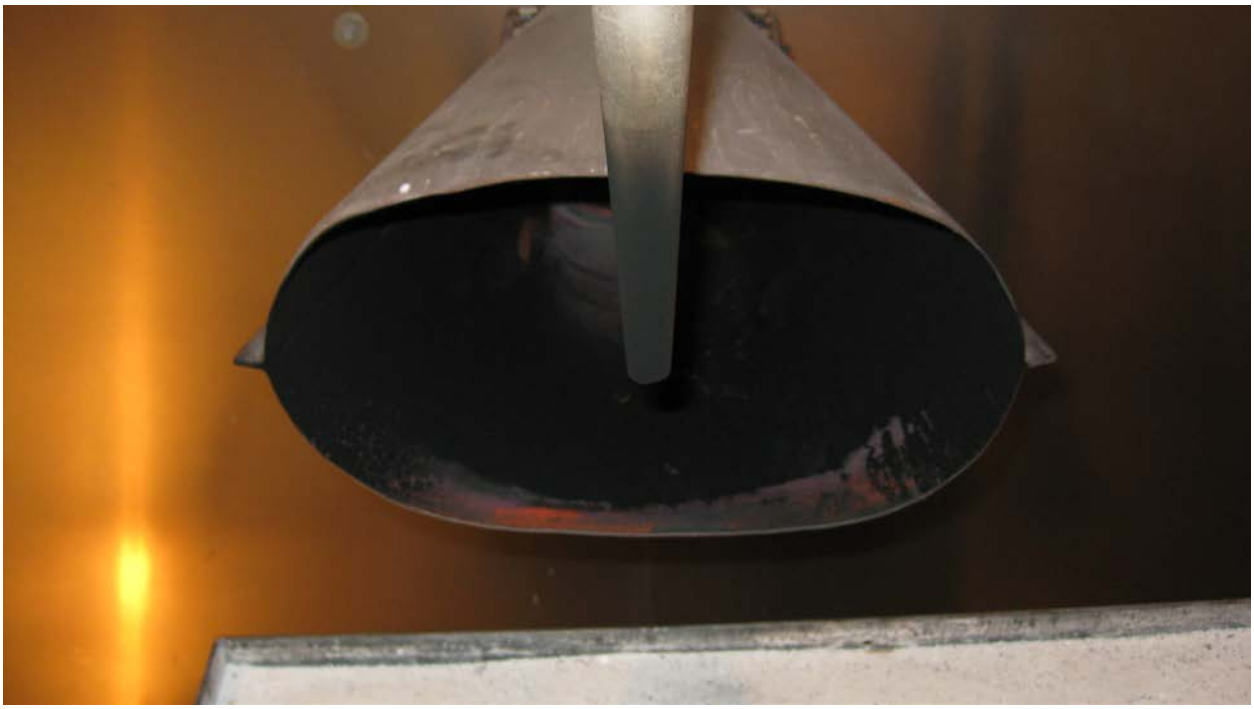


Figure 79. Inverted Pointed AZ31 Cone, Post-Test, Front View (9/29/2011)

2.4.3 Testing of Hollow Cylinder Samples.

The testing conducted thus far indicated the thin-walled hollow components ignited the most consistently. These included the seat-back frame rectangular cross-section elements and their baggage bar elements. In an effort to continue with experimentation and obtain additional information, a test was conducted on a section of the WE43 circular tubing used for the seat-frame cross tubes. As previously mentioned, various seat components salvaged from the full-scale demonstrations were available for testing. The cross tubes used in the seat had an outside diameter of 1.75 inches and a wall thickness of 0.120 inches. A new test fixture was fabricated to position an 8-inch length of tubing in a horizontal fashion. The end of the tube was positioned in line with the center of the burner cone, which was 4 inches away (figure 80). A hole was drilled in the test sample for bolt fastening to prevent movement during the heating process.

Figure 80. Horizontally Mounted Cylindrical Tubing Sample Cut From Cross Tube (9/30/2011)

After burner warmup and positioning of the sample, melting occurred at 2 minutes and 50 seconds. The sample ignited within 1 second of the melting, with the burning beginning at the rim of the tube, closest to the burner. The burning continued, with the end of the sample collapsing and bending down toward the catch pan. This sequence was reminiscent of the rectangular cross section tests, which produced a similar formation during the melting/burning process. A portion of the burning section of material separated from the test sample and fell into the catch pan at 3 minutes. The burner flames were terminated at 4 minutes and the burning continued for an additional 1 minute and 40 seconds (figure 81). Similar to the initial seat-back frame tests, this was a favorable result because the initial target was 90 seconds of burning of the WE43 prior to self-extinguishment.

Figure 81. Side View of Horizontally Mounted Cylindrical Tubing Sample, Post-Test (9/30/2011)

The test was repeated because of the favorable test result and because additional samples were easily produced by cutting lengths of the available cross tube. During the repeat test, the sample began to warp and collapse at approximately 2 minutes, with melting occurring at 2 minutes and 22 seconds. The sample ignited shortly thereafter at 2 minutes and 27 seconds, with continued melting of the material forming a thin shaft descending into the catch pan (figure 82). The thin shaft of material appeared nearly fluidlike, feeding into a small collection of material puddling on the surface of the catch pan (figure 83). The burner flames were terminated at 4 minutes and the sample continued to burn for an additional 90 seconds, which was the desired target of burn duration prior to self-extinguishment.

Figure 82. Horizontally Mounted Cylindrical Tubing Sample During Test (9/30/2011)

Figure 83. Horizontally Mounted Cylindrical Tubing Sample, Post-Test (9/30/2011)

Although both the duration of burning after burner flame termination and the repeatability were encouraging, it was clear that the vertical shaft formed during the melting process was quite irregular in shape and would likely be susceptible to variation during subsequent testing. During the previous test, a portion of the burning sample had completely separated and fallen into the pan. These types of results were suspect in terms of developing a repeatable test condition. Despite these shortcomings, the results were promising because of the intensity and consistency of the fire that resulted from testing of this particular sample shape.

In an effort to prevent separation of material during melting/burning, the circular tube was repositioned in a vertical orientation. The top of the cylinder was situated 2 inches above the horizontal centerline of the burner, at a distance of 4 inches from the exit plane of the burner cone. To prevent the sample from tipping during the test, a short stub of 1.5 by 1.5-inch box tubing was tack-welded onto a sheet of 0.125-inch steel, which was mounted onto the catch pan. The cylindrical sample fit snugly onto this sample holder (figures 84 and 85). The sample was moved into position in front of the flames after normal burner warmup. At 1 minute and 22 seconds, the sample began to yield with the front face of the cylinder beginning to collapse near the top. At 1 minute and 35 seconds, there was some initial sparking in this area, then burning started at 2 minutes and 28 seconds. The burning was initially concentrated on the cylinder edge closest to the burner, but the burning expanded to swirling inside the cylinder near the top. The burning was robust and sustained in this general area. The burner flames were terminated at 4 minutes and the burning continued for an additional 1 minute and 20 seconds. This was again a favorable result due to the robustness of the fire and the ability of the WE43 sample to self-extinguish in a short period of time after removal of the fire threat. A post-test inspection revealed collapsing of the material near the top, with the characteristic white oxidation (magnesium oxide) as evidence of the material burning (figures 86 and 87).

Figure 84. Box Tubing Stub Holder for Cylindrical Sample

Figure 85. Vertically Mounted Cylindrical Tubing Sample Cut From Cross Tube (9/30/2011)

Figure 86. Side View of Vertically Mounted Cylindrical Tubing Sample, Post-Test (9/30/2011)

Figure 87. Vertically Mounted Cylindrical Tubing Sample, Post-Test (9/30/2011)

A repeat test was arranged under identical conditions to confirm this positive result. After burner warmup, the sample was positioned in front of the burner flames. As in the previous test, the sample began to yield at 1 minute and 20 seconds, with sparking beginning at 1 minute and 33

seconds. The sparking could be described as brief, discontinuous blue/white flashes of light, indicative of ignition. At 2 minutes and 33 seconds, the ignition became sustained, was more robust, and was considered to be burning. The swirling flames were again evident inside the cylinder near the top edge. This burning continued unabated and the burner flames were terminated at 4 minutes. The sample continued to burn for an additional 1 minute and 35 seconds.

Four additional repeat tests were conducted, all with similar results. The time at which the sample began to yield was consistent, averaging approximately 1 minute and 33 seconds. The point of ignition of the four repeat tests was 3 minutes and the average burn duration after burner flame termination was 1 minute and 11 seconds. This level of consistency had not been exhibited during any of the previous test configurations, particularly of the solid, truncated cones. The yielding, melting, and ignition sequences were consistent, as was the shape of the post-test sample. These results were conveyed to a team of industry experts who were following the test developments closely. The team inquired into the possibility of conducting a test on an identically shaped sample of aircraft-grade aluminum for comparative purposes. Because additional aircraft seats were available from full-scale baseline tests (those conducted using OEM seats), it was easy to obtain an aluminum sample cut from an OEM cross tube (figure 88).

Figure 88. Vertically Mounted OEM Aluminum Cylindrical Tubing Sample (10/03/2011)

Following burner warmup, the aluminum cylinder was placed in front of the burner flames. The sample began to yield at 2 minutes, with the upper portion collapsing in a nearly identical sequence to that of the WE43 samples. However, no sparking, ignition, or burning was evident. The burner flames were terminated at 4 minutes and the sample was allowed to cool (figure 89). Although this result was expected, it was considered a necessary baseline comparison to the magnesium tests being conducted.

Figure 89. Vertically Mounted Aluminum Cylindrical Tubing Sample, Post-Test (10/03/2011)

Prior to conducting additional tests on the vertically oriented cylindrical samples, two tests were conducted on modified WE43 solid cones to determine the influence of increasing the wall thickness. Because it had been agreed that the solid truncated cones were not producing repeatable results, the concept of producing a thicker-walled sample by hollowing out the solid cones was suggested. This was accomplished by boring two of the samples with a 0.5625-inch drill (figure 90). A special mandrel was fabricated to mount the 5.5-inch-long test sample so the top was located 2 inches above the horizontal centerline of the burner cone; the centerline of the sample was located 4 inches away from the burner cone exit plane.

Following normal burner warmup, the modified cone was situated in front of the burner flames. Because of the sample's greater mass, it did not begin to yield until nearly 4 minutes. The sample ignited at 4 minutes and 30 seconds, again near the top of the sample, as expected. The burner flames were terminated at 5 minutes and the sample continued to burn for roughly 18 additional minutes. It appeared that during the melting/burning sequence, the sample collapsed inward, facilitating continued burning. Because all of the material became involved in the fire, it was difficult to judge exactly when the sample had self-extinguished (figure 91).

Figure 90. Truncated WE43 Cone Sample With 0.5625-Inch Center Bore (10/04/2011)

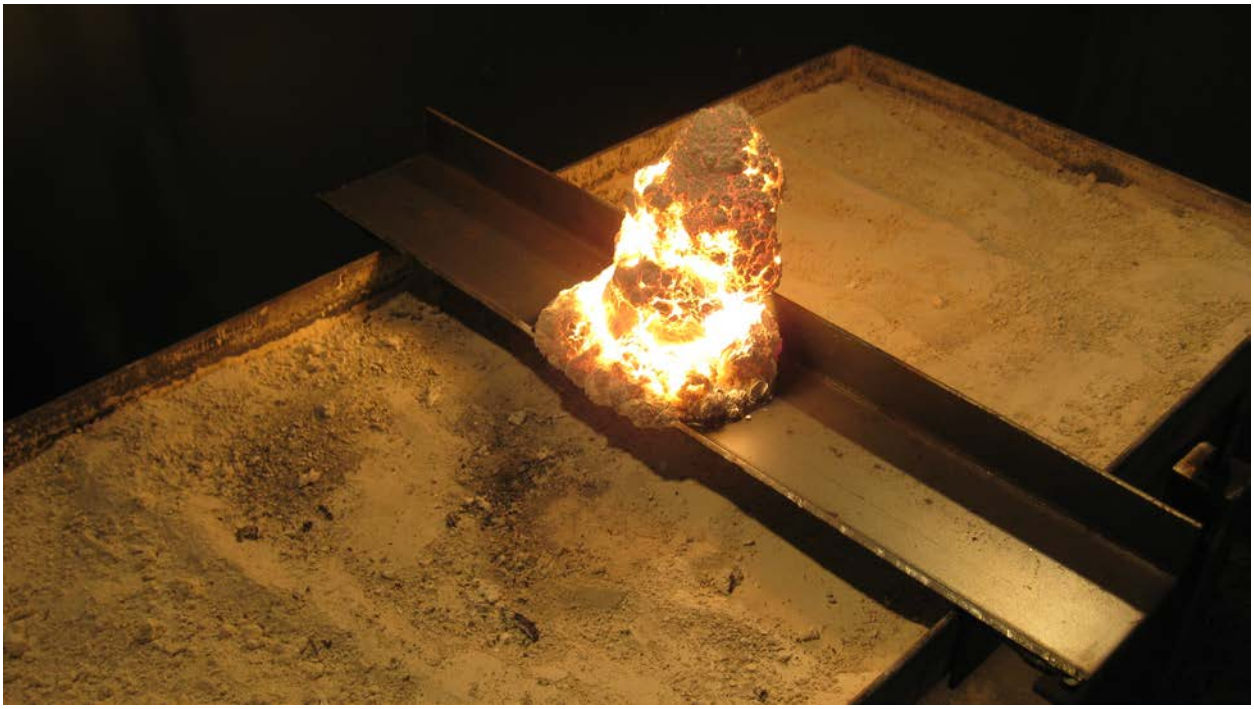


Figure 91. Truncated WE43 Cone Sample With Center Bore, Post-Test (10/04/2011)

As indicated, the test was repeated with an identically prepared solid WE43 truncated cone sample with central bore. A nearly identical yielding of the sample occurred 4 minutes after being exposed to the burner flames. However, during this test, the sample did not ignite and the

burner flames were terminated at 6 minutes. Whereas this result was inconsistent compared to the previous test on an identical sample, it illustrated the relative repeatability of the thin-walled cylindrical sample tests by comparison.

Because of the success of the vertically oriented cylindrical samples, a similar test was conducted using a rectangular cross section seat-back frame sample oriented vertically. As described previously, the sample cross section measured 0.75 i nch by 1.5 inches outside dimensions, with a 0.125-inch wall thickness and squared edges. The 8-inch-long sample was drilled near the bottom and through-bolted to secure the sample during the test (figure 92). As with previous tests, the upper end of the sample was situated at 2 inches above the horizontal centerline of the burner cone; the face of the sample was set at a distance of 4 inches from the exit plane of the burner cone.

Figure 92. Vertically Oriented Rectangular Cross-Section Sample (10/6/2011)

Following burner warmup and positioning of the sample, evidence of the material yielding occurred at 2 minutes and 50 seconds. In a sequence similar to the vertically oriented cylinders, the front face of the sample began to fold inward while the rear face collapsed over top. Some minor sparking began at 3 minutes and 20 seconds near the collapsed mass, but the ignition was intermittent and not sustained. The burner flames were terminated at 5 minutes with no additional sample burning (figures 93 and 94).

Figure 93. Vertically Oriented Rectangular Cross-Section Sample, Post-Test (10/6/2011)

Figure 94. Closeup of Vertically Oriented Rectangular Cross-Section Sample, Post-Test (10/6/2011)

Because an abundance of samples were available, an additional test was conducted on the rectangular cross-section component. Normally, the wider face of the material is oriented toward

the burner to maximize the amount of heat transfer into the sample. In this test, the sample was rotated such that the short face was facing the burner (figure 95). Aside from this change, the test remained the same as the previous one. After normal preparations, the sample was positioned in front of the burner flames. The sample began to yield at 2 minutes and 10 seconds. The quicker time to yield was unexpected, as it was theorized that the orientation of the sample would result in a lower amount of heat transfer. The front face began to collapse and this mass of material ignited at 2 minutes and 40 seconds. The ignition could not be fully sustained, which resulted in sparking and minor burning in an intermittent manner. However, when the burner flames were terminated at 5 minutes, the sample continued to burn for an additional 3 minutes and 30 seconds (figure 96).

Figure 95. Vertically Oriented Rectangular Cross-Section Sample (10/6/2011)

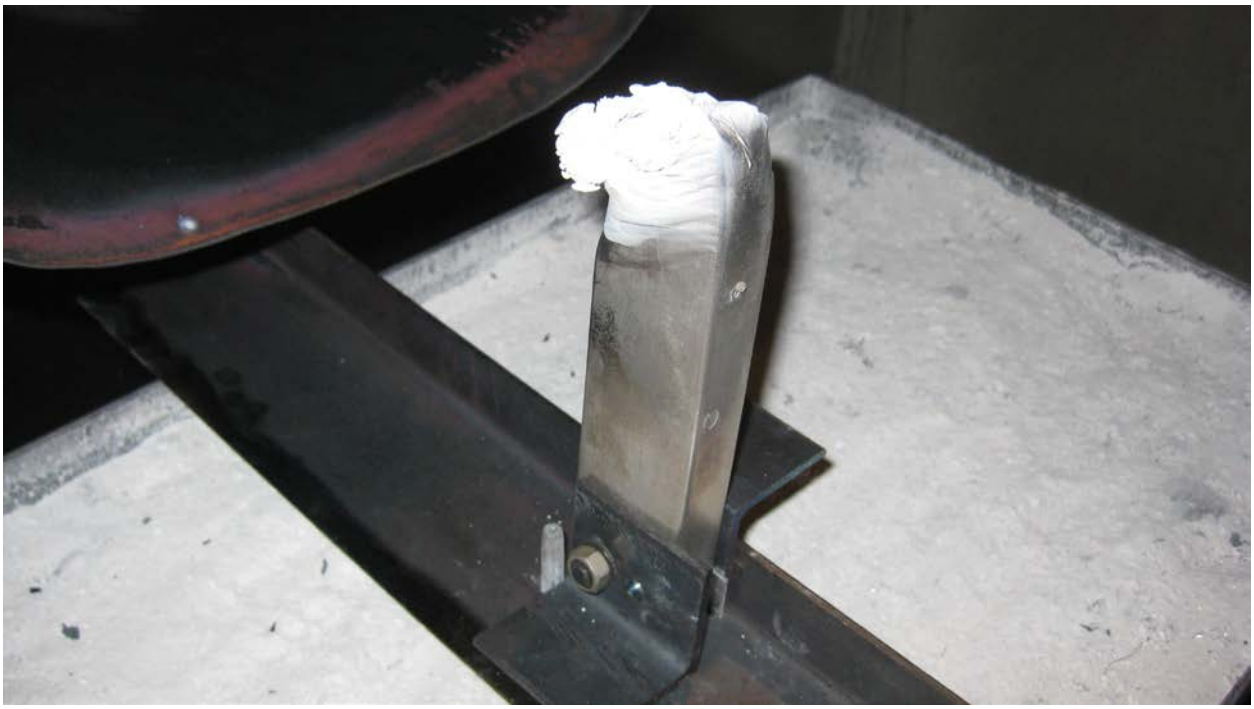


Figure 96. Vertically Oriented Rectangular Cross-Section Sample, Post-Test (10/6/2011)

While the results of the rectangular cross section were being studied, a specially prepared, truncated cone sample of WE43 became available. This 5.5-inch-long sample was sent out for machining after the initial tests on the bored-out truncated cones. The present sample had been bored out to the point that the wall thickness was 0.125 inch (similar to the hollow cylinders that produced favorable results) at the upper end of the component (figures 97 and 98). However, the large bore did not go through to the other end; it was only 3 inches deep. The remaining 2.5 inches of the sample were solid near the base end.

Figure 97. Specially Prepared Truncated WE43 Cone Sample With Center Bore (10/11/2011)

Figure 98. Closeup of Specially Prepared Truncated WE43 Cone Sample With Center Bore (10/11/2011)

Following burner warmup and normal placement of the sample in front of the burner flames, the sample began to yield at 2 minutes 30 seconds. During the yield sequence, the material appeared

to collapse in a manner similar to the vertical cylinder cross-tube samples, with the front face of the sample (nearest the burner) folding inward and the rear face collapsing on top of that. Evidence of ignition began at 4 minutes and 10 seconds, growing more intense with time. The burner flames were terminated at 5 minutes, but no additional after-burning was evident (figure 99). It was theorized that the increased mass prevented the sample from reaching a temperature high enough to sustain ignition.

Figure 99. Specially Prepared Truncated WE43 Cone Sample Post-Test (10/11/2011)

The testing of the various shapes and configurations provided a large amount of information and allowed for a greater understanding of the mechanisms that controlled the ignitability and length of burning. At this point, it appeared the cylindrical tubing samples offered the most consistent results, so additional testing on this sample configuration was conducted. The initial test configuration of locating the cylinder at a distance of 4 inches from the burner-cone exit plane seemed to be adequate, as was the top of the 8-inch sample being 2 inches above the horizontal centerline (figure 100). Four additional tests were run using this configuration (figure 101). The melting, ignition, and burning sequence appeared very repeatable, with the front surface of the test sample yielding and folding inward and the aft side collapsing over top. The burning was confined to this area, with the front side igniting first, followed by ignition of the material that collapsed on top (figure 102). It appeared that the cylindrical shape aided the burning; once ignited, the flames exhibited a swirling motion from the point of ignition onto the cylinder's inner surface.

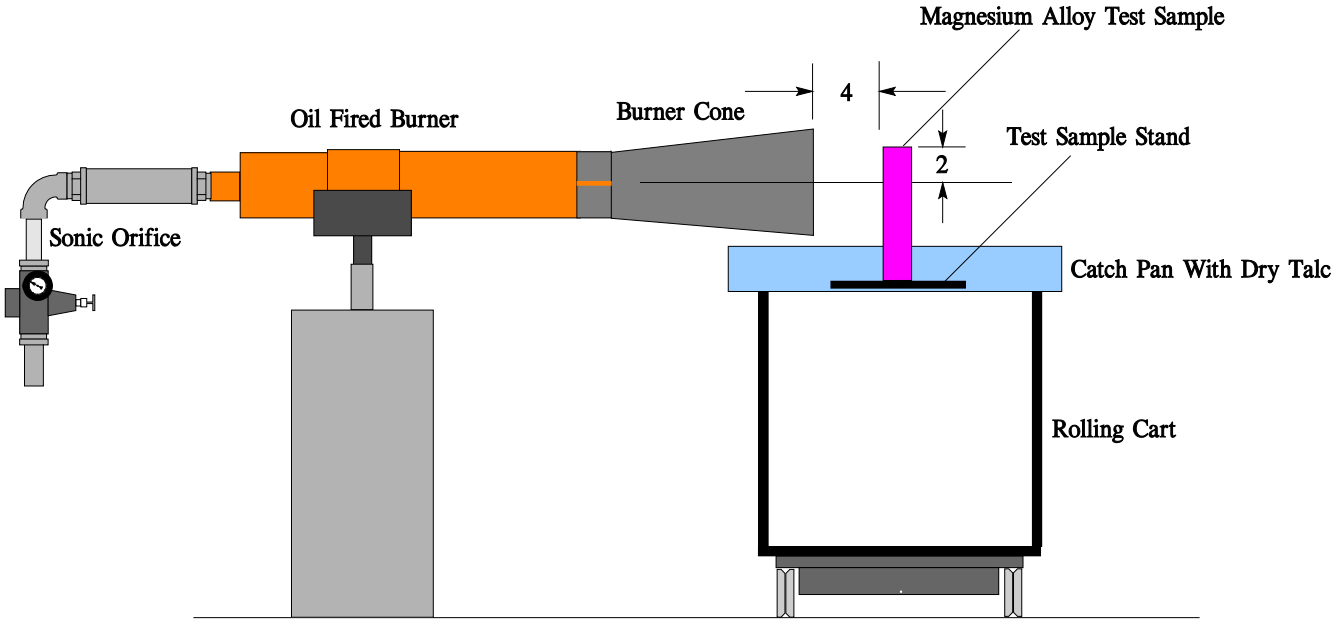


Figure 100. Test Configuration for Vertically Mounted Cylindrical Samples

Figure 101. Vertically Mounted Cylindrical Tubing Sample Cut From Cross Tube (10/12/2011)

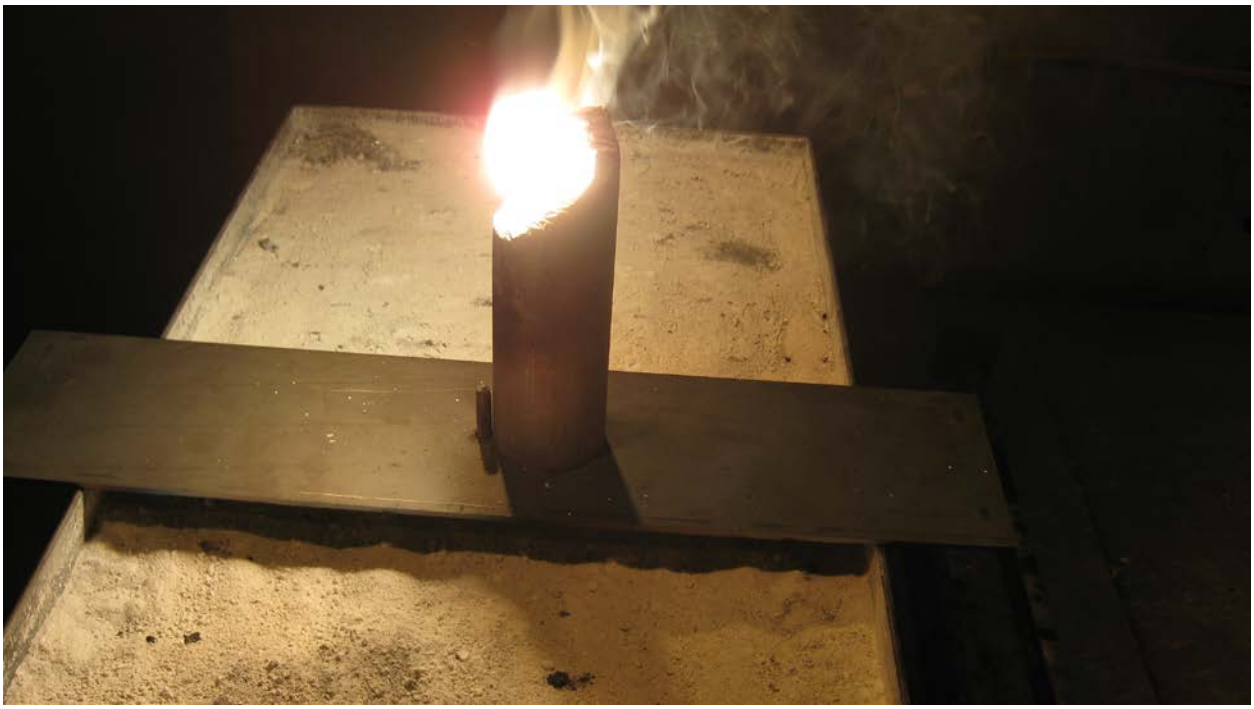


Figure 102. Flaming of Vertically Mounted Cylindrical Tubing Sample After Burner Removal (10/12/2011)

Post-test inspection of the samples revealed that a consistent shape resulted during the tests, with the telltale white oxidation forming on the upper portion of the test samples, but only slight discoloration of a section of the lower portion. It appeared that approximately 50% of the sample had remained intact, with a combination of yielding, melting, and burning impacting the remaining 50% of the sample (figures 103, 104, and 105). This was an encouraging test result when compared to the previous results on the solid, truncated cones, in which a random appendage had formed during the melting process.

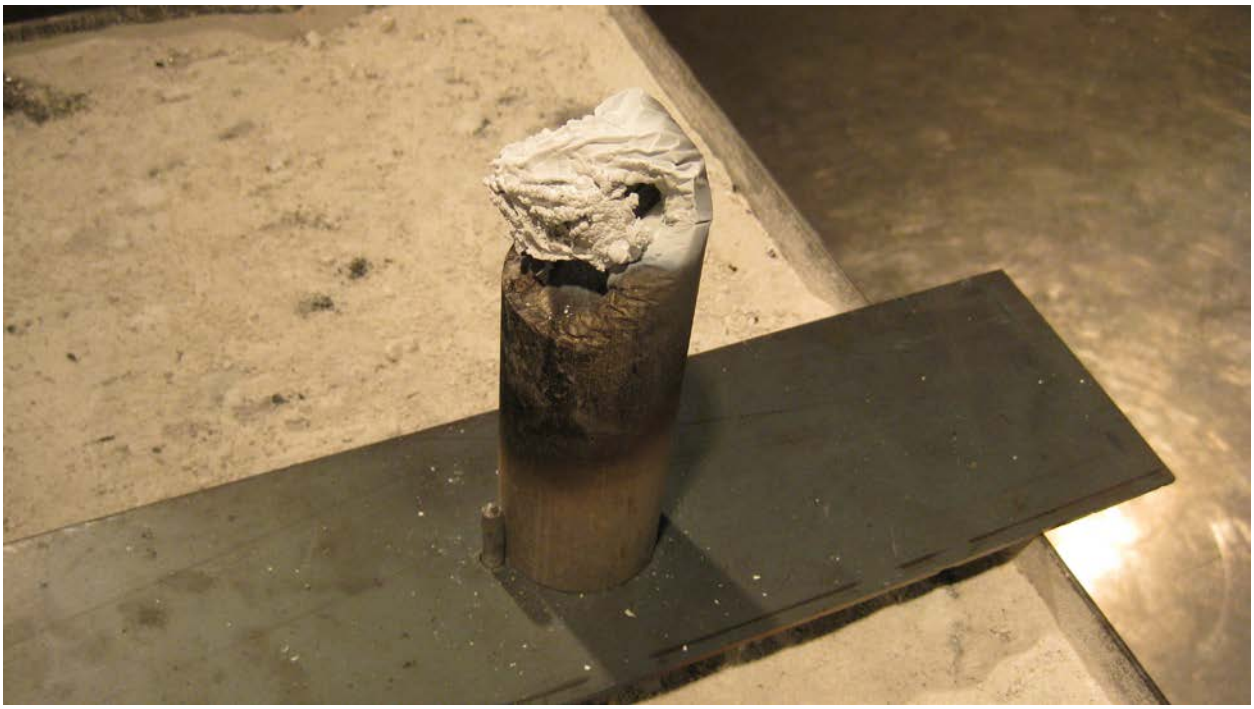


Figure 103. Vertically Mounted Cylindrical Tubing Sample Cut From Cross Tube, Post-Test (10/12/2011)

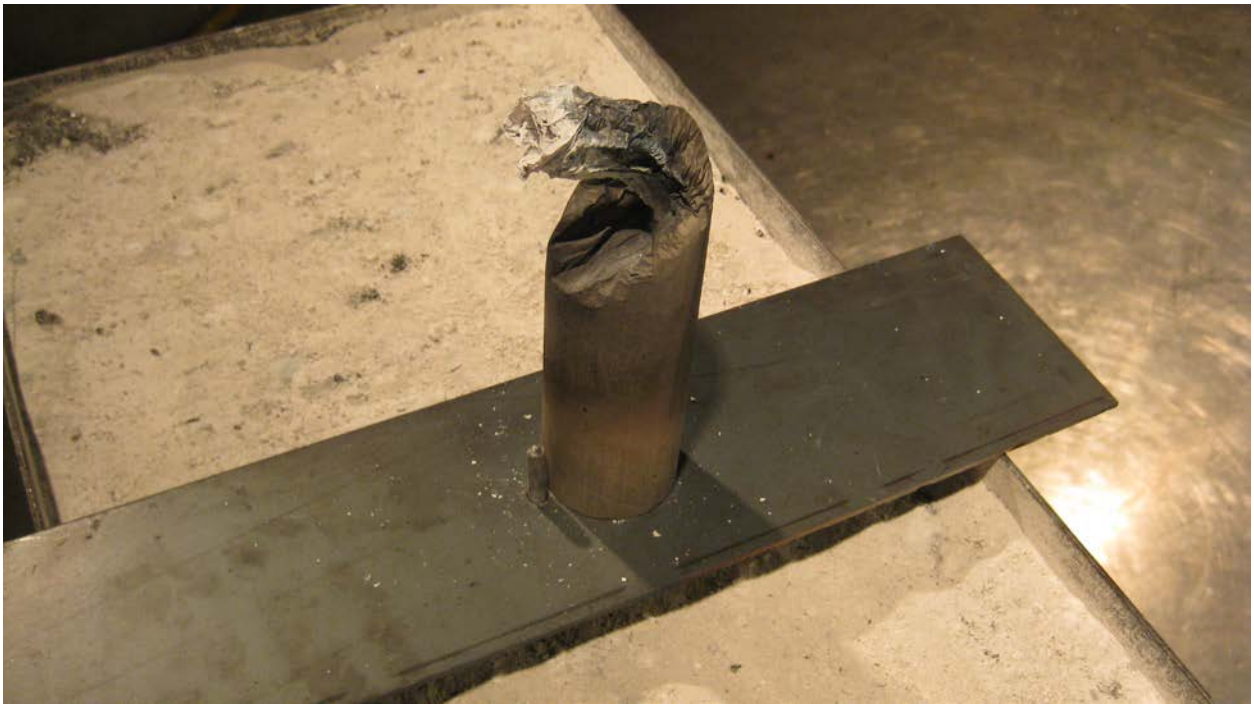


Figure 104. Post-Test View of Vertically Mounted Cylindrical Tubing Sample, Showing Result Similar to Previous Test (10/12/2011)

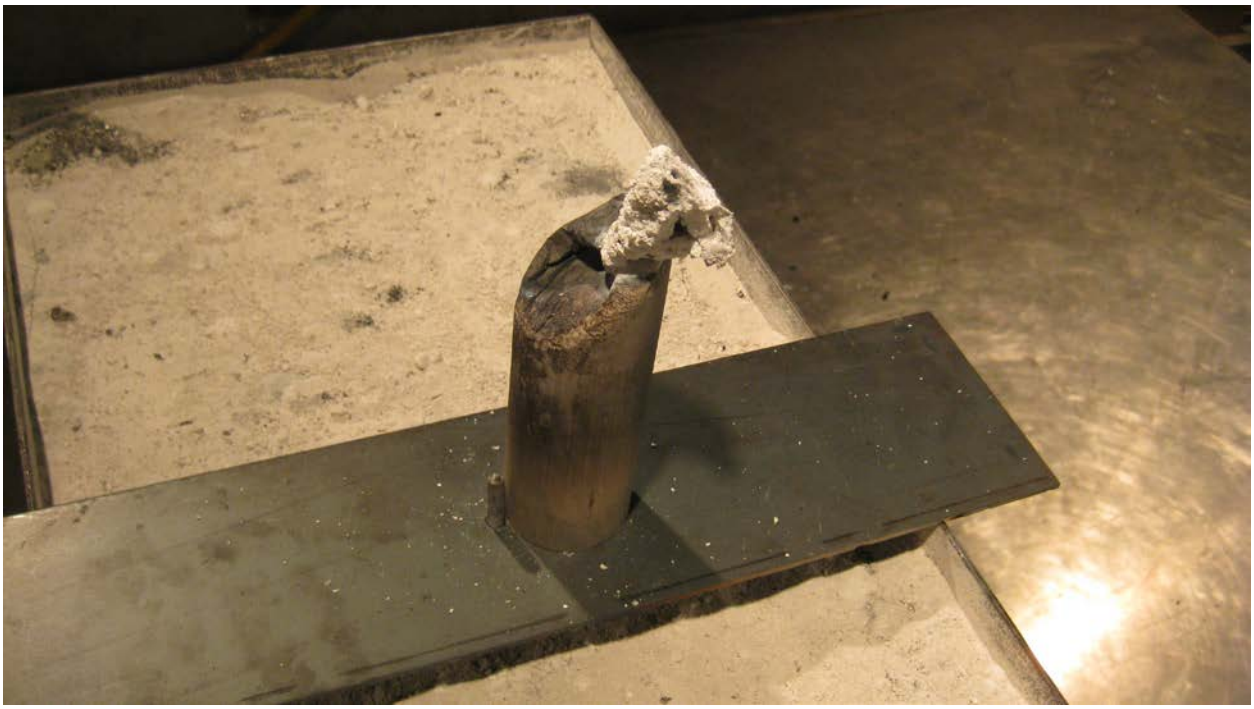


Figure 105. Post-Test View of Vertically Mounted Cylindrical Tubing Sample, Showing Result Similar to Previous Test (10/12/2011)

A summary of the results of the previous 31 tests is shown in table 7. It was clear that the vertically oriented hollow cylinder test configuration offered the greatest amount of correlation to full-scale results in terms of the duration of the burning after burner flame termination. The results also indicated consistency when compared to the other experimental test configurations.

Table 7. Test Results on Various Sample Shapes and Configurations

Date Tested	Material Type	Time to Melt	Time to Ignition	Burner Exposure	Time Ignition Ends	Duration of Ignition	Comments
9/20/11	WE-43	03:25	x	06:00	06:00	00:00	Cone laying horizontally
9/20/11	AZ-31	03:55	03:55	05:00	07:30	02:30	Cone laying horizontally
9/21/11	AZ-31	06:15	06:15	07:00	22:00	15:00	Cylinder, horizontal, end facing burner
9/22/11	WE-43	02:50	02:50	05:00	06:20	01:20	0.75 by 1.5 inch seat back box section, horizontal
9/22/11	WE-43	01:00	02:00	04:00	04:20	00:20	0.5 by 1.0 inch small baggage bar box section, horizontal
9/22/11	WE-43	03:15	03:32	05:00	06:30	01:30	Machined H-bar from seat leg, horizontal
9/27/11	WE-43	03:20	03:40	05:00	08:30	03:30	Machined T-bar, 0.1875-inch web X .5-inch web, horizontal
9/28/11	WE-43	03:12	04:12	05:00	05:00	00:00	Machined T-bar, 0.125-inch web X .5-inch web, horizontal
9/28/11	WE-43	03:05	04:50	05:00	05:50	00:50	Machined T-bar, 0.0625-inch web X .5-inch web, horizontal
9/29/11	WE-43	01:59	02:01	04:00	04:00	00:00	Inverted truncated cone suspended
9/29/11	WE-43	x	x	05:00	05:00	00:00	Inverted truncated cone suspended
9/29/11	AZ-31	00:35	00:35	04:00	04:00	00:00	Inverted pointed cone suspended
9/29/11	AZ-31	00:33	00:33	04:00	04:00	00:00	Inverted pointed cone suspended
9/30/11	WE-43	02:50	02:50	04:00	05:40	01:40	Horizontal cylindrical tube
9/30/11	WE-43	02:22	02:27	04:00	05:30	01:30	Horizontal cylindrical tube
9/30/11	WE-43	01:22	02:28	04:00	05:20	01:20	Upright cylindrical tube
9/30/11	WE-43	01:20	02:33	04:00	05:35	01:35	Upright cylindrical tube (repeat)
10/3/11	WE-43	01:45	02:50	04:00	05:05	01:05	Upright cylindrical tube (repeat)
10/3/11	WE-43	01:20	03:15	04:00	05:15	01:15	Upright cylindrical tube (repeat)
10/3/11	WE-43	01:30	03:32	04:00	05:15	01:15	Upright cylindrical tube (repeat)
10/3/11	WE-43	01:35	02:27	04:00	05:10	01:10	Upright cylindrical tube (repeat)
10/3/11	alum	02:00	x	04:00	04:00	00:00	Upright cylindrical tube (aluminum)
10/4/11	WE-43	04:00	04:30	05:00	23:00	18:00	5.5-inch cone with 9/16-inch hole
10/5/11	WE-43	04:00	x	06:00	06:00	00:00	5.5-inch cone with 9/16-inch hole (repeat)
10/6/11	WE-43	02:50	03:20	05:00	05:00	00:00	0.75 inch by 1.5 inch seat back box, vertical

Table 7. Test Results on Various Sample Shapes and Configurations (Continued)

Date Tested	Material Type	Time to Melt	Time to Ignition	Burner Exposure	Time Ignition Ends	Duration of Ignition	Comments
10/6/11	WE-43	02:10	02:40	05:00	08:30	03:30	0.75 inch by 1.5 inch seat back box, vertical (twisted 90 degree)
10/11/11	WE-43	02:30	04:10	05:00	05:00	00:00	5.5-inch cone bored to produce 1/8-inch wall thickness
10/12/11	WE-43	01:35	01:48	04:00	05:45	01:45	Upright cylindrical tube (repeat)
10/12/11	WE-43	01:20	01:30	04:00	05:00	01:00	Upright cylindrical tube (repeat)
10/12/11	WE-43	01:23	01:42	04:00	05:50	01:50	Upright cylindrical tube (repeat)
10/12/11	WE-43	01:20	01:30	04:00	05:15	01:15	Upright cylindrical tube (repeat)

2.4.4 Testing of Vertically Oriented Hollow Cylinders.

The remaining original WE43 cross-tube material salvaged from the full-scale tests was cut into an additional five samples for testing. The results are shown in table 8. An additional test was conducted on an AZ31 sample for comparison to confirm that the exposure conditions provided by the burner had not changed. During this confirmation test, the AZ3 ignited quickly and burned completely, as expected (these results were not recorded in the tabulated data). For the 15 WE43 samples tested, the averages and standard deviations were calculated for the measured parameters. The yield time was the most consistent measurement recorded, with a % standard deviation of only 8.3. The times of ignition and burning were slightly less repeatable, with a % standard deviation of 29.1 and 28.1, respectively. As expected, the time the sample was declared self-extinguished resulted in the most uncertainty, with a % standard deviation of 40.9. This was an expected result since it was often difficult to determine exactly when the molten mass of material was extinguished during the gradual cool-down process. Depending on the tester, there was a high amount of individual interpretation. In addition, there were two samples (tests 12 and 14) that had an abrasive wire-wheel surface finish that may have impacted the amount of burning. An abrasive wire wheel was used to remove an epoxy-based resin material used to attach decals on the original cross tubes. The resin was removed because it was likely this would have impacted the test results. The amount of burning of these two samples was substantially higher than any of the other samples, which indicated the surface preparation had an impact on the result. If these burn times were removed from the data set, the % standard deviation would have been substantially lower.

Table 8. Vertically Oriented Hollow-Cylinder Test Results

Date Tested	Material Type	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
9/30/2011	WE43	NR	95	148	240	320	80	Yield time not recorded
9/30/2011	WE43	80	93	153	240	335	95	
10/3/2011	WE43	100	165	170	240	305	65	
10/3/2011	WE43	80	180	195	240	315	75	
10/3/2011	WE43	90	128	212	240	315	75	
10/3/2011	WE43	80	95	147	240	310	70	
10/12/2011	WE43	95	108	108	240	345	105	
10/12/2011	WE43	80	90	90	240	300	60	
10/12/2011	WE43	83	102	102	240	350	110	
10/12/2011	WE43	80	90	90	240	315	75	
10/27/2011	WE43	110	137	180	240	375	135	
10/27/2011	WE43	104	114	127	240	900	660	Wire-wheel finish
10/27/2011	WE43	95	100	190	240	335	95	
10/28/2011	WE43	125	145	145	240	440	200	Wire-wheel finish
10/28/2011	WE43	95	106	220	240	285	45	

Average	92.6	116.5	151.8	240.0	369.7	129.7
Standard Deviation	7.7	33.9	42.6	0.0	151.4	151.4
% Standard Devivation	8.3	29.1	28.1	0.0	41.0	116.7

The 15 tests on the vertically-oriented hollow cylinders are also displayed graphically in figure 106.

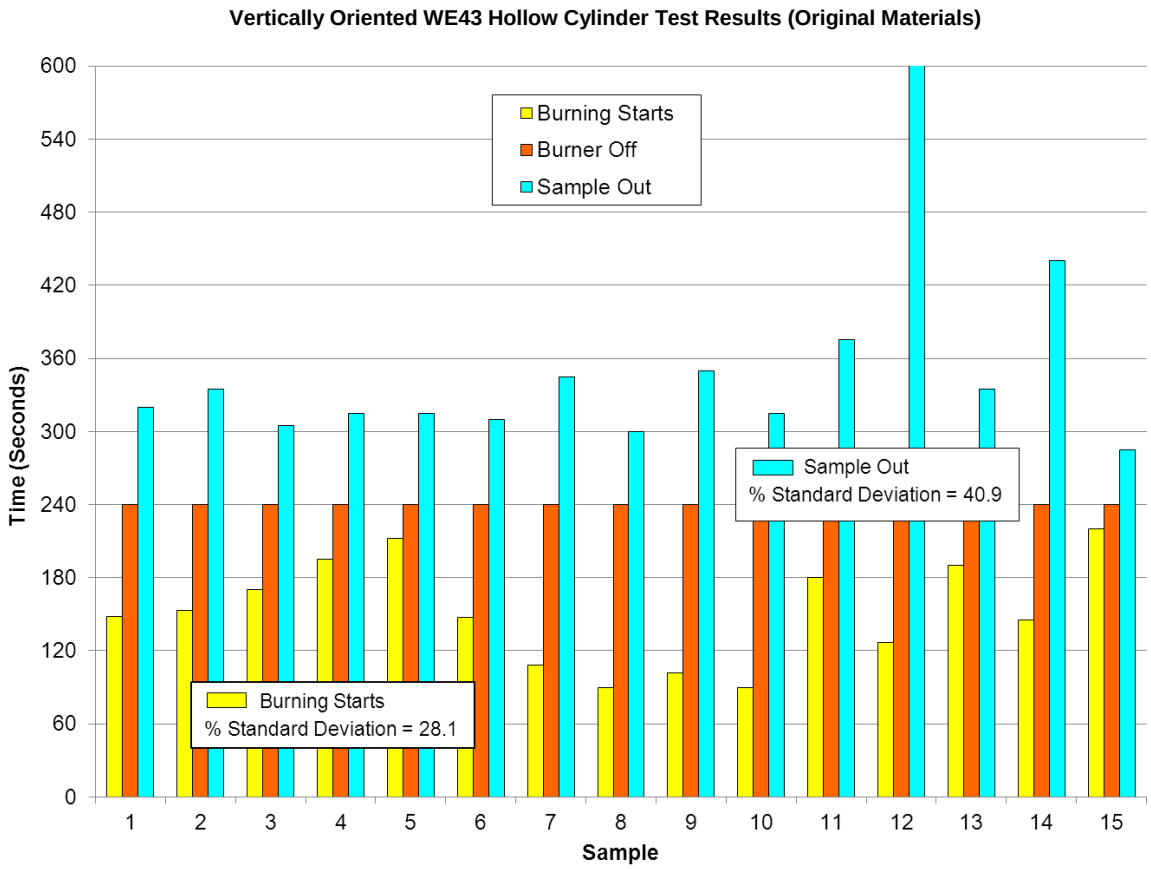


Figure 106. Bar Chart of Vertically Oriented Hollow Cylinder Results (original materials)

In an effort to determine how robust the vertically oriented hollow cylinder configuration was, additional samples were fabricated with a slightly smaller diameter. The original cross tubes measured 1.75 inches outside diameter (OD), with a wall thickness of 0.120 inch. Samples supplied by Magnesium Elektron (ME) measured 1.25 inches OD, with a wall thickness of 0.125 inch (figure 107).

Figure 107. Comparison of Original Sample (left) and 1.25-Inch OD Sample (12/19/2011)

A nine-test series was run on these newly supplied cylindrical samples to determine if a similar yield, ignition, and burn sequence resulted with a slightly smaller diameter. A smaller sample holder was required to firmly mount the reduced-diameter sample. To accomplish this, a small stub of solid-steel rod was machined to the correct inside diameter (ID) over which the samples were fit. This stub was welded to the sheet steel mounting plate that was attached to the catch pan (figure 108). The bore pictured in the sample holder was blocked off at the base for these tests, preventing air entrainment that could potentially feed any resulting fire.

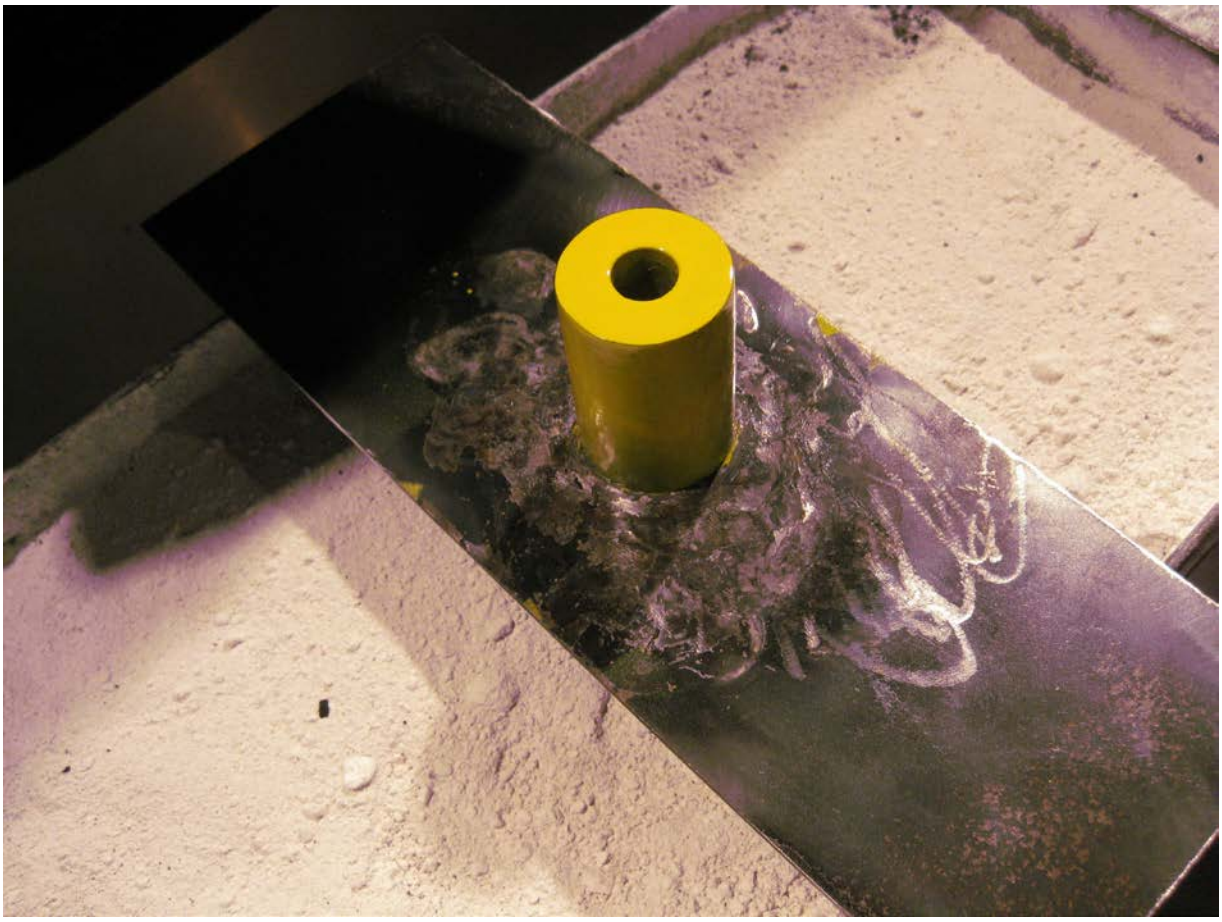


Figure 108. Cylindrical Steel Mounting Stub for Reduced-Diameter Test Samples

The sample yielded at 85 seconds during the first test, which was comparable to the results obtained on the original samples. However, no ignition or burning was evident and the burner flames were terminated at 4 minutes. No after flame ignition resulted. This was an unexpected result, so the test was repeated on a second sample with the same nonignition result. A third test was run and, although no ignition occurred during burner flame exposure, the sample ignited immediately following termination of the flames. The sample burned for only 28 additional seconds and then self-extinguished. Six additional tests were run. Ignition did not result in any of these cases (table 9 and figure 109).

Table 9. Test Results on Reduced-Diameter Cylindrical WE43 Samples

Date Tested	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
12/19/2011	85	x	x	240	240	0	No ignition
12/19/2011	87	x	x	240	240	0	No ignition
12/19/2011	85	240	241	240	268	28	Burning starts following flame removal
12/19/2011	82	x	x	240	240	0	No ignition
12/19/2011	77	x	x	240	240	0	No ignition
12/19/2011	80	x	x	240	240	0	No ignition
12/19/2011	82	x	x	240	240	0	No ignition
12/19/2011	82	x	x	240	240	0	No ignition
12/19/2011	82	x	x	240	240	0	No ignition

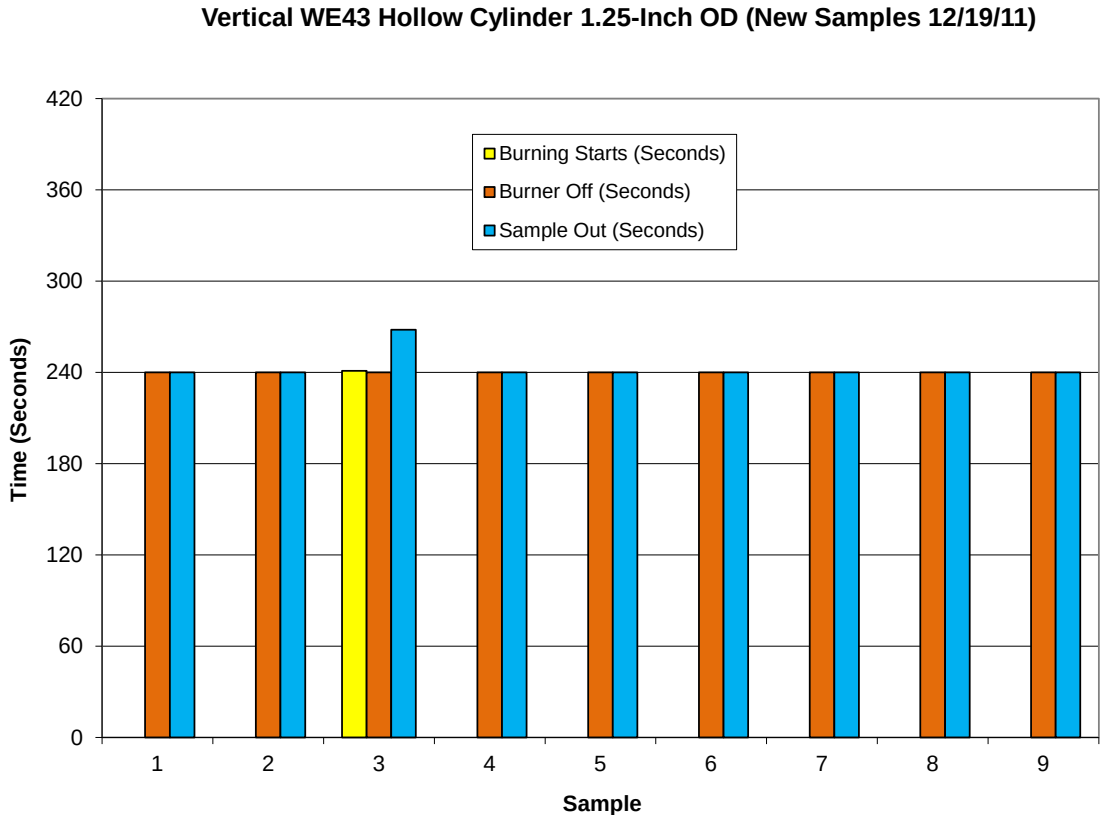


Figure 109. Test Results on 1.25-Inch Diameter Vertically Oriented Hollow Cylinders

No explanation could be given for the lack of ignition of the samples because the burner flames were calibrated prior to test and showed temperature profile results nearly identical to those obtained previously. The testing booth used to house the equipment remained unchanged, including the amount of exhaust ventilation.

Testing continued on a second batch of materials that were closer in size to the original samples cut from the cross tubes. The samples measured 1.75 inches OD, with a marginally heavier wall thickness of 0.125 inch. To accommodate the resulting slightly smaller sample ID, a new cylindrical stub of threaded rod was used as a sample holder (figure 110). Although a small-diameter hole is pictured in the top of the cylindrical holder, the hole is very shallow and does not penetrate to the bottom of the cylinder.

Figure 110. Sample Holder Used for 1.75-Inch OD Samples With 0.125-Inch Wall Thickness

During the first test, the sample began to yield at 100 seconds, which was comparable to the original samples. However, no ignition or burning was evident and the burner flames were terminated at 4 minutes. Again, no after flame was observed. Because of the unanticipated result, the test was repeated, resulting in a slightly quicker yield time, but an identical nonignition outcome. At this point, the researchers grew suspicious of the test equipment so an original cross-tube sample was prepared and mounted in place. The sample was positioned in front of the burner after warmup. As expected, a slightly quicker yield time was observed because of the marginally thinner wall thickness of 0.120 inch. At 92 seconds, the sample ignited and burned vigorously. The burner flames were terminated at 4 minutes and the sample self-extinguished 75 seconds later at 5 minutes and 15 seconds. This was a clear indication that the new batch of materials differed from the original materials in terms of ignition and flammability. A side-by-side comparison of the post-test samples revealed a striking difference,

with the original sample on the left displaying evidence of burning and the sample on the right was simply heat deformed with no evidence of ignition or burning (figure 111).

Figure 111. Post-Test Comparison of Original Sample (left) and Newer Sample (right)

To ensure that the new style cylindrical sample holder was not impacting the results, the next test was conducted using the original stub of box tubing. This also resulted in nonignition and was ruled out as a factor in the test. For completeness, additional tests were conducted, all with identical nonignition results. In one test, the inner diameter of the sample was machined out to produce a wall thickness of only 0.100 inch, but this did not result in sample ignition or burning. During another test, the burner flames were not terminated until 7 minutes of exposure (3 minutes longer than typical) but, again, no resulting ignition. A final test was run using another sample of the original cross-tube material. It ignited at 105 seconds and again burned vigorously. After burner flame termination at 4 minutes, the sample burned for an additional 40 seconds before self-extinguishing. This was solid evidence that the newer batch of materials was much more fire resistant than the original materials. Details of the test results are shown in table 10 and figure 112. Post-test photographs are shown in figure 113.

Table 10. Test Results From Newer 1.75-Inch OD Samples

Date	Material Type	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
12/20/2011	WE43	100	x	x	240	240	0	No burning
12/20/2011	WE43	93	x	x	240	240	0	No burning
12/20/2011	WE43	82	92	92	240	315	75	Original cross-tube sample
12/20/2011	WE43	93	x	x	240	240	0	No burning
12/20/2011	WE43	72	x	x	240	240	0	Wall machined to 0.100-inch thickness
12/21/2011	WE43	100	x	x	240	240	0	No burning
12/21/2011	WE43	92	x	x	240	240	0	No burning
12/21/2011	WE43	84	135	x	240	240	0	No burning
12/21/2011	WE43	82	131	x	420	420	0	Extended exposure, no burning
1/10/2012	WE43	117	x	x	240	240	0	New sample w/hole in bottom mandrel
1/10/2012	WE43	100	105	105	240	280	40	Original sample w/hole in mandrel

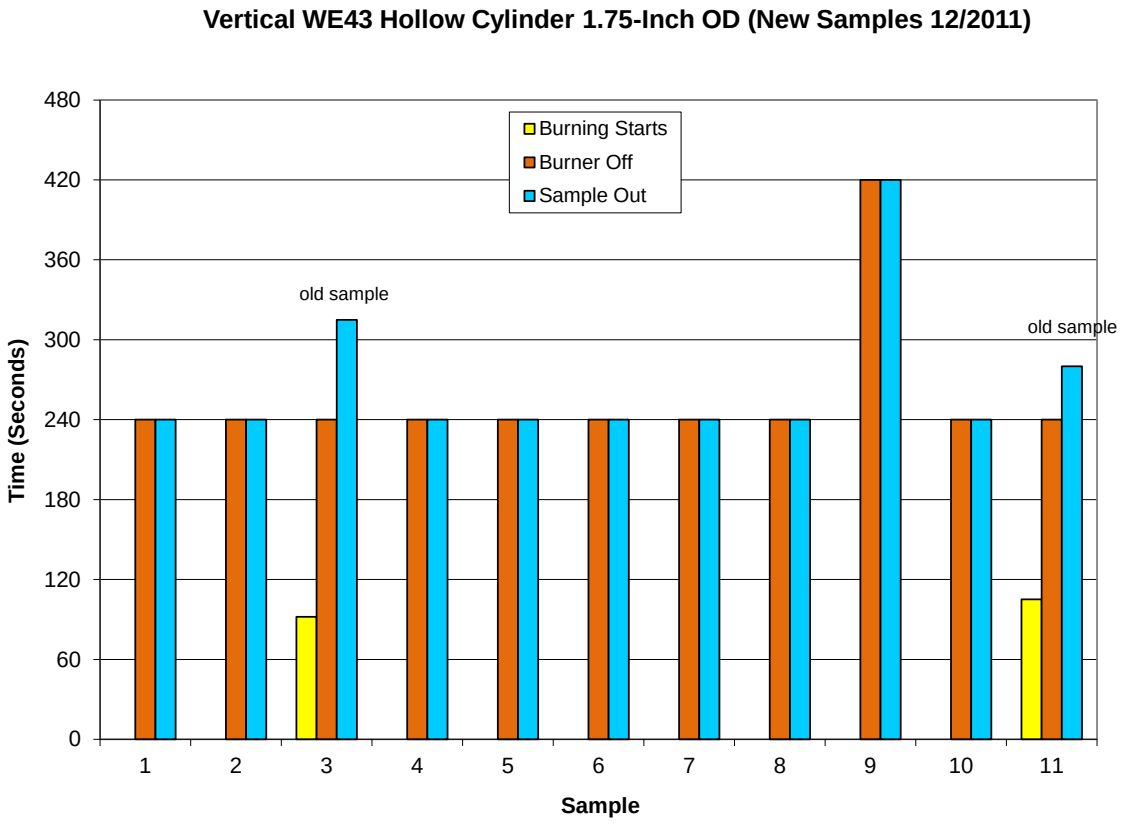


Figure 112. Test Results of Newer 1.75-Inch OD Samples

Figure 113. Post-Test Photograph of 1.25-Inch (background) and 1.75-Inch (foreground) Samples

Numerous theories over the unexpected test results were discussed with the sample manufacturer, Magnesium Elektron (ME). In an effort to uncover differences in the material properties that could lead to the vast difference in results, ME agreed to perform an electron microscope analysis of the tested samples. ME suggested that a difference in grain structure of the new samples compared to the original samples could be the culprit, but didn't rule out the possibility that the original samples had been altered as a result of the heat they were exposed to during the full-scale tests, rendering them more susceptible to ignition. ME's analysis was inconclusive; both the original samples and newer samples were within specification for the WE43 classification.

In an effort to replicate the performance of the original material, samples of various WE43 formulations were extruded by ME into hollow cylinders with an average OD of 1.7 inches and an average wall thickness of 0.100 inch. These were purpose-built samples designed to ignite after melting, but also self-extinguish after removal of the fire threat. A total of 17 tests were conducted, plus an additional test on an AZ31 sample for comparison. Although WE43 was the basic material used in the fabrication of the various samples, the extrusion processes were altered slightly in an effort to investigate cause/effect in terms of sample ignitability and flammability.

Unexpectedly, a majority of the samples did not ignite or burn, but several of them ignited and burned until completely consumed. Therefore, there was a wide range of test results (table 11 and figure 114).

Table 11. Test Results on 1.70-Inch Cylindrical Samples Designed to Ignite

Date Tested	Material Designation	Outside Diameter (Inches)	Wall Thickness (Inches)	Inside Diameter (Inches)	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
2/15/2012	52942C	1.692	0.100	1.492	90	x	x	240	240	0	No ignition
2/15/2012	52942C	1.705	0.100	1.505	85	x	x	240	240	0	No ignition
2/15/2012	52942	1.696	0.108	1.480	88	120	x	240	240	0	No after burn
2/15/2012	AZ-31	1.721	0.103	1.515	99	120	125	240	780	540	Completely consumed
2/15/2012	9824A	1.705	0.100	1.505	90	110	110	240	385	145	
2/15/2012	52942C	1.701	0.105	1.491	87	112	112	240	240	0	No after burn
2/15/2012	9824A	1.723	0.100	1.523	85	119	119	240	1140	900	
2/15/2012	52942B	1.728	0.109	1.510	90	x	x	240	240	0	No ignition
2/15/2012	52942C	1.710	0.100	1.510	70	x	x	240	240	0	Sample moved closer to fire
2/22/2012	52942C	1.730	0.100	1.530	110	140	172	240	240	0	No after burn
2/22/2012	9824A	1.716	0.100	1.516	107	152	152	240	415	175	
2/22/2012	52942B	1.682	0.105	1.472	108	142	142	240	240	0	No after burn
2/23/2012	52942	1.696	0.103	1.490	99	133	133	240	465	225	
2/23/2012	52942B	1.682	0.103	1.476	105	151	151	240	240	0	No after burn
2/23/2012	9824A	1.716	0.104	1.508	105	133	133	240	1200	960	Completely consumed
2/27/2012	52942	1.720	0.103	1.514	102	147	147	240	410	170	
2/27/2012	52942	1.723	0.102	1.519	102	141	141	240	1440	1200	Completely consumed
2/27/2012	52942B	1.722	0.100	1.522	125	196	196	240	240	0	No after burn

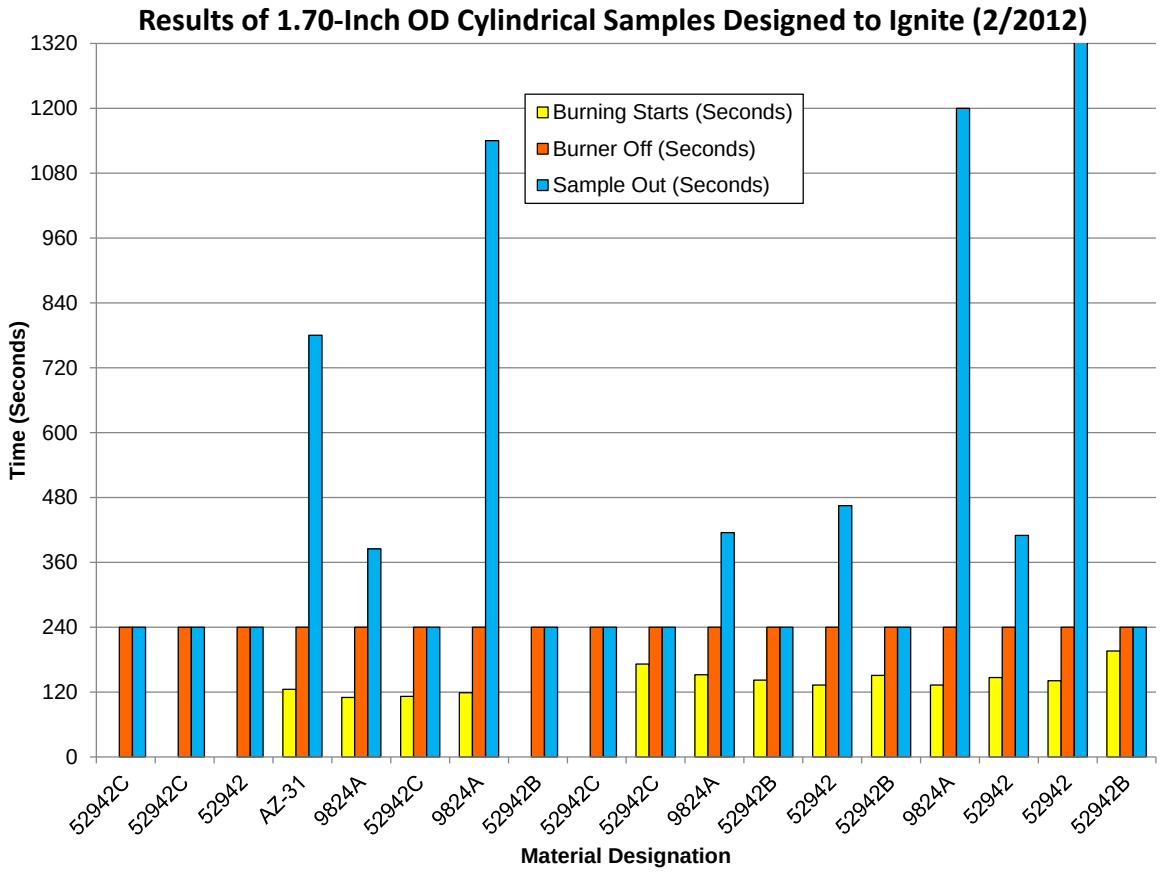


Figure 114. Test Results on 1.70-Inch Cylindrical Samples Designed to Ignite

The lack of consistency with the testing was viewed as a setback for the vertically oriented cylindrical sample configuration. In light of this, industry experts familiar with the magnesium flammability test-method development suggested that the horizontal bar configuration be evaluated again. The horizontal bar configuration was the chosen setup for the initial evaluation of various magnesium alloys. As previously documented, the horizontal bar configuration was effective at separating poor-performing alloys from more fire-resistant alloys, but typically resulted in a large portion of the sample melting and separating from the main sample. This was viewed as troublesome during the early testing because the molten material was not subjected to the burner flames once it separated and fell into the catch pan below. This outcome was the reason for experimenting with the truncated cones and making an effort to allow the sample to burn continuously without separation.

Despite this apparent shortcoming, the industry experts pointed out that the results of the initial bar tests showed its effectiveness at ranking the relative flammability of the various alloys. The bar configuration was also much more economical, because it was costly and time consuming to machine truncated cones or extrude thin-walled cylinders, whereas bar samples could be cut and machined from plate material more easily. Based on this knowledge, one final effort was put in place to compare the two configurations (cylinders versus bars). It was necessary to fabricate and test a large number of samples to provide the best opportunity for an accurate assessment of the repeatability of each test method.

2.4.5 Comparison of Vertically Oriented Cylinder and Horizontally Oriented Bar Configurations.

2.4.6 Testing of Vertically Oriented Cylinders.

Cylindrical samples were fabricated from 5 basic materials: AZ31, AZ80, ZE41, WE43, and Elektron®21 (designated as EL21). A sixth experimental material (proprietary in nature) was also used in the comparison (designated as EXP-). A total of 59 cylinder samples were produced by ME, with a slightly smaller OD of 1.625 inches, and an approximate wall thickness of 0.120 inches. The smaller diameter of the samples required the use of a slightly smaller cylindrical test mandrel. The 59 vertical cylinder tests were run over a 3-week period, with the results tabulated in table 12.

Table 12. Cylindrical Test Sample Results in Chronological Order

Date Tested	Material	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
04/23/12	AZ31	114	114	114	240	1140	900	Totally consumed
04/23/12	ZE41	150	159	159	240	383	143	
04/23/12	ZE41	135	152	152	240	324	84	
04/23/12	WE43	111	x	x	240	240	0	No burning
04/23/12	WE43	102	x	x	240	240	0	No burning
04/23/12	WE43	98	x	x	240	240	0	No burning
04/23/12	WE43	104	x	x	240	240	0	No burning
04/24/12	AZ80	91	92	92	240	1140	900	Totally consumed
04/24/12	EL21	108	240	240	240	324	84	
04/24/12	EL21	102	154	212	240	360	120	
04/24/12	AZ80	89	90	90	240	1140	900	Totally consumed
04/24/12	EL21	119	240	240	240	310	70	
04/24/12	EL21	101	125	125	240	293	53	
04/24/12	ZE41	117	206	240	240	276	36	
04/24/12	ZE41	113	221	284	240	310	70	
04/25/12	AZ80	90	90	90	240	1140	900	Totally consumed
04/25/12	EXP-1	95	194	194	240	240	0	No burning
04/25/12	EXP-1	88	118	118	240	390	150	
04/25/12	EXP-1	90	x	x	240	240	0	No burning
04/25/12	EXP-3	95	x	x	240	240	0	No burning

Table 12. Cylindrical Test Sample Results in Chronological Order (Continued)

Date Tested	Material	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
05/02/12	WE43	103	134	135	240	240	0	No burning
05/02/12	WE43	99	124	125	240	372	132	
05/02/12	WE43	97	120	121	240	240	0	No burning
05/02/12	WE43	97	120	121	240	240	0	No burning
05/02/12	EL21	110	x	x	240	240	0	No burning
05/02/12	EL21	103	x	x	240	240	0	No burning
05/03/12	ZE41	120	142	143	240	1140	900	Totally consumed
05/03/12	ZE41	131	155	156	240	310	70	
05/03/12	ZE41	133	153	154	240	395	155	
05/03/12	ZE41	138	156	157	240	1140	900	Totally consumed
05/03/12	ZE41	143	156	157	240	353	113	
05/03/12	ZE41	126	143	144	240	470	230	
05/03/12	ZE41	117	254	255	240	392	152	
05/07/12	ZE41	124	144	145	240	345	105	
05/07/12	ZE41	130	144	145	240	339	99	
05/07/12	ZE41	139	150	151	240	1140	900	Totally consumed
05/07/12	ZE41	141	151	152	240	1140	900	Totally consumed
05/08/12	WE43	105	148	x	240	240	0	No burning
05/08/12	WE43	105	x	x	240	240	0	No burning
05/08/12	WE43	106	136	137	240	240	0	No burning
05/08/12	WE43	96	x	x	240	240	0	No burning
05/08/12	WE43	102	134	135	240	240	0	No burning
05/08/12	WE43	88	121	122	240	240	0	No burning
05/08/12	ZE41	124	136	137	240	1140	900	Totally consumed
05/08/12	EL21	122	x	x	240	240	0	No burning
05/08/12	EL21	120	x	x	240	240	0	No burning
05/08/12	EL21	120	x	x	240	240	0	No burning
05/09/12	EL21	121	x	x	240	240	0	No burning
05/09/12	EL21	112	231	232	240	350	110	
05/09/12	EL21	116	x	x	240	240	0	No burning
05/09/12	EL21	108	224	225	240	460	220	
05/09/12	EL21	104	219	220	240	493	253	
05/09/12	EL21	122	x	x	240	240	0	No burning

Table 12. Cylindrical Test Sample Results in Chronological Order (Continued)

Date Tested	Material	Yield Time (Seconds)	Ignition Time (Seconds)	Burning Starts (Seconds)	Burner Off (Seconds)	Sample Out (Seconds)	After Burn (Seconds)	Comments
05/09/12	EL21	105	235	x	240	240	0	No burning
05/09/12	EL21	99	208	247	240	418	178	
05/09/12	EL21	98	202	203	240	413	173	
05/09/12	WE43	109	142	143	240	240	0	No burning
05/10/12	ZE41	143	150	151	240	400	160	
05/10/12	ZE41	132	140	141	240	330	90	

The samples appeared to melt and yield in a consistent manner as described previously. Figure 115 shows the post-test results for the last 12 tests conducted. The post-test inspection highlights the presence of white, powdery magnesium oxide at the top of some of the samples, indicative of ignition/burning of the material during the test.

Figure 115. Post-Test Inspection of Cylinder Samples

Post-test inspections also revealed that molten material would solidify near the base of the sample, effectively blocking air from entering the sample from below (figure 116). This was noteworthy because there had been considerable debate over the impact of air feeding the fire when using a cylindrical sample holder with a bore through the center.

Figure 116. Post-Test Inspection of Sample Bottom Showing Collection of Molten Material

The results of all of the tests are displayed in bar charts (figures 117 and 118). Figure 117 displays the results from the WE43 and EL21 tests, whereas figure 118 shows the results of the ZE41 and AZ alloys. For each test, there are three colored bars indicating the times at which burning started, the burner flames were terminated (240 seconds in all cases), and the sample was declared as no longer burning.

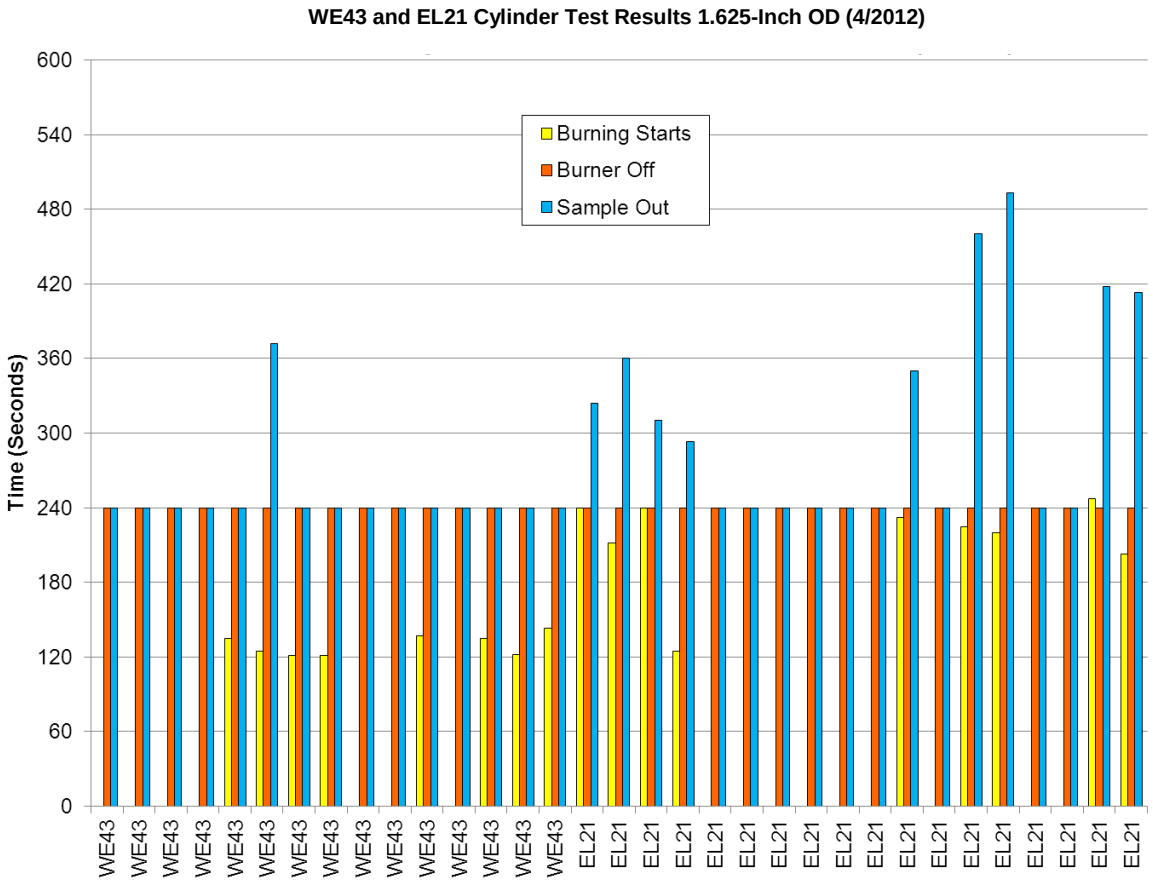


Figure 117. Test Results on WE43 and EL21 Cylindrical Samples

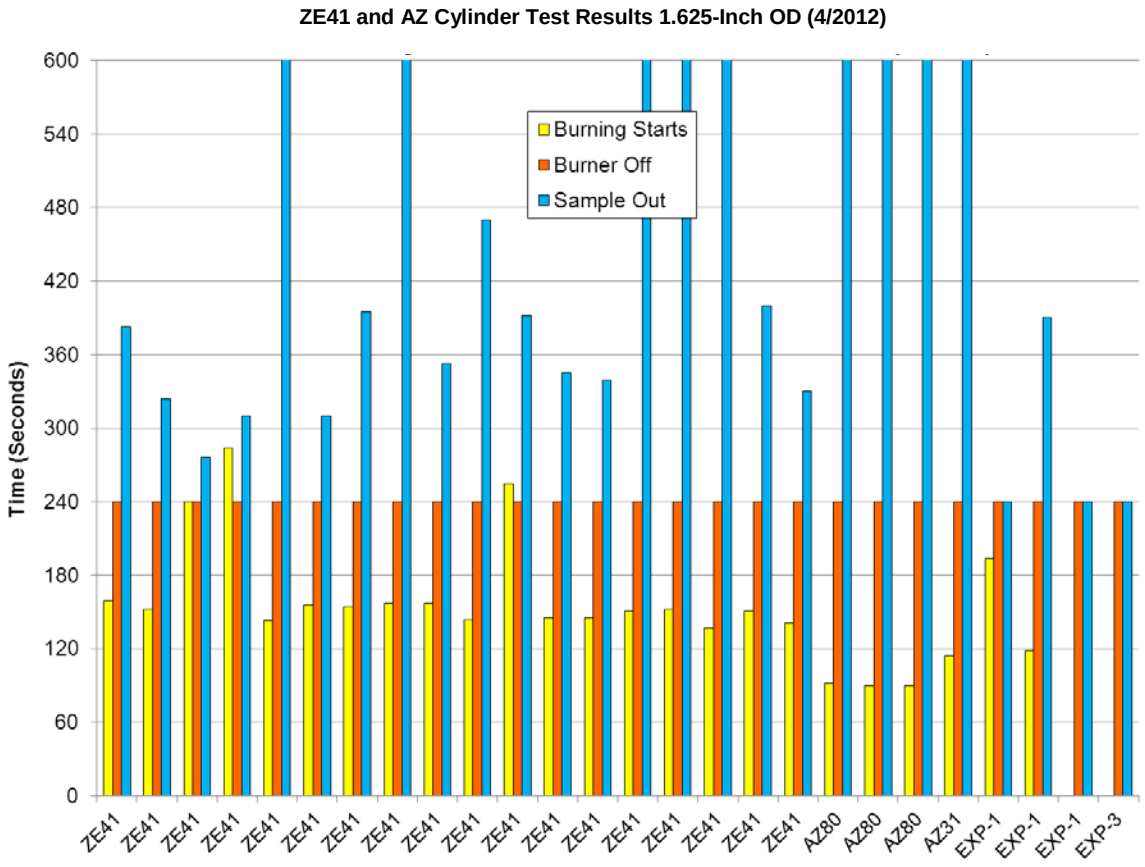


Figure 118. Test Results on ZE-41 and AZ-80 Cylindrical Samples

Table 13 shows the results of 51 of the 59 tests conducted (AZ and experimental EXP alloys were excluded), including the average times when burning begins and stops and the standard deviations for each alloy. Also shown is the % relative standard deviation (%RSD), which is calculated by dividing the standard deviation by the average.

Table 13. Cylindrical Test Sample Results (separated by alloy type)

	Material	Burning Starts	Burner Off	Sample Out	Material	Burning Starts	Burner Off	Sample Out	Material	Burning Starts	Burner Off	Sample Out
	WE43	0	240	240	EL21	240	240	324	ZE41	159	240	383
	WE43	0	240	240	EL21	212	240	360	ZE41	152	240	324
	WE43	0	240	240	EL21	240	240	310	ZE41	240	240	276
	WE43	0	240	240	EL21	125	240	293	ZE41	284	240	310
	WE43	135	240	240	EL21	0	240	240	ZE41	143	240	1140
	WE43	125	240	372	EL21	0	240	240	ZE41	156	240	310
	WE43	121	240	240	EL21	0	240	240	ZE41	154	240	395
	WE43	121	240	240	EL21	0	240	240	ZE41	157	240	1140
	WE43	0	240	240	EL21	0	240	240	ZE41	157	240	353
	WE43	0	240	240	EL21	0	240	240	ZE41	144	240	470
	WE43	137	240	240	EL21	232	240	350	ZE41	255	240	392
	WE43	0	240	240	EL21	0	240	240	ZE41	145	240	345
	WE43	135	240	240	EL21	225	240	460	ZE41	145	240	339
	WE43	122	240	240	EL21	220	240	493	ZE41	151	240	1140
	WE43	143	240	240	EL21	0	240	240	ZE41	152	240	1140
					EL21	0	240	240	ZE41	137	240	1140
					EL21	247	240	418	ZE41	151	240	400
					EL21	203	240	413	ZE41	141	240	330
Average		69.3		248.8		108		310.1		167.9		573.7
Standard Deviation		67.3		34.1		114.0		86.4		43.3		363.9
% RSD		97.2		13.7		105.5		27.9		25.8		63.4

The test results again pointed to some difficulty with repeatability. Beginning with the WE43 samples, the %RSD for the time when the sample begins to burn is 97.2%. The %RSD for the time when the sample self-extinguishes is much lower, at 13.7%. This was understandable because the samples did not burn after burner flame termination in 14 of the 15 tests, so the recorded time for extinguishment was defaulted to 240 seconds in these cases. The EL21 tests were even less consistent, with a %RSD of 105.5% for the time when the sample began to burn. Similarly, the %RSD for the time when the sample self-extinguishes was calculated to be 27.9%. This result was also aided by a large population of the EL21 samples not continuing to burn after the burner flames were terminated, mandating a default 240-second data entry each time. This occurred in 9 of the 18 tests. The ZE41 tests were the most consistent in terms of when the sample began to burn (%RSD of 25.8%), but the least consistent in terms of when the sample self-extinguished (%RSD of 63.4%). This result was expected because all samples continued to

burn after the burner flames were removed at 240 seconds, unlike many of the WE43 and EL21 samples. For reference, a %RSD below 10% is the target for a laboratory-scale flammability test. A summary of the averages, standard deviations, and %RSDs is shown in table 14.

Table 14. Summary of Vertical Cylinder Test Averages, Standard Deviations, and %RSDs

	WE43		EL21		ZE41	
	Cylinder Begins to Burn (Sec)	Cylinder Out	Cylinder Begins to Burn (Sec)	Cylinder Out	Cylinder Begins to Burn (Sec)	Cylinder Out
Average	69.3	248.8	108.0	310.1	167.9	573.7
Standard Deviation	67.3	34.1	114.0	86.4	43.3	363.9
% RSD	97.2	13.7	105.5	27.9	25.8	63.4

2.4.7 Testing of Horizontally Oriented Rectangular Cross-Section Bars.

Several years prior, during initial investigative tests conducted on horizontally oriented bar samples, two thicknesses of bars were used. The thinner bar sample measured 0.394 inch thickness by 1.57 inches wide by 19.69 inches long (10 mm by 40 mm by 500 mm). A thicker sample measured 0.591 inch by 1.57 inches by 19.69 inches (15 mm by 40 mm by 500 mm). These width and length dimensions were a reasonable starting point for fabricating the newer samples, in combination with four different thicknesses: 0.669, 0.500, 0.375, and 0.250 inch (17, 12.7, 9.5, and 6.4 mm). The thinner 0.375- and 0.250-inch-(9.5 and 6.4 mm) thickness samples were fabricated because the time required for melting the thicker samples seemed excessive during initial testing.

Six different alloys were used in the fabrication of the samples: Elektron®WE43, Elektron®43 (Elektron®43 is an optimized variant of Elektron®WE43 produced for wrought applications and falls within a tighter, more controlled chemical specification and is abbreviated to EL43), EL21, ZE41, AZ80, AZ31, and an experimental alloy (designated as EXP-2). Eighty-four samples were initially prepared by ME for testing. This initial batch of samples measured 19.69 inches (500 mm) in length.

The original sample holder used in the testing of the horizontally-oriented bars was updated to include a mechanism for securely mounting the samples (figure 119). This consisted of two box-section steel uprights that supported U-shaped cradles with threaded fasteners (figure 120).

Figure 119. Updated Horizontal Bar Sample Holder

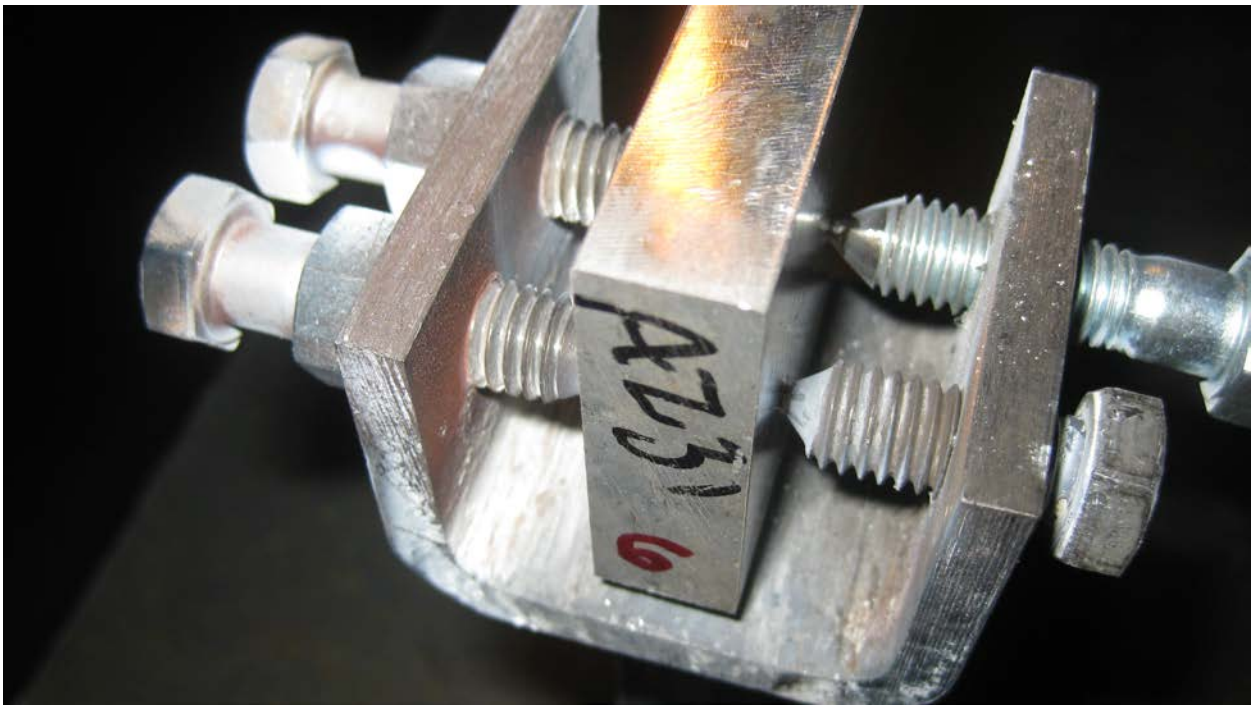


Figure 120. Updated Sample Securing Mechanism

The U-shaped cradles were fabricated from 2-inch by 2-inch box-section steel with one of the faces cut off. The resulting U-shaped component was drilled and tapped, then fitted with 3/8-16 UNC bolts with locking nuts (two per side). The bolt tips were machined to a point to minimize surface contact with the sample, thereby reducing the amount of heat absorption by the bolts. The sample was also shimmed from below, then the bolts were tightened to secure the sample. Once this was complete, the shims were removed, further reducing the amount of contact the sample had with the sample holder. This arrangement allowed for the mounting of various thickness samples, and also allowed for minor adjustments to maintain the proper distance between the sample and the burner.

In addition, a s maller catch pan was used because an increased confidence level had been established. This was because a considerable amount of testing had been performed up to this point. The testing revealed that only a minimal amount of back-splashing of molten material resulted during tests. The reduced-size catch pan measured 8 by 16 inches, with a depth of 1.5 inches. A layer of dry talc was used to prevent splashing of the molten material falling into the catch pan. A screed device was used to level off the talc layer prior to each test (figure 121).

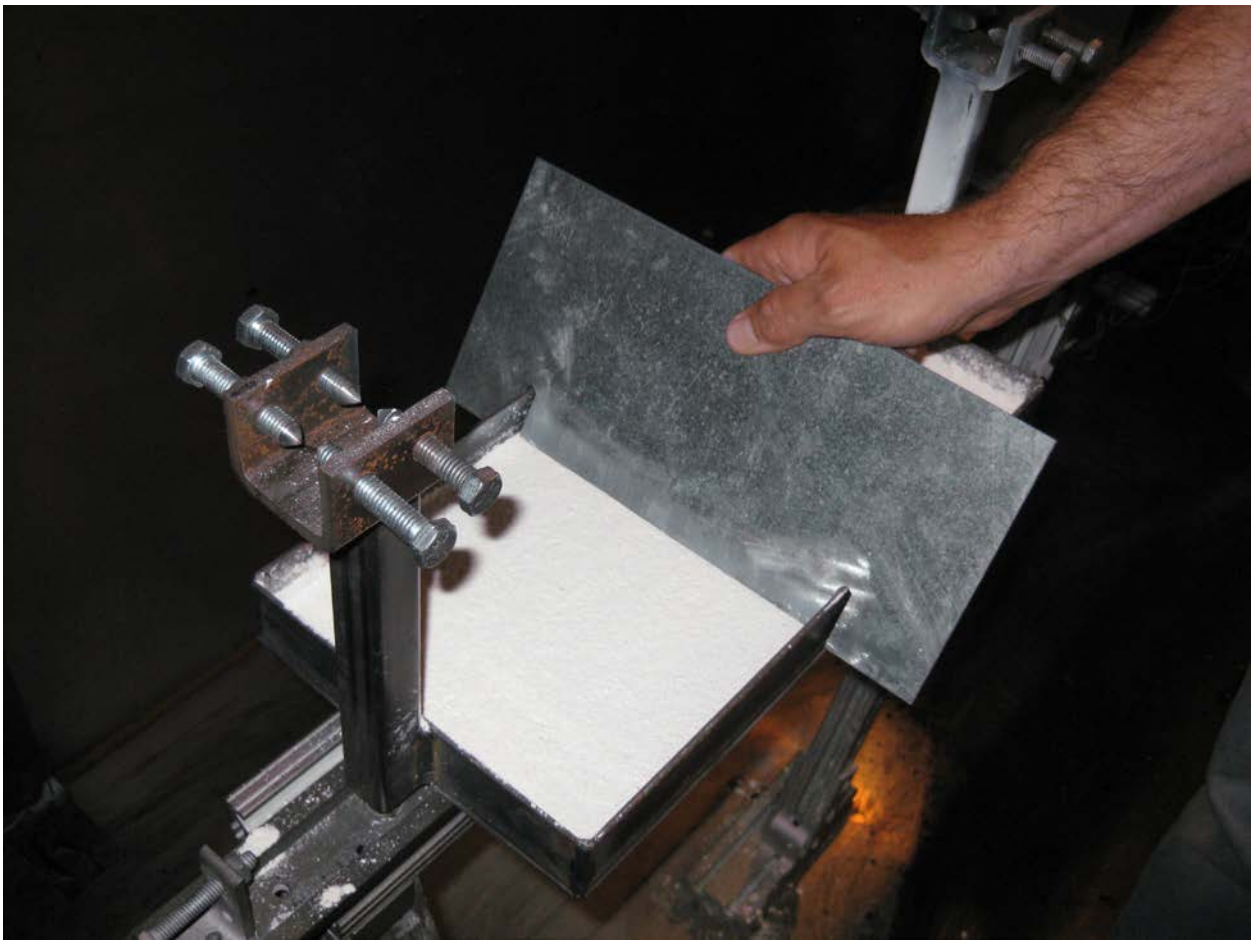


Figure 121. Screeding Device Used to Level off Layer of Talc in Catch Pan

The test sample's face was positioned 4 inches from the burner cone's exit plane, with the center of the sample's width located 1 inch above the burner's horizontal centerline (figure 122).

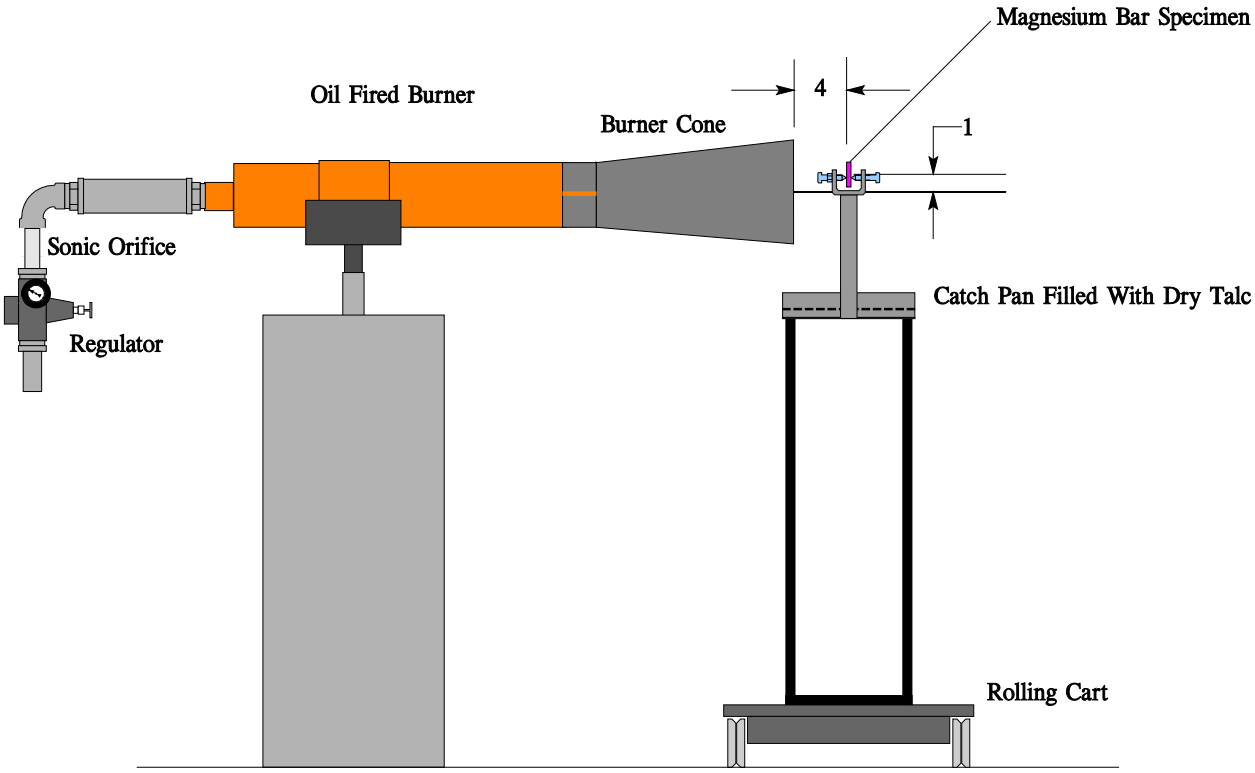


Figure 122. Basic Test Configuration for Horizontal Bar Sample Tests

Prior to running the first test on the horizontal bar samples, researchers agreed that it would be useful to measure the weight of the samples before and after the tests. This would determine the amount of material mass lost because of burning. This measurement is conducted in the seat-cushion flammability test currently required by the FAA for transport category airplanes. The test method requires that seat-cushion samples not lose more than 10% of their initial weight during a test. Although there were no projected values for weight-loss pass/fail criteria for the magnesium alloy samples, it was agreed that the data could be studied post-test to determine the utility of this measurement. A simple electronic scale was employed to measure the pre-test weight of the samples. In addition, researchers agreed to forego any conclusions regarding the flammability performance acceptability of the samples at this point, and to simply run the tests to completion, regardless of the outcome. Although there had been considerable discussion regarding the projected pass/fail criteria, the main focus of the exercise was to generate data to determine the repeatability of the two configurations (vertical cylinders and horizontal bars).

The tests commenced and continued over a 2-month period. Normal measurements of the samples were made prior to each test, including its weight, thickness, width, length, and alloy type. Numerous additional parameters were measured during the test, including the time required for the sample to melt, the time at which any sparking (ignition) occurred, the time the sample began to burn, and the time that any molten residue falling into the pan began to burn. Finally, the time the burner flames were terminated and the times of self-extinguishment of the bar sample and residue in the catch pan were recorded. Once the sample and residue were cooled sufficiently, they were weighed individually.

The first 84 bar samples were machined to metric dimensions (40 mm width and 500 mm length). The remaining 53 samples were supplied in English Units (1.5-inch width and 20-inch length). The small difference in the width and length dimensions did not appear to impact the results. The testing began on the thickest 0.669-inch (17 mm) samples and continued with the other thicknesses of 0.500, 0.375, and 0.250 inch respectively. The tests were primarily conducted in order from thickest to thinnest and grouped by material type rather than randomly. The results of the 137 tests are shown in table 15 in chronological order. The purple-shaded areas denote the results of the 0.669-inch samples, and the blue areas denote the results of the 0.500-inch samples. The copper-colored areas indicate the 0.375-inch sample results, and the 0.250-inch results are white. An "x" indicates that a particular event did not occur; for example, melting or ignition.

As the tests progressed, the spreadsheet data fields were populated with the test results, with programmed functions automatically calculating the weight loss and the burning duration of the bar sample and any molten bar residue. A final column was used to calculate the burn duration of the bar and the molten residue by adding these two values together. A cursory look at this particular column indicates a wide range of test results were obtained. Values ranged from 0 seconds (indicating no burning of either the bar sample or the molten residue had occurred) to a maximum value of 2103 seconds of combined burn duration for an AZ31 sample.

Table 15. Horizontally Oriented Bar Test Results (in chronological order)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
04/23/12	ZE41	0.669	1.57	19.69	344	x	x	x	360	x	x	1.350	1.160	0.000	14.1	0	0	0
04/23/12	WE43	0.669	1.57	19.69	290	290	290	x	360	403	x	1.350	0.980	0.370	0.0	113	0	113
04/23/12	WE43	0.669	1.57	19.69	298	298	330	x	360	415	x	1.350	1.000	0.350	0.0	85	0	85
04/23/12	AZ31	0.669	1.57	19.69	332	294	294	332	360	960	960	1.310	0.250	0.000	80.9	666	628	1294
04/24/12	EL21	0.669	1.57	19.69	339	x	x	x	360	x	x	1.320	1.050	0.270	0.0	0	0	0
04/24/12	EL-21	0.669	1.57	19.69	308	x	x	x	360	x	x	1.320	1.030	0.290	0.0	0	0	0
04/24/12	WE43	0.500	1.57	19.69	227	227	227	227	300	336	900	1.040	0.700	0.080	25.0	109	673	782
04/24/12	WE43	0.500	1.57	19.69	222	222	222	222	300	360	360	1.040	0.680	0.350	1.0	138	138	276
04/24/12	AZ80	0.669	1.57	19.69	247	286	286	247	360	470	960	1.340	0.840	0.000	37.3	184	713	897
04/24/12	ZE41	0.669	1.57	19.69	343	350	x	343	360	x	960	1.350	1.070	0.000	20.7	0	617	617
04/24/12	EL21	0.669	1.57	19.69	324	x	x	x	360	x	x	1.320	1.030	0.290	0.0	0	0	0
04/24/12	WE43	0.669	1.57	19.69	300	300	330	300	360	477	820	1.350	0.960	0.290	7.4	147	520	667
04/25/12	ZE41	0.669	1.57	19.69	346	420	x	346	360	x	960	1.350	1.180	0.000	12.6	0	614	614
04/25/12	EL21	0.500	1.57	19.69	231	x	x	x	240	240	x	1.040	0.820	0.220	0.0	0	0	0
04/25/12	EL21	0.500	1.57	19.69	225	274	285	x	300	300	x	1.030	0.730	0.290	1.0	15	0	15
04/25/12	EXP-2	0.669	1.57	19.69	304	302	302	302	360	420	304	1.410	1.010	0.400	0.0	118	2	120
04/25/12	EXP-2	0.669	1.57	19.69	309	305	305	309	360	445	600	1.400	0.990	0.390	1.4	140	291	431
05/10/12	AZ80	0.500	1.57	19.69	252	222	x	292	300	x	900	1.030	0.674	0.000	34.6	0	608	608

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
05/10/12	AZ80	0.500	1.57	19.69	255	220	230	221	300	300	1080	1.040	0.682	0.062	28.5	70	859	929
05/10/12	AZ31	0.500	1.57	19.69	272	270	271	271	300	1140	1260	1.010	0.300	0.000	70.3	869	989	1858
05/10/12	ZE41	0.500	1.57	19.69	x	480	480	x	300	510	x	1.050	1.032	0.000	1.7	30	0	30
05/10/12	WE43	0.500	1.57	19.69	283	279	280	283	300	335	375	1.040	0.720	0.316	0.4	55	92	147
05/11/12	AZ80	0.500	1.57	19.69	246	232	x	238	300	x	1080	1.030	0.682	0.000	33.8	0	842	842
05/11/12	AZ80	0.500	1.57	19.69	246	220	221	268	300	390	1020	1.030	0.640	0.000	37.9	169	752	921
05/11/12	AZ80	0.500	1.57	19.69	257	214	215	225	300	255	900	1.030	0.684	0.000	33.6	40	675	715
05/11/12	ZE41	0.500	1.57	19.69	288	412	x	413	300	x	960	1.040	0.804	0.000	22.7	0	547	547
05/14/12	WE43	0.375	1.57	19.69	210	211	212	x	240	460	x	0.830	0.570	0.252	1.0	248	0	248
05/14/12	WE43	0.375	1.57	19.69	193	194	203	204	240	232	234	0.830	0.584	0.234	1.4	29	30	59
05/14/12	ZE41	0.375	1.57	19.69	211	254	x	255	240	x	1140	0.830	0.584	0.000	29.6	0	885	885
05/14/12	ZE41	0.375	1.57	19.69	199	236	237	273	240	320	900	0.830	0.598	0.000	28.0	83	627	710
05/14/12	EL21	0.375	1.57	19.69	187	x	x	x	240	x	x	0.820	0.584	0.222	1.7	0	0	0
05/14/12	EL21	0.375	1.57	19.69	181	227	228	244	240	375	312	0.810	0.560	0.239	1.4	147	68	215
05/14/12	WE43	0.375	1.57	19.69	190	191	192	x	240	296	x	0.820	0.570	0.244	0.7	104	0	104
05/15/12	WE43	0.375	1.57	19.69	200	202	203	x	240	365	x	0.830	0.580	0.234	1.9	162	0	162
05/15/12	ZE41	0.375	1.57	19.69	210	255	x	256	240	x	1020	0.830	0.624	0.000	24.8	0	764	764
05/15/12	ZE41	0.375	1.57	19.69	213	245	x	255	240	x	1140	0.820	0.594	0.000	27.6	0	885	885

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
05/15/12	EL21	0.375	1.57	19.69	201	x	x	x	240	x	x	0.810	0.590	0.214	0.7	0	0	0
05/15/12	EL21	0.375	1.57	19.69	190	236	237	x	240	405	x	0.810	0.572	0.230	1.0	168	0	168
05/15/12	EL43	0.500	1.57	19.69	286	287	309	288	300	350	900	1.040	0.726	0.256	5.6	41	612	653
05/15/12	EL43	0.500	1.57	19.69	280	281	283	x	300	370	x	1.030	0.776	0.250	0.4	87	0	87
05/15/12	EL43	0.500	1.57	19.69	284	279	280	292	300	342	367	1.030	0.712	0.310	0.8	62	75	137
05/15/12	EL43	0.500	1.57	19.69	268	266	290	x	300	293	x	1.030	0.740	0.276	1.4	3	0	3
05/16/12	ZE41	0.230	1.57	19.69	144	158	159	174	240	312	1020	0.540	0.324	0.000	40.0	153	846	999
05/16/12	WE43	0.246	1.57	19.69	142	158	159	x	240	248	x	0.570	0.392	0.168	1.8	89	0	89
05/16/12	WE43	0.255	1.57	19.69	141	142	143	x	240	305	x	0.560	0.386	0.170	0.7	162	0	162
05/16/12	EL43	0.245	1.57	19.69	147	215	x	x	240	x	x	0.560	0.410	0.150	0.0	0	0	0
05/16/12	EL43	0.241	1.57	19.69	150	190	191	x	240	320	x	0.550	0.392	0.152	1.1	129	0	129
05/16/12	EL21	0.239	1.57	19.69	141	178	179	237	240	267	345	0.580	0.406	0.168	1.0	88	108	88
05/16/12	EL21	0.249	1.57	19.69	140	194	195	257	240	350	270	0.560	0.358	0.192	1.8	155	13	155
05/16/12	AZ31	0.500	1.57	19.69	325	283	288	326	300	1200	1200	1.010	0.260	0.000	74.3	912	874	1786
05/17/12	EL21	0.500	1.57	19.69	281	x	x	x	300	x	x	1.040	0.778	0.244	1.7	0	0	0
05/17/12	EL21	0.500	1.57	19.69	264	x	x	x	300	x	x	1.040	0.752	0.270	1.7	0	0	0
05/17/12	WE43	0.500	1.57	19.69	290	288	289	289	300	323	510	1.040	0.754	0.282	0.4	34	221	255
05/17/12	AZ31	0.500	1.57	19.69	323	260	333	324	300	1380	1380	1.020	0.000	0.000	100.0	1047	1056	2103

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
05/21/12	EL43	0.373	1.57	19.69	212	209	209	213	240	240	780	0.800	0.548	0.208	5.5	31	567	598
05/21/12	EL43	0.371	1.57	19.69	220	220	220	x	240	315	x	0.800	0.580	0.216	0.5	95	0	95
05/21/12	AZ80	0.374	1.57	19.69	184	178	222	213	240	315	900	0.830	0.546	0.000	34.2	93	687	780
05/21/12	AZ80	0.370	1.57	19.69	232	233	187	206	240	415	1140	0.820	0.512	0.000	37.6	228	934	1162
05/21/12	AZ80	0.366	1.57	19.69	180	188	209	221	240	692	945	0.820	0.486	0.000	40.7	483	724	1207
05/21/12	AZ80	0.363	1.57	19.69	181	174	196	198	240	440	1140	0.810	0.490	0.000	39.5	244	942	1186
05/22/12	WE43	0.575	1.57	19.69	x	x	x	x	300	x	x	1.200	1.194	0.000	0.5	0	0	0
05/22/12	WE43	0.503	1.57	19.69	270	269	x	269	300	x	780	1.050	0.780	0.228	4.0	0	511	511
05/22/12	WE43	0.500	1.57	19.69	278	274	279	279	300	325	600	1.050	0.746	0.282	2.1	46	321	367
05/22/12	WE43	0.503	1.57	19.69	265	262	280	264	300	447	375	1.050	0.756	0.280	1.3	167	111	278
05/22/12	WE43	0.501	1.57	19.69	240	241	x	244	300	x	380	1.040	0.724	0.308	0.8	0	136	136
05/22/12	EL43	0.501	1.57	19.69	263	260	261	261	300	332	840	1.050	0.740	0.248	5.9	71	579	650
05/22/12	EL21	0.503	1.57	19.69	271	x	x	x	300	x	x	1.030	0.748	0.272	1.0	0	0	0
05/22/12	EL21	0.501	1.57	19.69	293	x	x	x	300	x	x	1.030	0.744	0.278	0.8	0	0	0
05/23/12	ZE41	0.501	1.57	19.69	298	336	349	337	300	393	900	1.050	0.916	0.000	12.8	44	563	607
05/23/12	AZ80	0.504	1.57	19.69	266	272	288	302	300	720	900	1.030	0.606	0.322	9.9	432	598	1030
05/23/12	AZ80	0.501	1.57	19.69	254	257	264	302	300	972	1200	1.030	0.560	0.000	45.6	708	898	1606
05/23/12	ZE41	0.317	1.57	19.69	195	195	206	298	300	385	500	0.660	0.420	0.204	5.5	179	202	381

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
05/24/12	EL21	0.245	1.57	19.69	147	208	208	245	240	295	330	0.560	0.382	0.166	2.1	87	85	172
05/24/12	EL21	0.245	1.57	19.69	145	205	205	245	240	300	285	0.560	0.370	0.182	1.4	95	40	135
05/24/12	ZE41	0.244	1.57	19.69	128	135	142	153	240	361	900	0.590	0.344	0.000	41.7	219	747	966
05/24/12	AZ80	0.251	1.57	19.69	132	126	161	166	240	378	810	0.570	0.296	0.000	48.1	217	644	861
05/24/12	AZ80	0.252	1.57	19.69	119	118	128	148	240	343	840	0.580	0.284	0.000	51.0	215	692	907
05/24/12	AZ80	0.245	1.57	19.69	132	148	172	149	240	423	840	0.560	0.298	0.000	46.8	251	691	942
05/24/12	AZ31	0.247	1.57	19.69	153	150	160	168	240	333	900	0.560	0.256	0.000	54.3	173	732	905
05/24/12	AZ31	0.246	1.57	19.69	162	153	153	162	240	385	900	0.550	0.250	0.000	54.5	232	738	970
06/04/12	EL21	0.250	1.57	19.69	142	185	185	247	240	280	300	0.564	0.382	0.180	0.4	95	53	148
06/04/12	AZ80	0.251	1.57	19.69	126	154	154	171	240	459	960	0.566	0.274	0.000	51.6	305	789	1094
06/04/12	AZ31	0.251	1.57	19.69	150	144	151	151	240	1140	960	0.566	0.082	0.000	85.5	989	809	1798
06/06/12	EL21	0.250	1.50	20	158	196	197	244	240	270	300	0.492	0.322	0.168	0.4	73	56	129
06/06/12	EL21	0.250	1.50	20	154	195	195	205	240	260	360	0.500	0.324	0.168	1.6	65	155	220
06/06/12	EL21	0.250	1.50	20	147	210	210	255	240	287	335	0.498	0.334	0.164	0.0	77	80	157
06/06/12	EL43	0.250	1.50	20	143	143	234	143	240	323	160	0.496	0.322	0.174	0.0	89	17	106
06/06/12	EL43	0.250	1.50	20	140	165	180	204	240	455	450	0.504	0.304	0.182	3.6	275	246	521
06/06/12	EL43	0.250	1.50	20	143	142	142	200	240	340	225	0.498	0.304	0.174	4.0	198	25	223
06/06/12	EL21	0.375	1.50	20	226	x	x	x	240	x	x	0.732	0.570	0.162	0.0	0	0	0

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
06/06/12	EL21	0.375	1.50	20	216	x	x	x	240	x	x	0.744	0.564	0.180	0.0	0	0	0
06/06/12	EL21	0.375	1.50	20	207	x	x	x	240	x	x	0.734	0.570	0.164	0.0	0	0	0
06/06/12	EL43	0.375	1.50	20	198	231	231	x	240	233	x	0.748	0.562	0.186	0.0	2	0	2
06/06/12	EL43	0.375	1.50	20	196	195	240	196	240	295	363	0.746	0.554	0.190	0.3	55	167	222
06/07/12	EL43	0.038	1.50	20	220	219	219	x	240	325	x	0.744	0.570	0.174	0.0	106	0	106
06/07/12	ZE41	0.250	1.50	20	138	145	162	194	240	297	900	0.490	0.292	0.000	40.4	135	706	841
06/07/12	ZE41	0.250	1.50	20	140	151	166	186	240	445	690	0.492	0.284	0.000	42.3	279	504	783
06/07/12	ZE41	0.250	1.50	20	140	148	149	176	240	275	960	0.498	0.280	0.000	43.8	126	784	910
06/07/12	ZE41	0.250	1.50	20	198	223	224	242	240	280	985	0.732	0.528	0.000	27.9	56	743	799
06/07/12	ZE41	0.250	1.50	20	196	254	255	232	240	270	960	0.738	0.530	0.000	28.2	15	728	743
06/07/12	ZE41	0.250	1.50	20	192	208	278	228	240	286	960	0.738	0.528	0.000	28.5	8	732	740
06/08/12	EL21	0.500	1.50	20	257	x	x	x	300	x	x	0.982	0.732	0.250	0.0	0	0	0
06/08/12	EL43	0.500	1.50	20	230	229	238	x	300	540	x	0.982	0.690	0.282	1.0	302	0	302
06/08/12	EL21	0.500	1.50	20	247	x	x	x	300	x	x	0.970	0.714	0.256	0.0	0	0	0
06/08/12	EL43	0.500	1.50	20	221	233	253	315	300	576	930	0.980	0.594	0.306	8.2	323	615	938
06/08/12	EL21	0.500	1.50	20	294	x	x	x	300	x	x	0.982	0.780	0.202	0.0	0	0	0
06/08/12	EL21	0.500	1.50	20	277	x	x	x	300	x	x	0.978	0.754	0.222	0.2	0	0	0
06/08/12	AZ80	0.250	1.50	20	119	135	136	156	240	357	900	0.494	0.222	0.000	55.1	221	744	965

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
06/08/12	AZ80	0.375	1.50	20	176	185	215	221	240	324	1080	0.738	0.484	0.000	34.4	109	859	968
06/08/12	ZE41	0.500	1.50	20	277	305	332	330	300	385	990	0.978	0.752	0.000	23.1	53	660	713
06/08/12	EL43	0.500	1.50	20	253	253	275	253	300	280	870	0.990	0.728	0.226	3.6	5	617	622
06/11/12	EL21	0.500	1.50	20	281	x	x	x	300	x	x	0.986	0.784	0.202	0.0	0	0	0
06/11/12	EL43	0.500	1.50	20	278	278	279	279	300	342	1320	0.998	0.728	0.000	27.1	63	1041	1104
06/11/12	EL21	0.500	1.50	20	284	x	x	x	300	x	x	0.982	0.784	0.198	0.0	0	0	0
06/11/12	EL43	0.500	1.50	20	265	264	291	266	300	333	1110	0.984	0.706	0.206	7.3	42	844	886
06/11/12	EL21	0.500	1.50	20	275	x	x	x	300	x	x	0.986	0.768	0.218	0.0	0	0	0
06/11/12	AZ80	0.500	1.50	20	230	218	218	231	300	702	1260	0.976	0.486	0.000	50.2	484	1029	1513
06/11/12	ZE41	0.500	1.50	20	279	303	x	304	300	x	960	0.980	0.754	0.000	23.1	0	656	656
06/11/12	EL43	0.500	1.50	20	259	259	270	260	300	275	262	0.978	0.724	0.254	0.0	5	2	7
06/12/12	AZ80	0.375	1.50	20	172	169	213	184	240	350	870	0.738	0.462	0.000	37.4	137	686	823
06/12/12	AZ80	0.375	1.50	20	170	174	225	201	240	735	1320	0.740	0.380	0.000	48.6	510	1119	1629
06/12/12	AZ80	0.250	1.50	20	116	137	158	138	240	346	900	0.490	0.240	0.000	51.0	188	762	950
06/12/12	AZ80	0.250	1.50	19.69	113	136	161	143	240	454	930	0.484	0.206	0.000	57.4	293	787	1080
06/12/12	EL21	0.500	1.50	20	279	x	x	x	300	x	x	0.980	0.750	0.230	0.0	0	0	0
06/12/12	EL21	0.500	1.50	20	274	x	x	x	300	x	x	0.986	0.762	0.224	0.0	0	0	0
06/12/12	EL21	0.500	1.50	20	272	x	x	x	300	x	x	0.988	0.790	0.198	0.0	0	0	0

Table 15. Horizontally Oriented Bar Test Results (in chronological order) (Continued)

Date Tested	Alloy Type	Thickness (inches)	Width (inches)	Length (inches)	Melt Time (Seconds)	Ignition (Seconds)	Bar Begins to Burn (Seconds)	Residue Begins to Burn (Seconds)	Burner Off (Seconds)	Bar Out (Seconds)	Residue Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)	Total Bar Burn Duration (Seconds)	Total Residue Burn Duration (Seconds)	Sample Total Burn Duration (Seconds)
06/12/12	EL43	0.500	1.50	20	274	272	272	0	300	380	0	0.980	0.724	0.256	0.0	108	0	108
06/12/12	EL43	0.500	1.50	20	x	x	x	x	300	x	x	0.984	0.984	0.000	0.0	0	0	0
06/13/12	AZ80	0.500	1.50	20	259	254	254	268	300	596	1320	0.984	0.610	0.000	38.0	342	1052	1394
06/13/12	AZ80	0.500	1.50	20	253	252	253	281	300	455	1170	0.970	0.706	0.000	27.2	202	889	1091
06/14/12	EL43	0.500	1.50	20	300	301	301	301	300	449	1410	0.982	0.738	0.000	24.8	148	1109	1257
06/14/12	ZE41	0.500	1.50	20	367	341	341	368	300	601	1200	0.978	0.762	0.000	22.1	260	832	1092
06/18/12	ZE41	0.500	1.50	20	NR	NR	NR	NR	300	NR	NR	NR	NR	NR	NR	NR	NR	NR
06/18/12	ZE41	0.500	1.50	20	NR	NR	NR	NR	300	NR	NR	NR	NR	NR	NR	NR	NR	NR
06/18/12	ZE41	0.500	1.50	20	NR	NR	NR	NR	300	NR	NR	NR	NR	NR	NR	NR	NR	NR
06/18/12	AZ80	0.500	1.50	20	NR	NR	NR	NR	300	NR	NR	NR	NR	NR	NR	NR	NR	NR
06/18/12	AZ80	0.500	1.50	20	NR	NR	NR	NR	300	NR	NR	NR	NR	NR	NR	NR	NR	NR

Because of the sizeable amount of data collected during the 137 tests, a series of bar charts were generated to help clarify the results. The charts were based on the thickness of the samples tested (figures 123 through 127). Each chart corresponds to a different bar thickness (two charts were used for the 0.500-inch bar results because there were too many tests to comfortably fit on a single chart). For each chart of a particular sample thickness, the tests were then displayed in groups of materials rather than in chronological order (the spreadsheet data are in chronological order). As shown in figure 123, there is a maximum of five values for each test conducted: the time the bar begins to burn, the time the residue begins to burn, the time when the bar self-extinguishes, the time when the molten residue self-extinguishes, and the calculated weight loss. In many instances, there are fewer than five values shown, which indicates one or more of the measured parameters did not occur during that particular test. It should also be noted that three different burner exposure times were used during the tests because of the different thickness of samples used. All of the 0.669-inch samples were exposed for 6 minutes, whereas all of the 0.500-inch samples were exposed for only 5 minutes. Both the 0.375- and 0.250-inch samples were exposed for 4 minutes. Test results indicated the extended amount of exposure time required to melt the 0.669-inch thickness samples did not result in more consistency when compared to any of the thinner samples. Researchers concluded there was no benefit to using this greater thickness and that it would be discontinued for future studies.

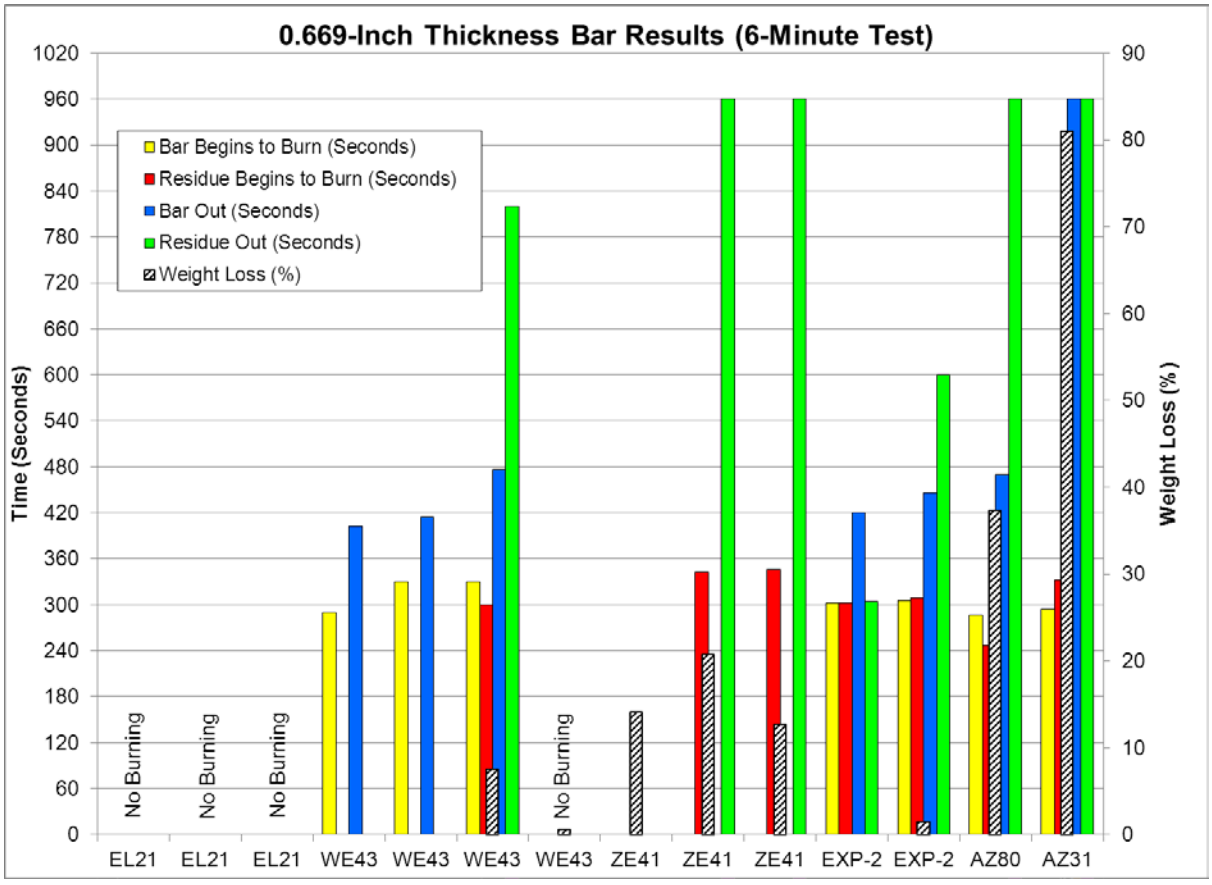


Figure 123. The 0.669-Inch-Thickness Bar Test Results

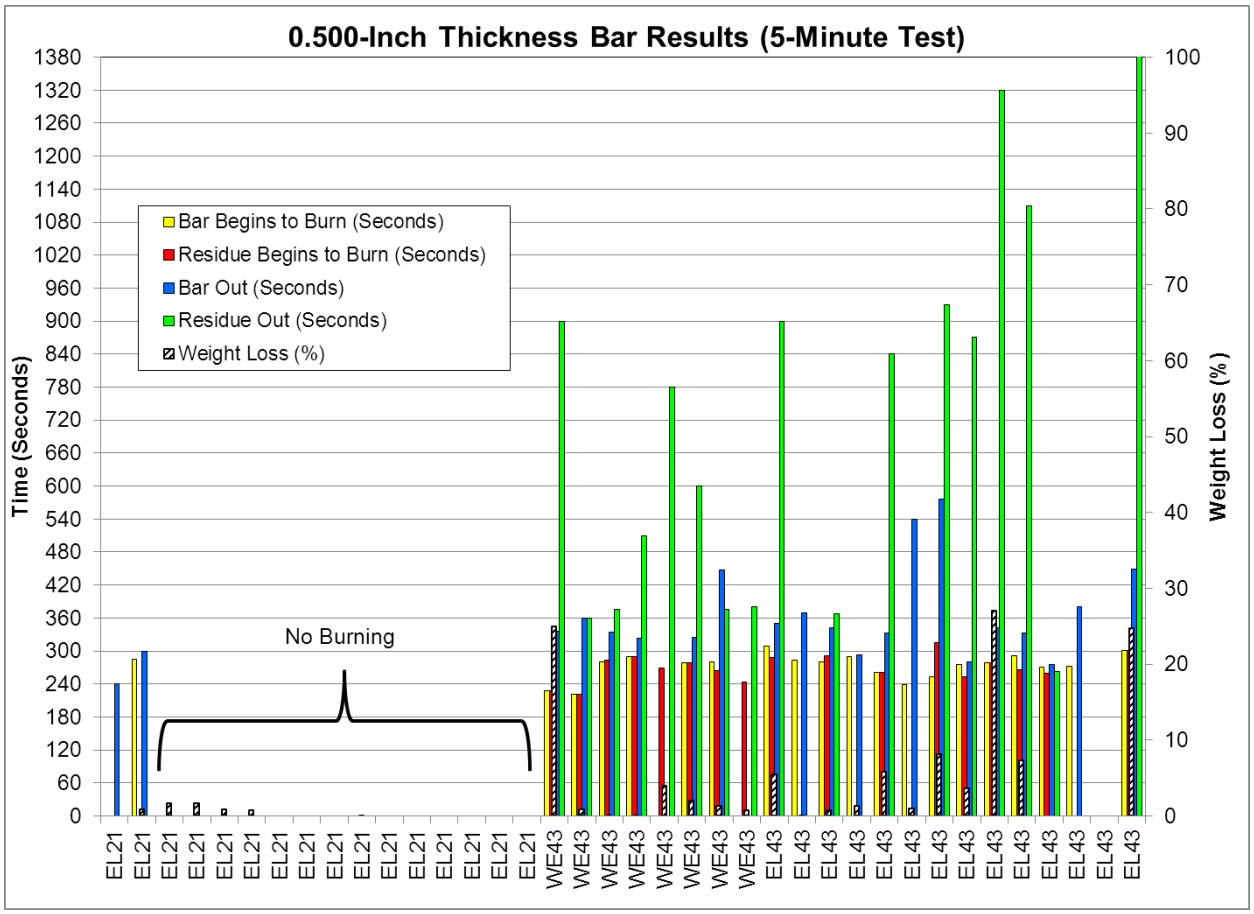


Figure 124. The 0.500-Inch-Thickness Bar Test Results of Well-Performing Alloys

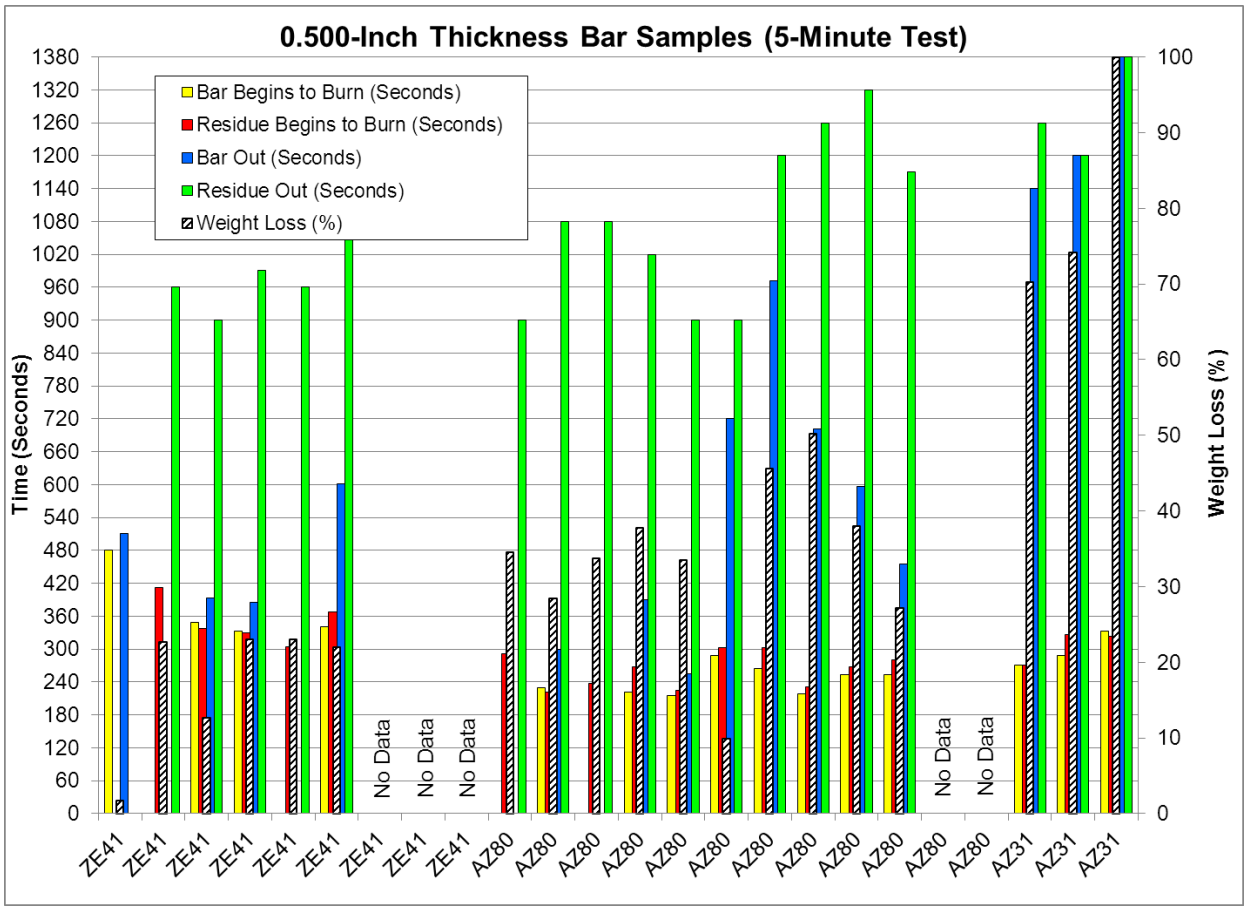


Figure 125. The 0.500-Inch-Thickness Bar Test Results of Poor-Performing Alloys

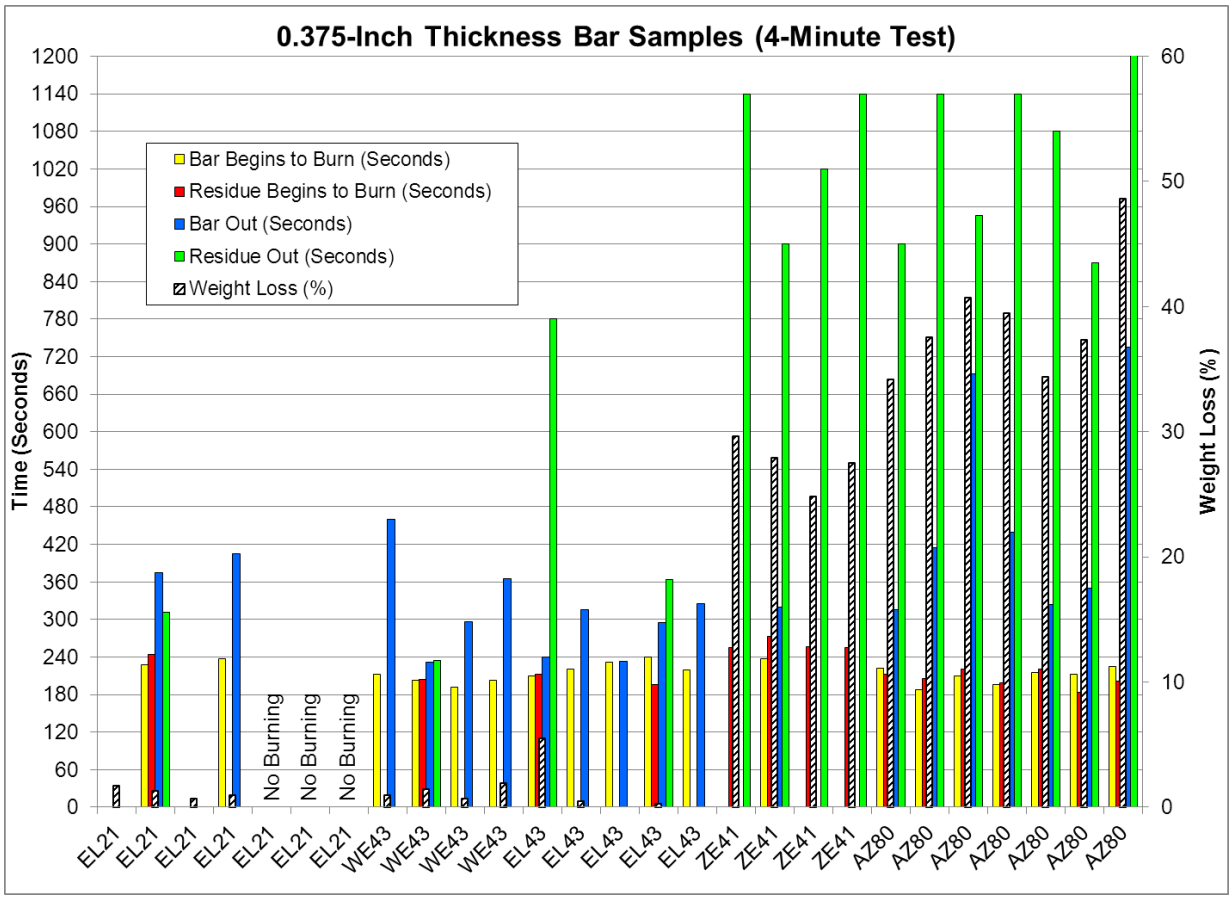


Figure 126. The 0.375-Inch-Thickness Bar Test Results

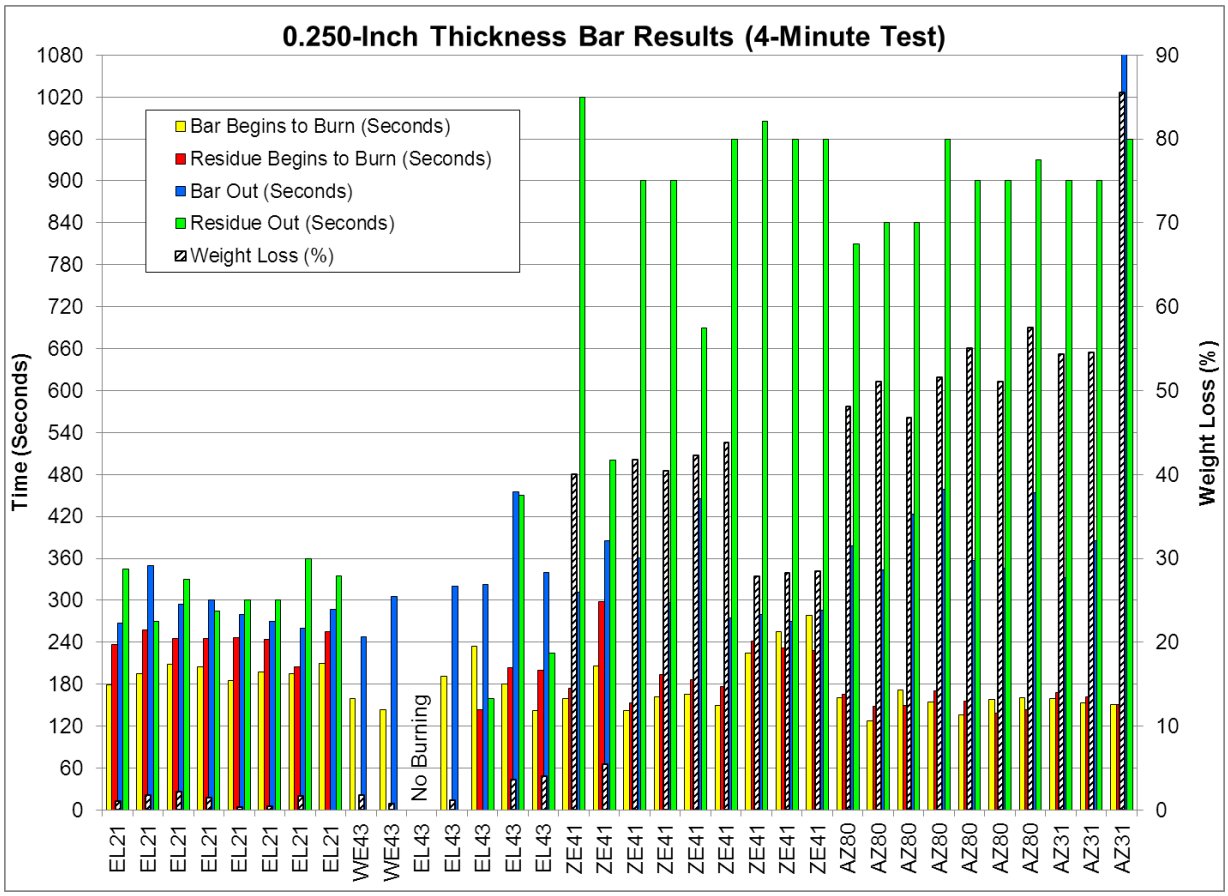


Figure 127. The 0.250-Inch-Thickness Bar Test Results

When the 0.500-, 0.375-, and 0.250-inch test results were viewed, a number of generalizations could be deciphered quickly. For example, the EL21 samples typically performed well, not burning at all in many cases. Conversely, the AZ alloys generally performed poorly, with high burn durations and calculated weight loss. Of the three thicknesses, it appeared that the 0.250-inch samples yielded the most consistency.

The determination of the time when the molten residue self-extinguished proved to be the most troublesome of all the measured parameters. This determination was difficult for several reasons. First, the molten mass of material would typically fall into the layer of talc, rather than on top of it. Once the molten material mass was partly or fully below the surface of the talc, it was difficult to visualize clearly. There was also considerable discussion over the role that the talc was playing in insulating the burning remnants, possibly lengthening the duration of burning by trapping heat. Second, there were instances in which more than one mass of material would fall into the catch pan from different locations. In general, a large mass in the center of the horizontal sample would break free during the melting process. However, in some cases, the mass would not break cleanly away from both ends of the sample and fall directly below, but would break first at one end and swing in a rotational fashion (figure 128). This would result in the mass of material landing closer to one side of the pan. At a later point in time, additional molten pieces would fall into the catch pan at different locations. The various pieces would cool at different rates, making the self-extinguishment measurement a difficult task.

Figure 128. Sample Material Melting and Rotating Into Catch Pan Below

Third, the measurement of the self-extinguishment time of a molten, burning mass of material was a challenging undertaking because it did not occur quickly, but gradually. This contributed to the overall error of the measurement; there was a good deal of individual interpretation involved. As an example, the following six pictures (figure 129) depict a burning, vertically oriented cone sample. As shown, the burning eventually subsides and the sample slowly begins to cool as a thick magnesium oxide layer also begins to form in the shape of a mushroom. Although the pictures document the progress of a burning cone and not the burning remnants of a horizontal bar, they illustrate the difficulty in determining the point of self-extinguishment of a cooling magnesium sample after robust burning.

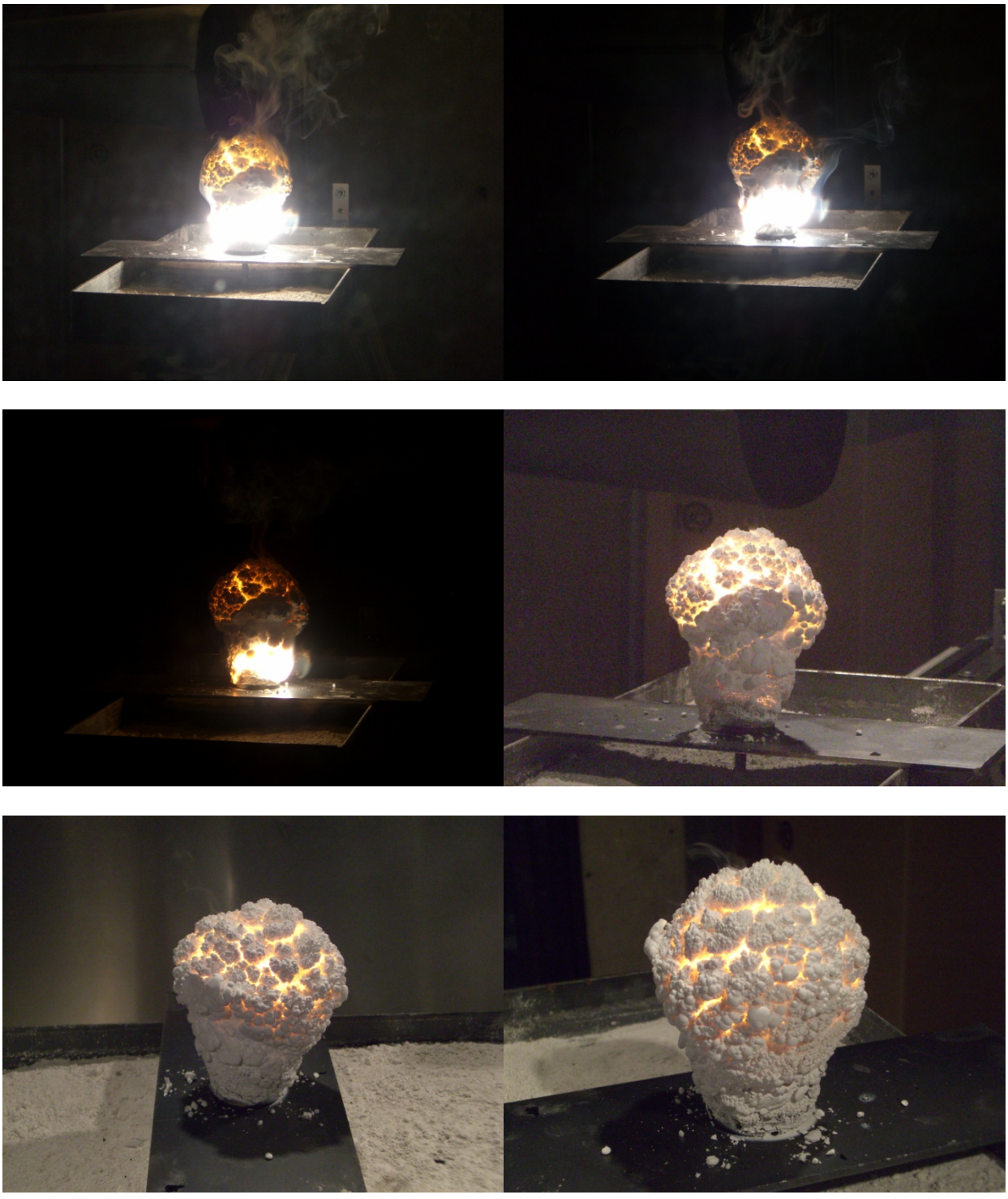


Figure 129. Burning and Cooling of a Magnesium Test Sample, Illustrating the Difficulty in Determining Self-Extinguishment Time

Although it was difficult to establish a point in time when the burning residue in the catch pan self-extinguished, it was much easier to make this determination on the remaining sample sections attached to the sample holder. Because a larger mass of solid material typically

remained, these sections cooled more rapidly than the pieces of molten residue in the pan. The rapid cooling facilitated a more concise point in time when the sample could be declared self-extinguished.

As previously mentioned, the samples were all weighed prior to testing and the sample remnants were again weighed after the test. This included the sections of material still attached to the sample holder, as well as any resolidified pieces collected from the catch pan. Technicians were careful to include only the metallic portion of the sample remnants during the weighing and not the burned/oxidized white magnesium oxide. To facilitate this measurement, all pieces collected from the catch pan were blown off with compressed air prior to weighing. This process also ensured that talc powder attached to the surface was not included in the final weight of any resolidified pieces retrieved. A simple calculation was used to determine weight loss by dividing the difference in pre- and post-test weight by the pre-test weight, and multiplying by 100. It became clear that the longer the burn duration of the sample, the higher the calculated weight loss that resulted. A graph of the burn duration versus weight loss was generated for each of the four sample thicknesses. As shown for a sample thickness of 0.250 inch in figure 130, there is a very close correlation between the two.

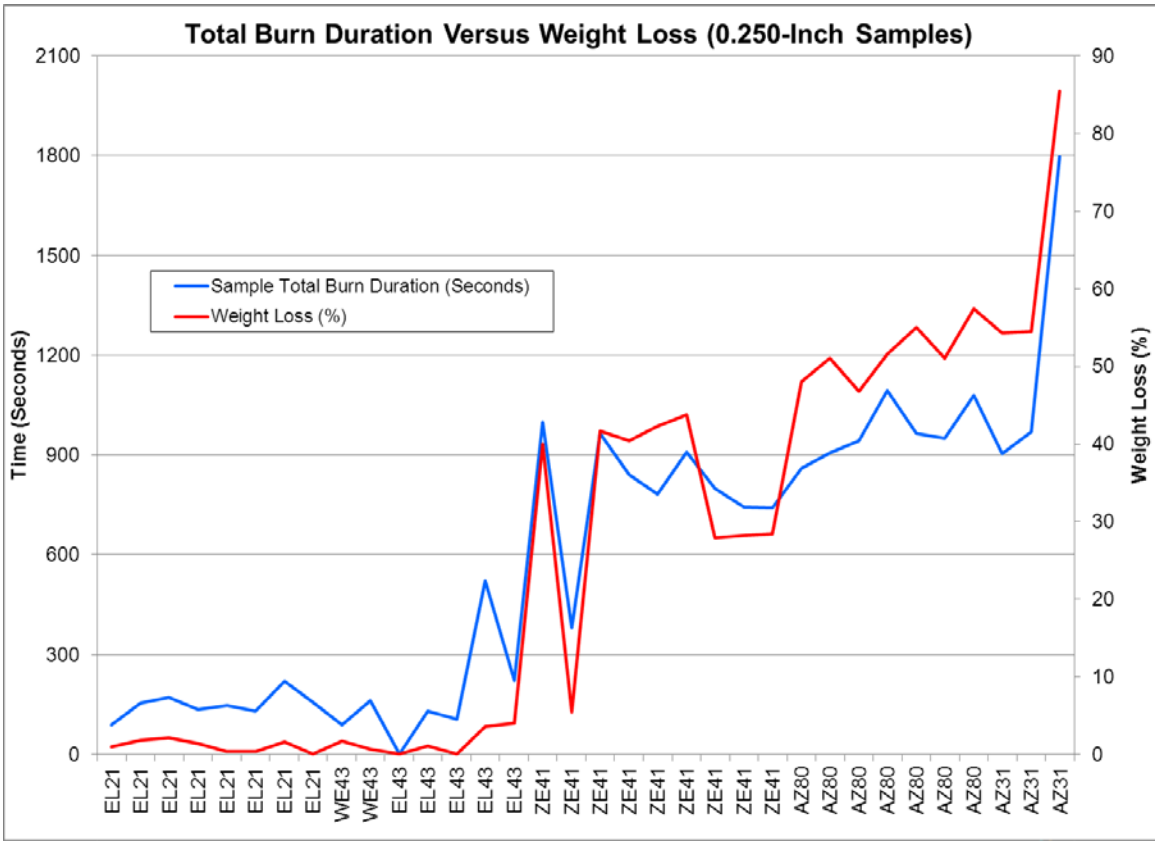


Figure 130. Burn Duration vs. Weight Loss of 0.250-Inch Thickness Samples

This resulting correlation was encouraging in that it could eliminate the need for testers to attempt to visually record the time of self-extinguishment of the burning sample, in particular the residue in the catch pan. Measurement of the pre- and post-test weights of all sample materials

was a much more accurate means of determining the amount of burning of the sample that occurred during the tests.

An additional series of tables shows the calculated averages, standard deviations, and %RSD for the time when the sample begins to burn, the time when the residue begins to burn, and the times when each of these self-extinguished. Averages, standard deviations, and %RSDs are also calculated for the weight loss. The tables display only 117 of the 137 tests conducted (the 0.500, 0.375, and 0.250-inch thickness tests; the AZ31 and EXP samples were not included). The EL21 data are shown in table 16; WE43 and EL43 data are shown in table 17; ZE-41 data are shown in table 18; and AZ80 data are shown in table 19.

Table 16. Averages, Standard Deviations, and %RSD for EL21 Tests

0.5																				
Date	04/25/12	04/25/12	05/17/12	05/17/12	05/22/12	05/22/12	06/08/12	06/08/12	06/08/12	06/08/12	06/11/12	06/11/12	06/11/12	06/12/12	06/12/12	06/12/12		Average	Standard Deviation	% RSD
Alloy	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21				
Bar Begins to Burn (Seconds)	0	285	0	0	0	0	0	0	0	0	0	0	0	0	0	0		17.8	71.3	400.0
Residue Begins to Burn (Seconds)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.0	0.0	0.0
Burner Off (Seconds)	240	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300				
Bar Out (Seconds)	240	300	0	0	0	0	0	0	0	0	0	0	0	0	0	0		33.8	92.9	275.2
Residue Out (Seconds)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.0	0.0	0.0
Weight Loss (%)	0.0	1.0	1.7	1.7	1.0	0.8	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0		0.4	0.6	158.2

Table 16. Averages, Standard Deviations, and %RSD for EL21 Tests (Continued)

0.375										
Date	05/14/12	05/14/12	05/15/12	05/15/12	06/06/12	06/06/12	06/06/12		Average	Standard Deviation	% RSD
Alloy	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21				
Bar Begins to Burn (Seconds)	0	228	0	237	0	0	0		66.4	113.5	170.8
Residue Begins to Burn (Seconds)	0	244	0	0	0	0	0		34.9	92.2	264.6
Burner Off (Seconds)	240	240	240	240	240	240	240				
Bar Out (Seconds)	0	375	0	405	0	0	0		111.4	190.5	171.0
Residue Out (Seconds)	0	312	0	0	0	0	0		44.6	117.9	264.6
Weight Loss (%)	1.7	1.4	0.7	1.0	0.0	0.0	0.0		0.7	0.7	103.3

Table 16. Averages, Standard Deviations, and %RSD for EL21 Tests (Continued)

0.25												
Date	05/16/12	05/16/12	05/24/12	05/24/12	06/04/12	06/06/12	06/06/12	06/06/12		Average	Standard Deviation	% RSD
Alloy	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21	EL-21				
Bar Begins to Burn (Seconds)	179	195	208	205	185	197	195	210		196.8	10.9	5.5
Residue Begins to Burn (Seconds)	237	257	245	245	247	244	205	255		241.9	16.2	6.7
Burner Off (Seconds)	240	240	240	240	240	240	240	240				
Bar Out (Seconds)	267	350	295	300	280	270	260	287		288.6	28.4	9.8
Residue Out (Seconds)	345	270	330	285	300	300	360	335		315.6	31.4	10.0
Weight Loss (%)	1.0	1.8	2.1	1.4	0.4	0.4	1.6	0.0		1.1	0.8	70.5

Table 17. Averages, Standard Deviations, and %RSD for WE43 and EL43 Tests

0.5																									
Date	04/24/12	04/24/12	05/10/12	05/17/12	05/22/12	05/22/12	05/22/12	05/22/12	05/15/12	05/15/12	05/15/12	05/15/12	05/22/12	06/08/12	06/08/12	06/08/12	06/11/12	06/11/12	06/11/12	06/12/12	06/12/12	06/14/12		Average	Standard Deviation	% RSD
Alloy	WE-43	WE-43	WE-43	WE-43	WE-43	WE-43	WE-43	WE-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43	E-43				
Bar Begins to Burn (Seconds)	227	222	280	289	0	279	280	0	309	283	280	290	261	238	253	275	279	291	270	272	0	301		232.3	99.4	42.8
Residue Begins to Burn (Seconds)	227	222	283	289	269	279	264	244	288	0	292	0	261	0	315	253	279	266	260	0	0	301		204.3	118.9	58.2
Burner Off (Seconds)	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300				
Bar Out (Seconds)	336	360	335	323	0	325	447	0	350	370	342	293	332	540	576	280	342	333	275	380	0	449		311.4	150.1	48.2
Residue Out (Seconds)	900	360	375	510	780	600	375	380	900	0	367	0	840	0	930	870	1320	1110	262	0	0	1410		518.0	404.5	78.1
Weight Loss (%)	25.0	1.0	0.4	0.4	4.0	2.1	1.3	0.8	5.6	0.4	0.8	1.4	5.9	1.0	8.2	3.6	27.1	7.3	0.0	0.0	0.0	24.8		4.6	7.6	165.2

Table 17. Averages, Standard Deviations, and %RSD for WE43 and EL43 Tests (Continued)

0.375													
Date	05/14/12	05/14/12	05/14/12	05/15/12	05/21/12	05/21/12	06/06/12	06/06/12	06/07/12		Average	Standard Deviation	% RSD
Alloy	WE-43	WE-43	WE-43	WE-43	E-43	E-43	E-43	E-43	E-43				
Bar Begins to Burn (Seconds)	212	203	192	203	209	220	231	240	219		214.3	14.9	7.0
Residue Begins to Burn (Seconds)	0	204	0	0	213	0	0	196	0		68.1	102.3	150.1
Burner Off (Seconds)	240	240	240	240	240	240	240	240	240				
Bar Out (Seconds)	460	232	296	365	240	315	233	295	325		306.8	73.3	23.9
Residue Out (Seconds)	0	234	0	0	780	0	0	363	0		153.0	270.2	176.6
Weight Loss (%)	1.0	1.4	0.7	1.9	5.5	0.5	0.0	0.3	0.0		1.3	1.7	136.2

Table 17. Averages, Standard Deviations, and %RSD for WE43 and EL43 Tests (Continued)

0.25											
Date	05/16/12	05/16/12	05/16/12	05/16/12	06/06/12	06/06/12	06/06/12		Average	Standard Deviation	% RSD
Alloy	WE-43	WE-43	E-43	E-43	E-43	E-43	E-43				
Bar Begins to Burn (Seconds)	159	143	0	191	234	180	142		149.9	73.4	49.0
Residue Begins to Burn (Seconds)	0	0	0	0	143	204	200		78.1	99.4	127.2
Burner Off (Seconds)	240	240	240	240	240	240	240				
Bar Out (Seconds)	248	305	0	320	323	455	340		284.4	140.0	49.2
Residue Out (Seconds)	0	0	0	0	160	450	225		119.3	172.8	144.8
Weight Loss (%)	1.8	0.7	0.0	1.1	0.0	3.6	4.0		1.6	1.6	102.3

Table 18. Averages, Standard Deviations, and %RSD for ZE41 Tests

0.5													
Date	05/10/12	05/11/12	05/23/12	06/08/12	06/11/12	06/14/12	06/18/12	06/18/12	06/18/12		Average	Standard Deviation	% RSD
Alloy	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41				
Bar Begins to Burn (Seconds)	480	0	349	332	0	341	NR	NR	NR		250.3	201.3	80.4
Residue Begins to Burn (Seconds)	0	413	337	330	304	368	NR	NR	NR		292.0	147.8	50.6
Burner Off (Seconds)	300	300	300	300	300	300	NR	NR	NR				
Bar Out (Seconds)	510	300	393	385	0	601	NR	NR	NR		364.8	207.5	56.9
Residue Out (Seconds)	0	960	900	990	960	1200	NR	NR	NR		835.0	421.9	50.5
Weight Loss (%)	1.7	22.7	12.8	23.1	23.1	22.1	NR	NR	NR		17.6	8.7	49.7

Table 18. Averages, Standard Deviations, and %RSD for ZE41 Tests (Continued)

0.375								
Date	05/14/12	05/14/12	05/15/12	05/15/12		Average	Standard Deviation	% RSD
Alloy	ZE-41	ZE-41	ZE-41	ZE-41				
Bar Begins to Burn (Seconds)	0	237	0	0		59.3	118.5	200.0
Residue Begins to Burn (Seconds)	255	273	256	255		259.8	8.8	3.4
Burner Off (Seconds)	240	240	240	240				
Bar Out (Seconds)	0	320	0	0		80.0	160.0	200.0
Residue Out (Seconds)	1140	900	1020	1140		1050.0	114.9	10.9
Weight Loss (%)	29.6	28.0	24.8	27.6		27.5	2.0	7.3

Table 18. Averages, Standard Deviations, and %RSD for ZE41 Tests (Continued)

0.25												
Date	05/16/12	05/23/12	05/24/12	06/07/12	06/07/12	06/07/12	06/07/12	06/07/12	06/07/12		Average	Standard Deviation	% RSD
Alloy	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41	ZE-41				
Bar Begins to Burn (Seconds)	159	206	142	162	166	149	224	255	278		193.4	49.5	25.6
Residue Begins to Burn (Seconds)	174	298	153	194	186	176	242	232	228		209.2	44.9	21.4
Burner Off (Seconds)	240	300	240	240	240	240	240	240	240				
Bar Out (Seconds)	312	385	361	297	445	275	280	270	286		323.4	60.5	18.7
Residue Out (Seconds)	1020	500	900	900	690	960	985	960	960		875.0	169.9	19.4
Weight Loss (%)	40.0	5.5	41.7	40.4	42.3	43.8	27.9	28.2	28.5		33.1	12.3	37.1

Table 19. Averages, Standard Deviations, and %RSD for AZ80 Tests

0.5															
Date	05/10/12	05/10/12	05/11/12	05/11/12	05/11/12	05/23/12	05/23/12	06/11/12	06/13/12	06/13/12	06/18/12	06/18/12		Average	Standard Deviation	% RSD
Alloy	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80				
Bar Begins to Burn (Seconds)	0	230	0	221	215	288	264	218	254	253	NR	NR		194.3	104.9	54.0
Residue Begins to Burn (Seconds)	292	221	238	268	225	302	302	231	268	281	NR	NR		262.8	31.8	12.1
Burner Off (Seconds)	300	300	300	300	300	300	300	300	300	300	NR	NR				
Bar Out (Seconds)	0	300	0	390	255	720	972	702	596	455	NR	NR		439.0	315.9	72.0
Residue Out (Seconds)	900	1080	1080	1020	900	900	1200	1260	1320	1170	NR	NR		1083.0	153.9	14.2
Weight Loss (%)	34.6	28.5	33.8	37.9	33.6	9.9	45.6	50.2	38.0	27.2	NR	NR		33.9	11.0	32.4

Table 19. Averages, Standard Deviations, and %RSD for AZ80 Tests (Continued)

0.375											
Date	05/21/12	05/21/12	05/21/12	05/21/12	06/08/12	06/12/12	06/12/12		Average	Standard Deviation	% RSD
Alloy	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80				
Bar Begins to Burn (Seconds)	222	187	209	196	215	213	225		209.6	13.7	6.5
Residue Begins to Burn (Seconds)	213	206	221	198	221	184	201		206.3	13.4	6.5
Burner Off (Seconds)	240	240	240	240	240	240	240				
Bar Out (Seconds)	315	415	692	440	324	350	735		467.3	174.7	37.4
Residue Out (Seconds)	900	1140	945	1140	1080	870	1320		1056.4	161.1	15.2
Weight Loss (%)	34.2	37.6	40.7	39.5	34.4	37.4	48.6		38.9	4.9	12.6

Table 19. Averages, Standard Deviations, and %RSD for AZ80 Tests (Continued)

0.25										
Date	05/24/12	05/24/12	05/24/12	06/04/12	06/08/12	06/12/12	06/12/12		Average	Standard Deviation	% RSD
Alloy	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80	AZ-80				
Bar Begins to Burn (Seconds)	161	128	172	154	136	158	161		152.9	15.4	10.1
Residue Begins to Burn (Seconds)	166	148	149	171	156	138	143		153.0	12.0	7.9
Burner Off (Seconds)	240	240	240	240	240	240	240				
Bar Out (Seconds)	378	343	423	459	357	346	454		394.3	50.3	12.8
Residue Out (Seconds)	810	840	840	960	900	900	930		882.9	54.4	6.2
Weight Loss (%)	48.1	51.0	46.8	51.6	55.1	51.0	57.4		51.6	3.7	7.2

The averages, standard deviations, and %RSDs for the 117 tests shown tables 16-19 are condensed and summarized in table 20.

Table 20. Summary of Horizontal Bar Test Averages, Standard Deviations, and %RSDs

	0.500-Inch EL21			0.375-Inch EL21			0.250-Inch EL21		
	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)
Average	17.8	33.8	0.4	66.4	111.4	0.7	196.8	288.6	1.1
Standard Deviation	71.3	92.9	0.6	113.5	190.5	0.7	10.9	28.4	0.8
% RSD	400.0	275.2	158.2	170.8	171.0	103.3	5.5	9.8	70.5

	0.500-WE43			0.375-Inch WE43			0.250-Inch WE43		
	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)
Average	235.4	317.6	5.5	214.3	306.8	1.3	149.9	284.4	1.6
Standard Deviation	98.1	149.4	8.6	14.9	73.3	1.7	73.4	140.0	1.6
% RSD	41.7	47.0	155.5	7.0	23.9	136.2	49.0	49.2	102.3

	0.500-ZE41			0.375-Inch ZE41			0.250-Inch ZE41		
	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)
Average	250.3	364.8	17.6	59.3	80.0	27.5	193.4	323.4	33.1
Standard Deviation	201.3	207.5	8.7	118.5	160.0	2.0	49.5	60.5	12.3
% RSD	80.4	56.9	49.7	200.0	200.0	7.3	25.6	18.7	37.1

	0.500-AZ80			0.375-Inch AZ80			0.250-Inch AZ80		
	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)	Bar Begins to Burn (Sec)	Bar Out (Sec)	Weight Loss (%)
Average	194.3	439.0	33.9	209.6	467.3	38.9	152.9	394.3	51.6
Standard Deviation	104.9	315.9	11.0	13.7	174.7	4.9	15.4	50.3	3.7
% RSD	54.0	72.0	32.4	6.5	37.4	12.6	10.1	12.8	7.2

When considering the %RSD of the time when the bar begins to burn, the time the bar self-extinguishes, and the calculated % weight loss, the 0.250-inch thickness results are the most consistent, with the 0.500-inch thickness the least consistent.

2.4.8 Comparison of Vertically Oriented Cylinders and Horizontally Oriented Rectangular Cross-Section Bar Test Results.

A careful comparison of the two test configurations followed. Several generalizations were made, including:

1. Alloys AZ80 and AZ31 consistently fail both the vertical cylinder and horizontal bar tests.

2. Alloy ZE41 consistently fails both the cylinder and bar tests because of excessive after-burning once the burner flames are terminated.

3. Alloy WE43 consistently passes the cylinder test, but often fails the bar test in certain thicknesses, particularly 0.5-inch.

4. Alloy EL21 consistently passes the bar test, but often fails the cylinder tests, assuming a maximum afterburn of 2 minutes (5 of 18 failures).

5. Bar test results seem to be more configuration dependent than cylinder tests.

6. Weight-loss criteria provide increased accuracy of the amount of burning compared to a visual determination.

7. Bar samples are easier/less expensive to produce.

A comparison of the repeatability of vertically oriented cylinder results versus the horizontally oriented bars can be done by comparing table 14 from section 2.4.6 and table 20 from section 2.4.7.

The best measure of test repeatability is with the %RSD of the various parameters measured. Beginning with the WE43 alloys tests, the cylinders resulted in a %RSD of 97.2% and 13.7% for the time when the sample began to burn and when it self-extinguished, respectively. This can be compared to the same alloy for the horizontal bar tests (0.250-inch thickness because this generally yielded the most consistent results), which had %RSD of 49.0% and 49.2%, respectively. For this particular alloy, although the time when the sample ignites is more consistent for the horizontal bars, the time when the sample self-extinguishes is more consistent for cylinders. This comparison can also be made with the two other alloys tested, EL21 and ZE41. For the EL21 alloy, the %RSD was 105.5% and 27.9%, respectively, for the time to ignite and the time to self-extinguish. For the 0.250-inch-thickness horizontal bars, the %RSD was 5.5% and 9.8%, indicating the horizontal bar was a much more consistent configuration for this alloy. Finally, the ZE41 cylinders produced a %RSD of 25.8% and 63.4%, whereas the 0.250-inch thickness ZE41 bars produced %RSD of 25.6% and 18.7%. Whereas the

repeatability of the time to ignite was comparable for this alloy, the time to self-extinguish was much more consistent for the bar configuration.

These data were presented at various IAMFTWG meetings as they became available. During task group discussions it was unanimous that the 0.250-inch thickness horizontal bar configuration was preferred. Task group participants cited the superior repeatability of this configuration along with the fact that cylinders were much more difficult and costly to produce when compared to bar samples.

2.4.9 Refinement of Horizontally Oriented Bar-Test Configuration.

Following unanimous industry support of a 0.250-inch-thickness horizontal bar sample test configuration, the primary focus was to refine the test method to make it as repeatable as possible so it could be used by industry as a standard test for certifying the flammability of magnesium alloys. Until this point, a considerable amount of testing had been completed and refinements had been made to the test apparatus along the way, including the sample holder and catch pan. The sample thickness had been agreed on at 0.250 inch, and the exposure time was 4 minutes. Although the test burner had remained constant during these trials, small refinements were made to standardize some of the burner components, such as the exit cone thickness and the fuel nozzle type. In addition, the inlet pressure of the regulated air used to feed the burner was also standardized. Several procedural elements of the test were also agreed on, including the required parameters to be measured during a test. These included the time at which the sample ignites, the time the sample self-extinguishes (the material still attached to the sample holder), and the pre- and post-test weights of the sample and residue. Measurement of the molten/burning residue times to ignite and self-extinguish were eliminated in favor of a weight-loss calculation, which was shown to be much more accurate.

Although well-defined, there were several elements of the test method that needed to be finalized, including the level of talc in the catch pan, the minimum amount of time at which a sample could ignite, the maximum allowable time a sample could burn before self-extinguishing (following burner flame termination), and the maximum allowable weight loss of the test samples. These items are discussed in section 2.5.

2.5 DISCUSSION OF TALC DEPTH.

During the development phase, there was considerable discussion over the talc used in the catch pan and what influence it had on the test outcome. In particular, questions surfaced over the insulating effect the talc had on the burning residue, possibly lengthening the duration of the burning by trapping heat. During the initial phase of test development, there was no agreed-on depth of talc used in the pan; it was replaced periodically because of contamination. The primary purpose of the talc was to prevent splashing of molten alloy that dropped into the pan below. In some instances, the talc nearly filled the full 1.5 inches of pan depth (figure 131), whereas during other tests it was approximately half full (figure 132). When the talc was at these depths, there were instances when the molten mass of material would fall into the layer of talc (often settling below the surface of the talc layer), making it difficult to clearly visualize the burning, if any.

Figure 131. Test Showing a Talc Depth of Approximately 1 Inch

Figure 132. Test Showing an Approximate Talc Depth of 0.75 Inch

To determine if the burning duration of the sample residue could be extended by the insulating effects of the talc, a test was arranged in which the catch pan was covered by a 0.125-inch-thick sheet of steel. The purpose was to run a test and allow the molten pieces of the sample to fall onto a totally uninsulated medium to determine if the molten residue would self-extinguish more quickly. A sample of ZE41 was used for the evaluation because of the propensity of its residue to continue to burn. During the test, the sample melted at 195 seconds and began to burn at 206 seconds, which was typical. The molten residue began to burn at 298 seconds (also typical); however, the residue self-extinguished at 500 seconds from test start (figure 133). A prior test of ZE41 yielded a residue burn duration of 846 seconds from test start, so the 500 second self-extinguishment was considerably shorter than the previous result. This was an indication the uninsulated steel sheet catch pan prevented prolonged residue burning.

Figure 133. Test Showing the Use of Sheet Steel in Place of a Catch Pan (5/23/2012)

2.5.1 Discussion of Ceramic Board Versus Talc.

The use of a steel plate below the test sample was for comparative purposes only with tests using talc to determine the likelihood that prolonged sample residue burning resulted when talc was used. The use of a steel plate was not a realistic solution for replacing the talc in the catch pan for the test under development. An additional suggestion by industry was to experiment with rigid ceramic Kaowool™ board in place of the talc, which would not offer the high level of conductivity and heat transfer offered by a steel plate. The ceramic boards were used in numerous fire-testing applications and were suggested as a low-cost alternative to using talc in the catch pan, which seemed to increase the duration of residue burning (figure 134).

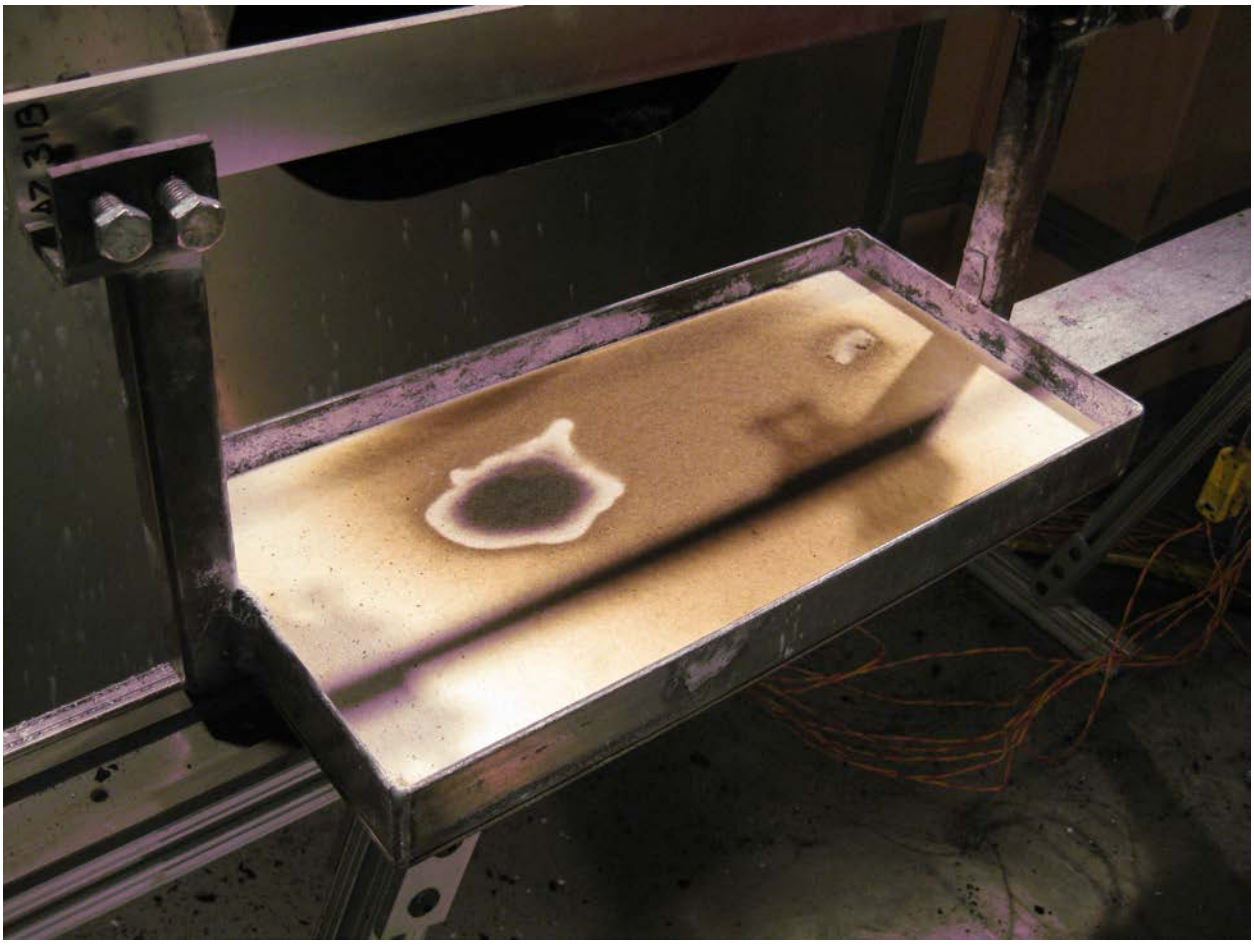


Figure 134. Test Arrangement Using Kaowool™ Board in Catch Pan (2/20/2013)

Tests were conducted using AZ31, AZ80, and ZE41 samples, all alloys in which the molten residue typically burned for a long duration when using the talc in the catch pan. During the first test using AZ31, a large central section of the test sample melted and fell onto the Kaowool™ board at 137 seconds, which was typical. Additional drips of molten residue were scattered to various areas of the board, with self-extinguishment of the residue occurring at 825 seconds (figure 135). A repeat test was conducted with nearly identical results. The average burn duration of the residue for the two samples was 660 seconds. In three previous tests of AZ31 using talc in the catch pan, the residue burn durations were 732, 738, and 809 seconds, for an average of 760 seconds. Although this was a small sample set, the data indicated an average of 100 additional seconds of burning when using the talc in the catch pan compared to the ceramic board for this particular alloy.

Figure 135. The AZ31 Test Result Using Kaowool™ Board in Catch Pan (2/20/2013)

A second series of tests was run using AZ80. During the first test, a large central section of the test sample melted and fell onto the Kaowool™ board at 120 seconds, which was typical for this alloy. A second mass of molten residue fell onto the surface of the board at a later time. Self-extinguishment of the residue occurred at 920 seconds (figure 136). A repeat test was conducted with residue self-extinguishment occurring at 855 seconds. The average burn duration of the residue for the two samples was 730 seconds. In seven previous tests of AZ80 using talc in the catch pan, the residue burn durations were 644, 692, 691, 789, 744, 762, and 787 seconds, for an average of 730 seconds. This result indicated identical average residue burn durations for both configurations (talc and ceramic board) for this particular alloy.

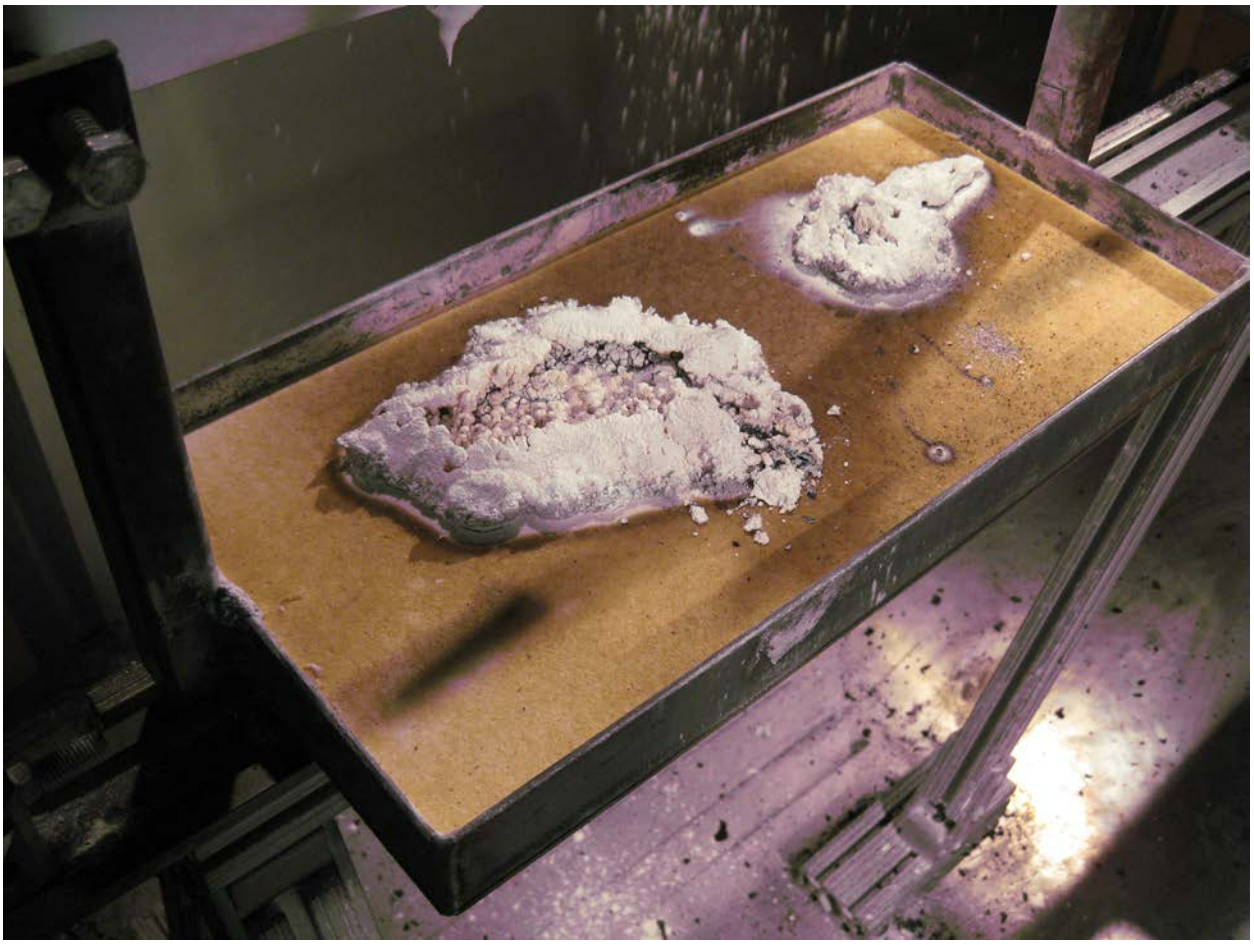


Figure 136. The AZ80 Test Result Using Kaowool™ Board in Catch Pan (2/20/2013)

A third and final series of tests was run using ZE41. During the first test, a large central section of the test sample melted and fell onto the Kaowool™ board at 140 seconds, which was typical for this alloy. No additional melting of the sample occurred. Self-extinguishment of the residue occurred at 885 s econds (figure 137). A repeat test was conducted with residue self-extinguishment occurring at 840 seconds. The average burn duration of the residue for the two samples was 775 seconds. In nine previous tests of ZE41 using talc in the catch pan, the residue burn durations were 846, 747, 706, 504, 784, 743, 728, 732, and 1178 seconds, for an average of 774 seconds. This result indicated a nearly identical average residue burn duration for both configurations for this particular alloy.

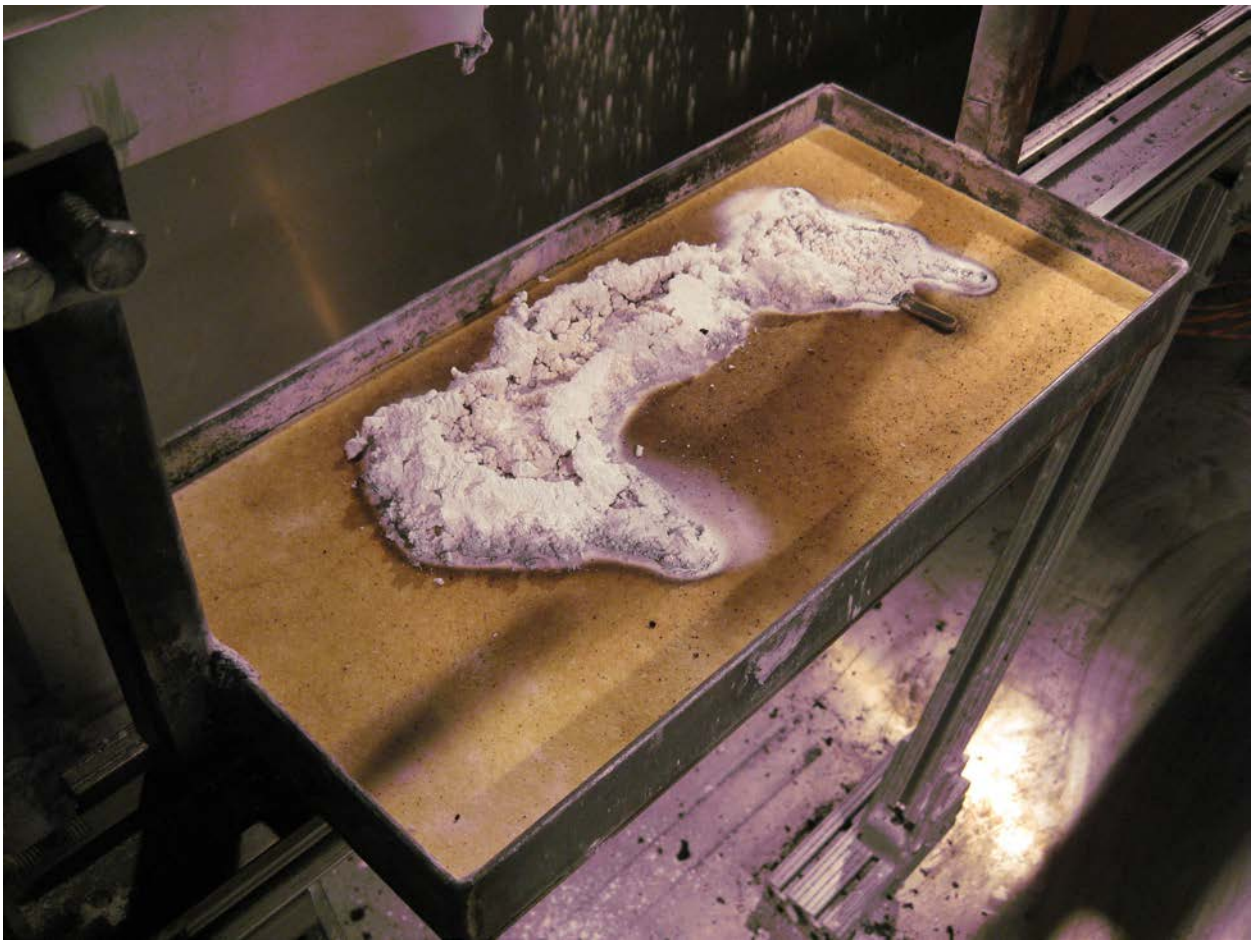


Figure 137. The ZE41 Test Result Using Kaowool™ Board in Catch Pan (2/20/2013)

The results of the ZE41 tests are charted in figure 138. The chart shows 11 tests of ZE41, with the first nine tests being conducted over talc and the last two tests using a rigid Kaowool™ ceramic board in the catch pan. The results indicate no apparent differences in the times required for the residue to burn or self-extinguish, resulting in similar burn durations for both talc and ceramic board. This information was presented to the members of a task group during an IAMFTWG meeting. Participants agreed that whereas there were essentially no differences when conducting tests over a rigid ceramic board, when compared to using talc in the catch pan, it was advisable to use the talc for safety purposes (prevention of splashing molten material). The agreed-on solution was to limit the depth of the talc to 0.250 inch, which would eliminate any possibility of the talc acting as an insulation medium to the burning residue, but at the same time provide a splash-free landing area for the molten material during a test. One task group participant also agreed to provide a suitable specification for the talc, which would be used in the final test standard.

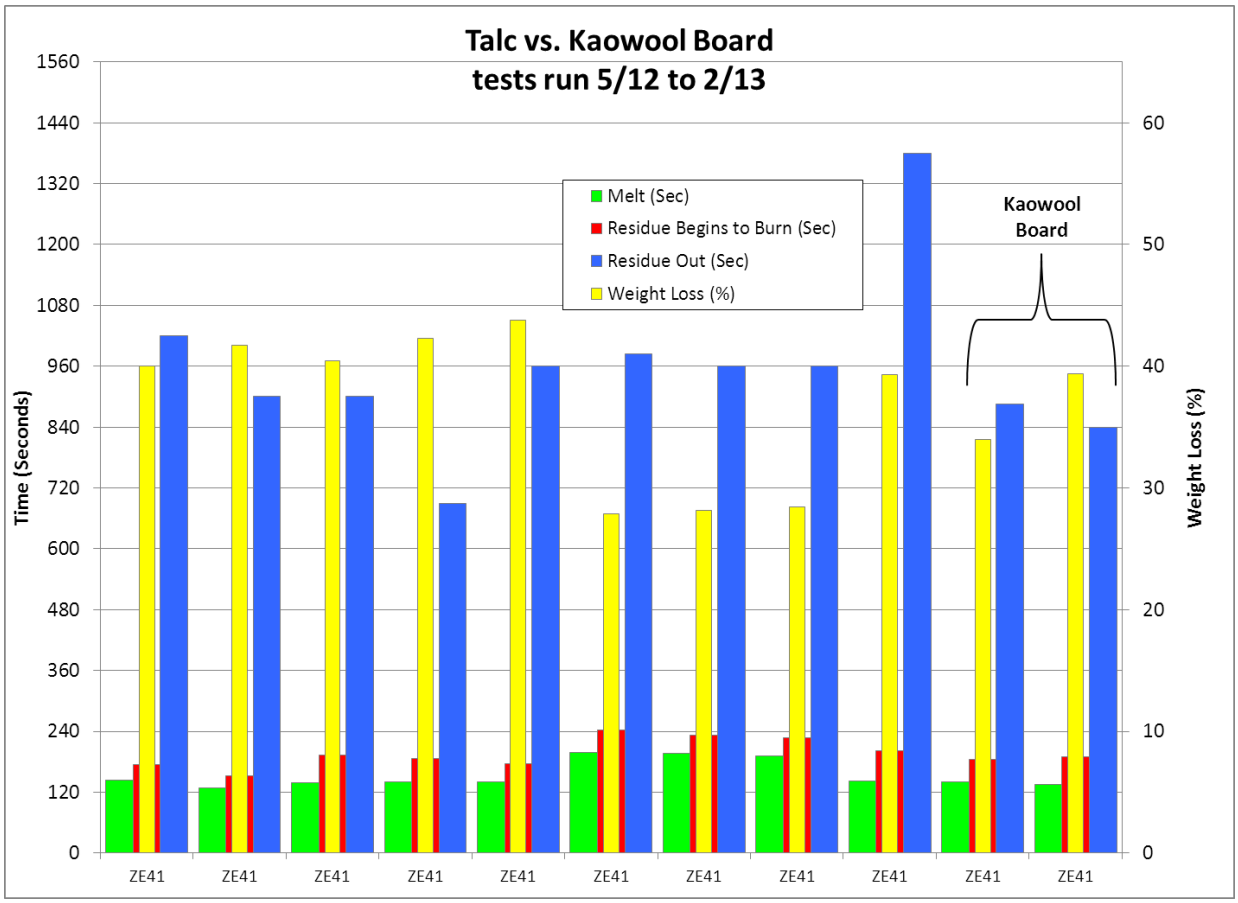


Figure 138. The ZE41 Test Results Comparing Talc and Kaowool™ Board in Catch Pan

2.5.2 Final Refinements to Test Procedure.

After tests to determine the influence of the talc were completed, the physical test apparatus was largely finalized. As discussed, the burner componentry and intake settings, sample holder, and catch pan had now been fully examined and agreed on. The only remaining items that needed to be vetted were establishment of the pass/fail criteria. The first criterion to be finalized was the minimum time required for the sample to ignite. The reason for measuring this parameter was simple—to prevent magnesium alloys that ignited easily from passing the requirement. During the development, over 400 tests had been completed on a variety of alloy types. Although the flammability performance of the alloys differed greatly, the time for the alloys to begin burning did not occur until after melting (or within seconds prior to melting). Depending on the alloy, the time to reach melting was reasonably close—in the range of 2 to 3 minutes, depending on test conditions, laboratory configuration, and other influences. Based on these results, it was agreed that no burning of the sample should occur prior to 2 minutes of flame exposure. This information and proposed criteria were presented to the participants of a task group during an IAMFTWG meeting. Participants unanimously agreed on the proposed 2-minute criteria.

Although the 2-minute criterion was widely accepted, there was considerable discussion regarding exactly what constituted burning. In many instances, magnesium alloy samples sparked momentarily, but did not fully ignite. The sparking could be very brief, lasting only a

fraction of a second. This intermittent sparking would eventually result in full ignition (burning) in most cases, but in a small percentage of tests, the sparking would not result in full ignition. This occurrence led to much confusion amongst labs that had participated in the development of the test method. To standardize the method of determining when a sample fully ignited, task group participants suggested that a 3-second dwell time of sparking would be sufficient to establish full ignition or burning. This meant that even if a sample sparked for 3 seconds or more, and the sparking subsequently discontinued, it would still be considered a full ignition or burning point. For clarity, the burn time would be recorded at the beginning of any continuous sparking that had a duration of 3 seconds or longer.

The next measured criterion to be finalized was the maximum allowable time until self-extinguishment of the sample occurred, following removal of the burner flames at 4 minutes. A majority of the tests was conducted using WE43 and EL43, which essentially set the standard in terms of acceptable flammability performance. These alloys typically burned for a period of 90 seconds before self-extinguishing, following burner flame removal. Conversely, the unacceptable alloys burned for numerous additional minutes, in most cases until completely consumed (AZ31, AZ80 for example). The FAA initially proposed a 2-minute allowable time for the sample to self-extinguish following burner removal (a 6-minute total test time). This proposed criterion was presented to the participants of a task group during an IAMFTWG meeting. The extinguishing time was the subject of much discussion, with the objective of allowing for variability of well-performing materials, while at the same time screening out poor-performing materials. After much discussion, it was decided that the 3-minute allowable time for the sample to self-extinguish (a 7-minute total test time) met both objectives.

Although the 3-minute self-extinguishment was acceptable to task group participants, there was still a high degree of individual interpretation involved in determining exactly when the bar sample self-extinguishes. In many instances, the flaming bar samples did not self-extinguish definitively, but gradually, over a period of seconds or even minutes. This occurrence led to much confusion among those from labs who had participated in the development of the test method. To help standardize the method of determining when a sample self- extinguishes, the FAA video recorded several tests and superimposed a time clock on the video. The time clock indicated at what point in time the FAA interpreted the sample to self-extinguish. Copies of the videos were circulated to task group participants for their inspection.

The last measured criterion to be finalized was the maximum allowable weight loss of the sample. The weight loss was calculated by dividing the difference in the pre- and post-test weights by the pre-test weight and multiplying by 100. The post-test weight included the remaining bar sample in the holder and sample remnants or residue in the catch pan. The FAA initially proposed a 6% allowable weight loss for the samples and presented this to the participants of a task group during an IAMFTWG meeting. The maximum allowable weight loss was the subject of much discussion with the objective of allowing for variability of well-performing materials, while at the same time screening out poor-performing materials. After much discussion, it was decided that a 10% maximum allowable weight loss met both objectives.

2.6 ROUND ROBIN TESTS.

Now that the test procedure, pass/fail criteria, and physical apparatus were well defined, the FAA proposed a small interlab study with industry to determine how reproducible the test was. The FAA had initiated these studies, also known as round robin studies, for other flammability tests in the past. A round robin typically involves the circulation of identically prepared test samples to participating labs, which conduct the tests according to a standard and report the results back to the FAA. The primary purpose of the round robin is to determine differences in test results and to help identify problem areas with a proposed test. Round robins have been an effective tool in refining flammability tests to make industry-run labs as equivalent as possible and have generally been well-received by industry.

Because the proposed magnesium alloy flammability test was completely new, there was only one industry-run lab that was able to participate in the initial study. The FAA William J. Hughes Technical Center had two independent labs within their fire-testing facilities to conduct round robin testing, for a total of three participating labs. Test samples were produced by ME and shipped to each of the participating labs. Although the two flammability test apparatus set up at the FAA William J. Hughes Technical Center were identical, the actual laboratory test chambers that housed the equipment were different. The laboratory chamber in which a majority of the test development was completed was a 10-foot by 10-foot room with a pyramid-shaped exhaust ventilation hood covering the entire ceiling area (figure 139). The ventilation hood directed combustion gases into a 2-foot by 2-foot exhaust duct that was centrally located in the hood. When the exhaust system was operational, intake air was drawn into the test chamber through four floor-mounted registers located at each corner (figure 140). This laboratory was designated as Lab A in the round robin study. The other FAA test chamber used a significantly larger floor area, which doubled as a general-purpose area for staging tests (figure 141). In this laboratory, the exhaust hood was situated in a corner and drew air into the exhaust ducting from the surrounding floor area (figure 142). This laboratory was designated as Lab B. The industry-run laboratory participating in the initial round robin was designated as Lab C.

Figure 139. Round Robin Test Arrangement in Lab A (10/12/2012)

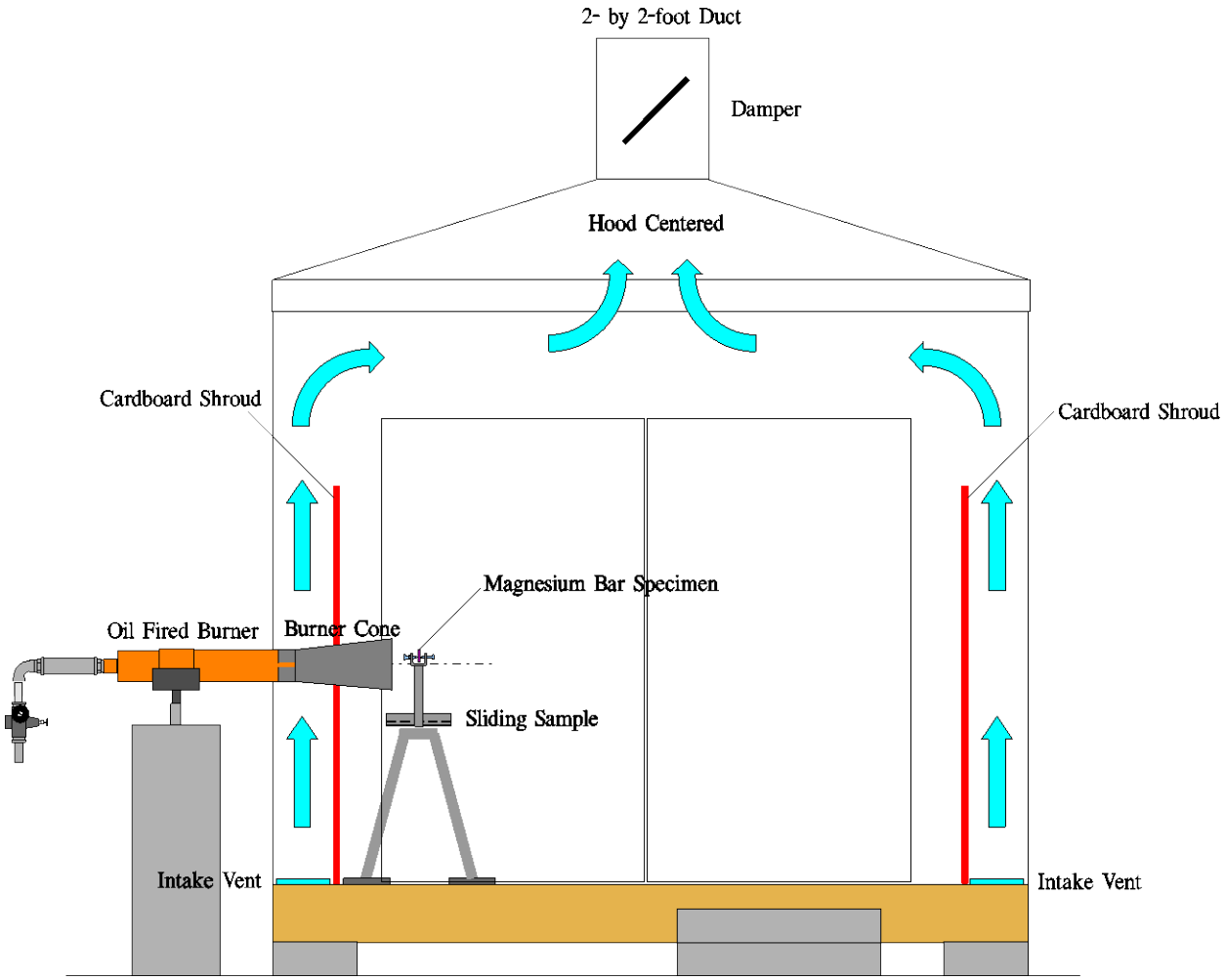


Figure 140. Laboratory A Arrangement

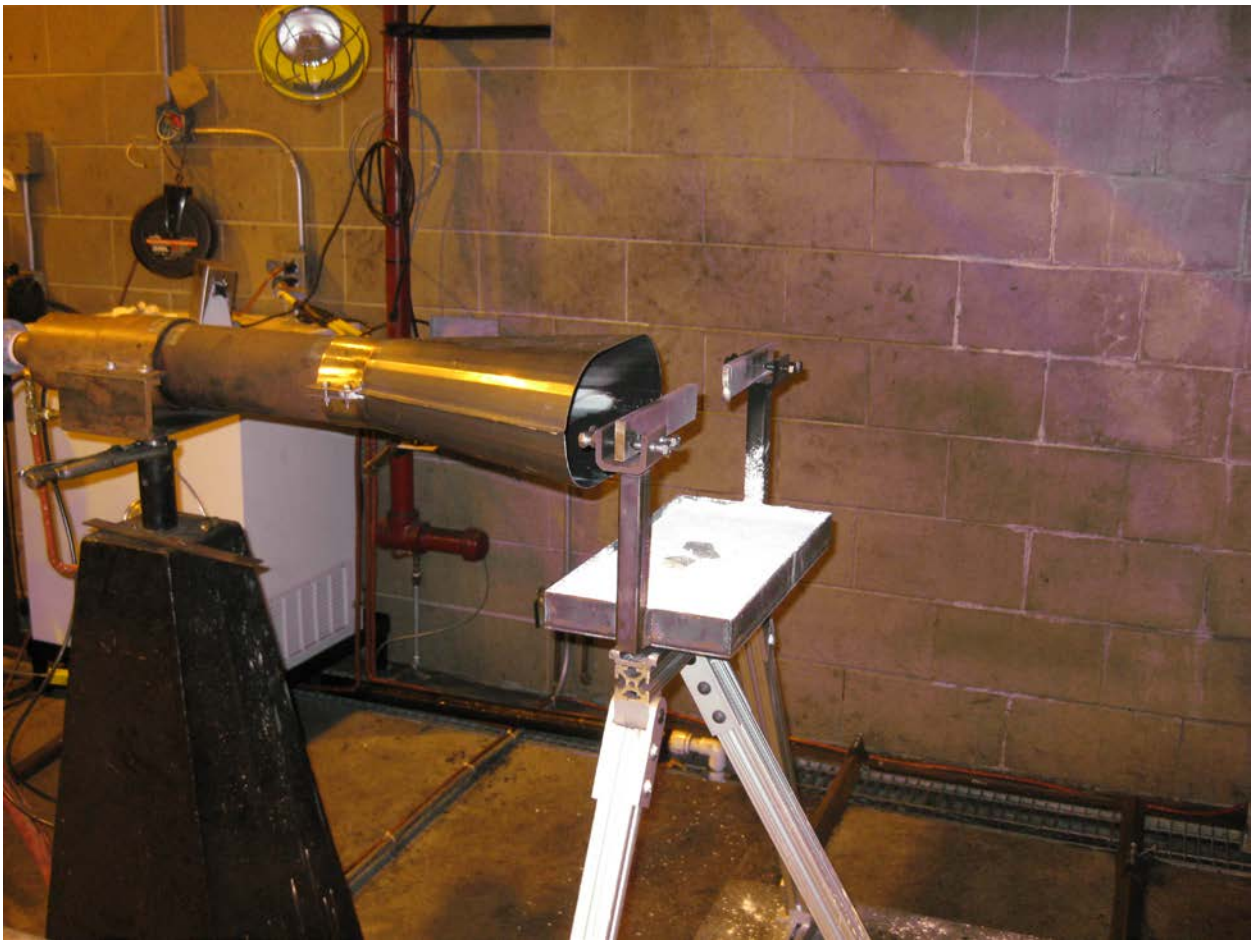


Figure 141. Round Robin Test Arrangement in Lab B (10/12/2012)

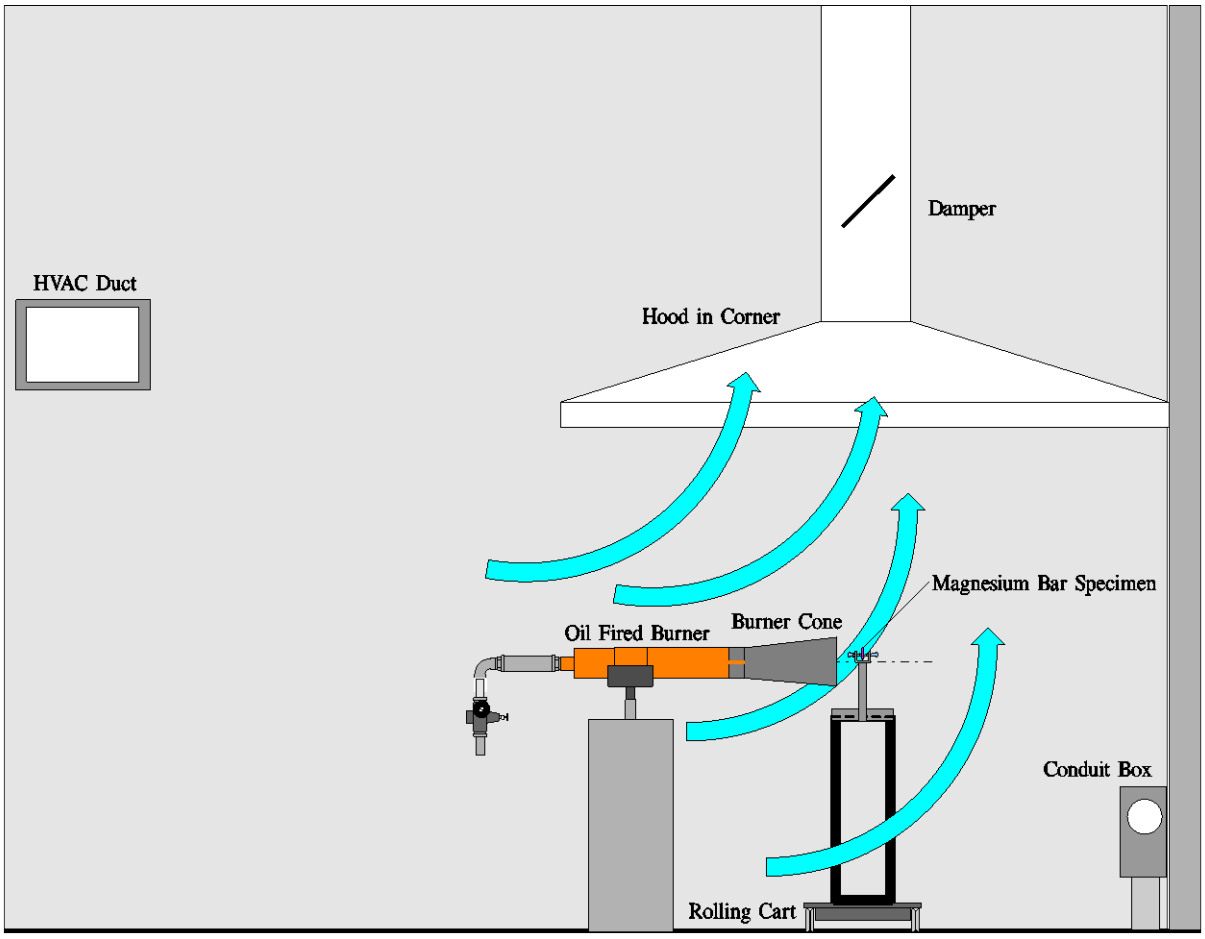


Figure 142. Laboratory B Arrangement

During the initial round robin, 20 samples of 0.250-inch-thickness EL43 were tested at each facility. The EL43 was chosen for the study primarily because of its lengthy history during the development of the test standard. At this point in the research, over 100 tests had been completed with this alloy in this particular thickness, so there was a significant amount of data available for comparison.

The test results are shown in figure 143. There are three colored bars for each test: the red bar denotes the time when the sample started burning and the blue bar indicates when the sample self-extinguished. The green bars indicate the weight loss of each sample. A shaded area of the chart establishes the passing boundaries (a 2-minute minimum for a sample to begin burning and a 7-minute maximum for a sample to self-extinguish). A cursory view of the test results indicates a large majority of the samples met these two criteria, with only 5% failing the self-extinguishment criteria. All samples passed the proposed weight-loss criteria with values below the 10% maximum allowable.

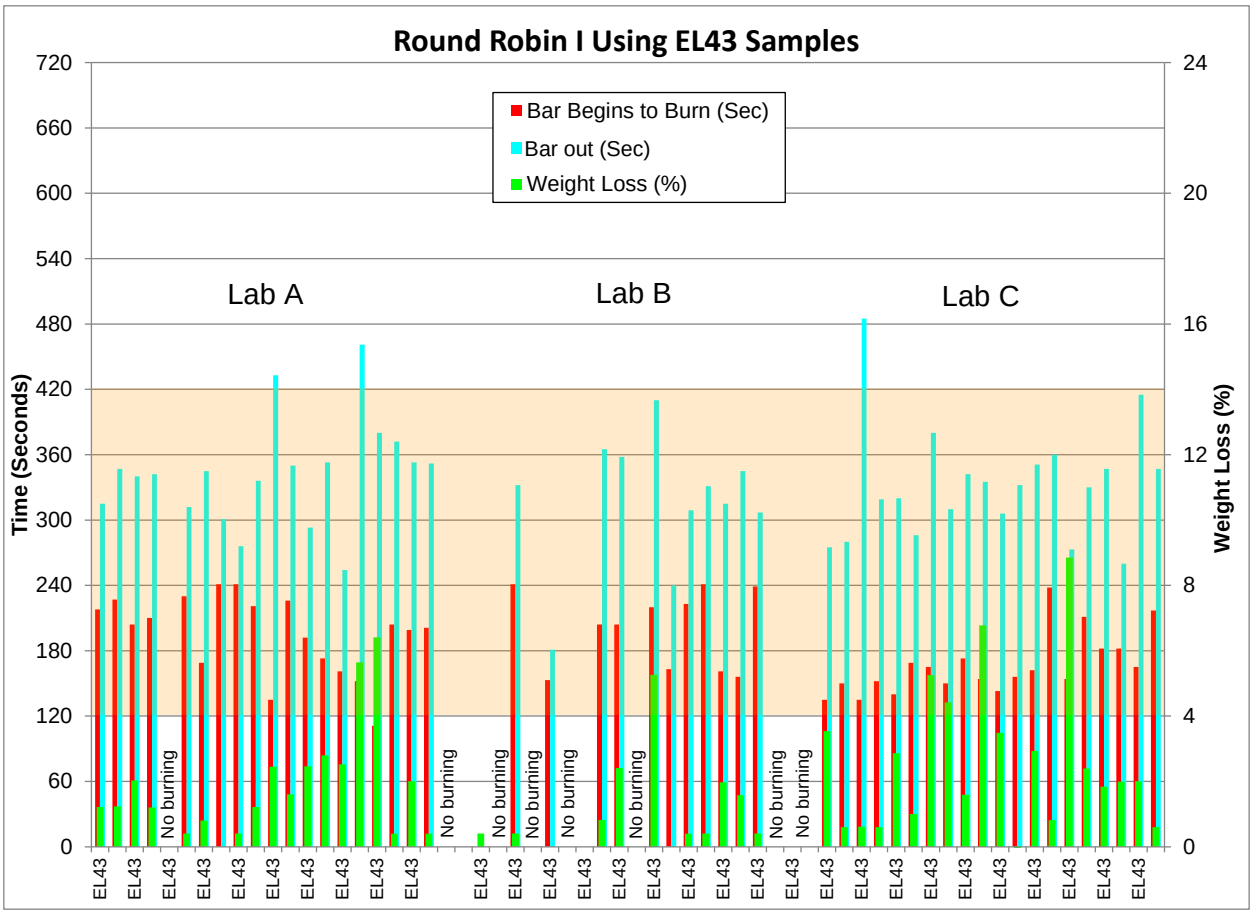


Figure 143. Round Robin I Test Results (three labs)

This was an encouraging result for an initial round robin on a newly developed test. Although the data indicated some scatter, the results were like those obtained during the development phase at the FAA William J. Hughes Technical Center. The nature of the test, exposing a flammable metal bar to the flames of an oil burner, is a complex process and was not expected to be highly repeatable. This is the reason the pass/fail criteria were established with a degree of margin factored in.

The averages, standard deviations, and %RSD were calculated for the measured test parameters as well as some additional results for comparison (table 20). As expected, the melt time produced a reasonable %RSD of 16.5% while the values for the time when the sample begins to burn and the time of self-extinguishment are much higher. The %RSD for the weight loss was noticeably high, indicating a more specific measuring process was necessary. This initial round robin was also a fairly small sample set, with only three laboratories and a minimal sample set (20). It was anticipated that an increased sample set would reduce the %RSD for many of the criteria.

Table 21. Round Robin I Statistical Data

	Melt (Seconds)	Bar Begins to Burn (Seconds)	Bar Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)
Average	138.9	154.2	277.7	0.494	0.321	0.165	1.68
Standard Deviation	23.0	76.8	134.3	0.0	0.0	0.0	2.0
%RSD	16.5	49.8	48.4	1.5	9.4	17.2	116.7

After presenting this information at an IAMFTWG meeting, the attendees were encouraged with the progress and results, but also agreed that additional refinement was necessary. After reviewing the proposed test method during a task group session, participants made small suggestions in various areas and reviewed the agreed-on method of recording the times of burning and self-extinguishment. A second round robin was initiated, with several additional laboratories participating. Identical samples of 0.250-inch thick EL43 were again produced by ME and shipped to the participating laboratories.

The tests were conducted and the results were recorded and tabulated by the FAA (figure 144). The FAA William J. Hughes Technical Center laboratories are shown as Lab A, Lab B, and Lab B' on the chart. The additional 20 tests designated as Lab B' were also conducted in the same laboratory as the Lab B tests, but under improved ventilation conditions. During this round robin, there were two weight loss failures at Lab D because residue from two samples continued to burn for extended periods. The extended burn duration resulted in total consumption of the residue, leading to the high weight loss. There was also a slight increase in the percentage of failures for the self-extinguishment criteria. Eleven of the 140 samples (7.9%) resulted in self-extinguishment failures, which was 5% in the initial round robin. However, the most discouraging result was from the weight-loss data, which indicated a fairly wide range of recorded results. Labs E and F recorded weight loss values noticeably lower than those of the other laboratories.

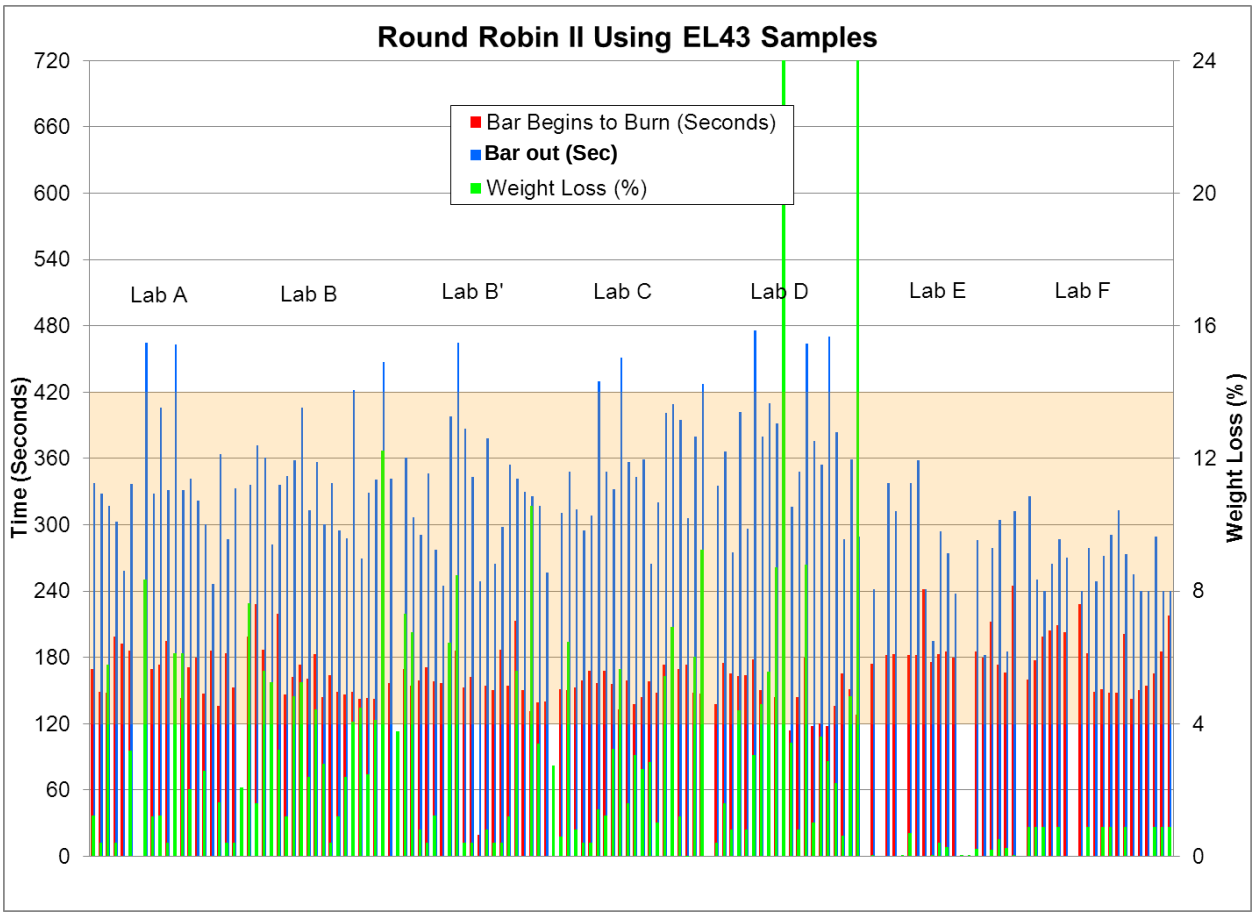


Figure 144. Round Robin II Test Results (seven labs)

The averages, standard deviations, and %RSD were calculated for the measured test parameters, as well as some additional results for comparison (table 21). The %RSD calculated for the melt time, time to burn, and self-extinguishment was reduced in comparison to the previous round robin, which was an encouraging result. However, as indicated, the %RSD for the weight loss increased significantly and would need to be investigated further. Elevated values for the %RSD were expected in these early round robins, as laboratories learned to conduct the test more proficiently and accurately.

Table 22. Round Robin II Statistical Data

	Melt (Seconds)	Bar Begins to Burn (Seconds)	Bar Out (Seconds)	Initial Weight (lbs)	Final Weight Bar (lbs)	Final Weight Residue (lbs)	Weight Loss (%)
Average	147.6	157.3	311.5	0.496	0.321	0.162	2.71
Standard Deviation	17.2	43.0	89.3	0.0	0.0	0.0	5.1
%RSD	11.6	27.3	28.7	1.1	10.8	21.5	186.8

The results of the round robin were presented at an IAMFTWG meeting. Attendees were optimistic with the progress, despite the setback with the weight-loss data. During a task group session, it was revealed that most of the round robin participants used various methods for removing the oxidation from the molten residue from the catch pan. Some of the laboratories used compressed air to blow off the oxidation, while others did not. Some laboratories waited longer periods of time to remove the residue from the catch pan than others. One laboratory also used a steel mallet to strike the pieces of resolidified residue after removing them from the catch pan, in an effort to mechanically remove the oxidation. This wide array of methodology was likely responsible for the high %RSD of the weight-loss data. As a result, the FAA William J. Hughes Technical Center agreed to conduct a series of experiments to determine the impact of the various methods on calculating the weight loss, and implement a standardized procedure in the test method.

3. SUMMARY OF RESULTS.

Recent advancements in the field of magnesium alloy development have resulted in the production of several new-technology fire-resistant alloys. As a result of these developments, the magnesium alloy community inquired about the possibility of using fire-resistant magnesium alloys in the construction of transport aircraft seats. Magnesium alloy suppliers approached the FAA to discuss current restrictions and future possibilities. A formal task group was then formed under the auspices of the IAMFTWG, and preliminary tests were conducted by the Fire Safety Branch at the FAA William J. Hughes Technical Center in Atlantic City. Preliminary tests used an oil burner and horizontally oriented bar samples to determine the relative flammability of an array of magnesium alloys. Various sample shapes, orientations, and small-test configurations were also examined to gain knowledge of the basic flammability of a number of legacy and new-technology alloys. Preliminary tests corroborated the industry assertion that several new-technology alloys were indeed highly fire-resistant compared to legacy alloys. The preliminary tests formed the basis for realistic full-scale tests conducted inside a mocked-up aircraft fuselage with a large jet-fuel fire entering the fuselage through an opening. Tests were initially conducted using standard aluminum-framed seats to establish a baseline hazard level inside the fuselage. In subsequent tests, seats were constructed of a new-technology fire resistant magnesium alloy (WE43) in the primary structure. A test was also done using seats constructed of a legacy alloy (AZ31) for comparison. Additional full-scale tests were conducted with new-technology alloys used in some of the secondary seat components. The tests confirmed that no significant change to survivability (based on the survivability model) resulted when using either

a well-performing or poor-performing magnesium alloy in the seat components. Although no change in survivability was noted, the performance of the poor-performing alloy was deemed unacceptable because of extinguishment difficulties.

After demonstrating that the new-technology magnesium alloy provided an equivalent level of safety to standard aluminum-framed seats, the final phase of the program was to develop a suitable laboratory-scale flammability test for magnesium alloys based largely on the full-scale results. Because a certain level of success was achieved during the preliminary tests using an oil burner, this test configuration was retained as the fire threat. Numerous test sample shapes were experimented with, in an effort to obtain consistent results that correlated with full-scale testing. Configurations included solid truncated cones, solid slender cylinders, pointed and stepped cones, shortened truncated cones, thin-walled box tubing, I- and T-beam cross-sectional shapes, hollow cylinders, and rectangular cross-section bars. Many of these configurations were experimented with in the vertical, horizontal, and suspended orientations. The objective was to expose a sample for a period of time that would be sufficient to initiate melting, which was a prerequisite to the sample igniting and burning. The design target was for a sample of WE43 to continue burning for approximately 90 seconds after removing the burner flames, and then self-extinguish. Testing indicated two favorable sample configurations, a vertically oriented hollow cylinder and a horizontally oriented solid bar. Comparative testing of these two configurations revealed the horizontal bar to be more consistent, so additional testing was conducted to determine suitable sample dimensions. Testing suggested that a 1.5-inch wide by 20-inch long sample would produce the desired result; four sample thicknesses were then evaluated at this configuration: 0.669-, 0.500-, 0.375-, and 0.250-inches. Various alloys were used during these trials. Results revealed that the 0.250-inch thickness provided the most consistent results across the range of alloys tested.

Various improvements to the test apparatus and procedure were implemented during test development, including establishment of the proper level of talc in the catch pan and refinement of the sample holder. Testing revealed difficulty in determining the extinguishment time of the burning residue that dropped into the catch pan because there was a high degree of interpretation involved and because the extinguishment was typically a gradual event. Experimentation with sample weight loss proved this measurement could more accurately predict the amount of sample burning, so this was introduced. As the test fully matured, all pass/fail criteria were also created.

Interlab round robin testing was conducted to determine how reproducible the test would be in various parts of the world. The interlab studies identified a problem area with the measurement of the post-test weight of the sample, which impacted the weight-loss calculation. As a result, a more standardized method of measuring the post-test sample weight was instituted.

4. CONCLUSIONS.

Advancements in the field of magnesium alloy formation have resulted in the development of several new-technology alloys with favorable flammability characteristics. Magnesium alloy suppliers and airframe manufacturers were interested in using this technology in the interior of transport-category aircraft, in particular the construction of seats. The opportunity for weight savings was certain, so the FAA was queried by industry about the existing restrictions and future use. A formal research project was initiated to investigate possibilities, which led to full-

scale demonstrations simulating a post-crash fire accident. These realistic tests confirmed that no additional hazard was created inside the cabin when using aircraft seats constructed of new-technology, fire-resistant magnesium alloy. As a result, a laboratory-scale flammability test was developed for magnesium alloys used in the construction of aircraft seats. The test uses an oil burner as the fire threat and exposes a 20-inch-long horizontally oriented bar sample for a period of 4 minutes. To pass the test, the sample must not ignite prior to 2 minutes and must self-extinguish within 3 minutes of the burner flames being removed. When exposed to the burner flames, the magnesium alloy samples typically melt and fall into a catch pan situated beneath the sample. In many cases, the molten residue continues to burn, often for extended periods. Because it is difficult to accurately measure the duration of the burning by visual observation, the samples are weighed before and after the test. The amount of weight loss is a more accurate method for determining the extent of sample burning, and the test limits samples to a maximum allowable value of 10%.

It is anticipated that the magnesium alloy flammability test will be placed in the current Aircraft Materials Fire Test Handbook, which is used by industry to establish acceptability to FAA flammability requirements.

5. REFERENCES.

1. Sarkos, C.P., 1988, "Development of Improved Fire Safety Standards Adopted by the Federal Aviation Administration," AGARD-CPP-467-5, *Propulsion and Energetics Panel 73rd Symposium on Aircraft Fire Safety*, Sintra, Portugal, May 22-26, 1989.

2. Khaled, T., "Magnesium in the Aerospace Industry", Media Release from the Federal Aviation Administration, Reference #ANM-112N-04-07, Rev. C, November 29, 2004.

3. TSO –C127, "Rotorcraft, Transport Airplane, and Normal and Utility Airplane Seating Systems."

4. Society of Automotive Engineers, International (SAE) Aerospace Standard AS8049, Revision A, September 1997.

5. Boris, P., "A Study of the Flammability of Magnesium," Federal Aviation Agency Technical Report ADS-14, April 1964.

6. Lyon, P., "Flammability Testing of Magnesium Alloys at FAATC, Atlantic City, NJ, USA," Magnesium Elektron Technical Report, MR10/Data/475, June 2007.

7. Marker, T.R., "Evaluating the Flammability of Various Magnesium Alloys During Laboratory- and Full-Scale Aircraft Fire Tests," FAA report DOT/FAA/AR-11/3, January 2013.

8. Speitel, L.C., "Toxicity Assessment of Combustion Gases and Development of a Survival Model," FAA report DOT/FAA/AR-95/5, July 1995.

APPENDIX A—PROPOSED FLAMMABILITY TEST METHOD FOR MAGNESIUM ALLOYS USED IN THE FABRICATION OF SEAT STRUCTURAL COMPONENTS

A.1 SCOPE.

A.1.1 APPLICABILITY.

This test method evaluates the ignition resistance and flammability of magnesium alloy when used in the construction of aircraft seat primary structural components by using a high-intensity open flame to show the material adequately resists involvement in a postcrash fire.

A.2 DEFINITIONS.

A.2.1 MAGNESIUM ALLOY.

A magnesium alloy is defined as any solid form of magnesium containing a variety of alloying materials (e.g., zinc) or rare earth elements (e.g., yttrium). Any component or material containing more than 10% elemental magnesium by weight shall be considered a magnesium alloy.

A.2.2 PRIMARY LOAD PATH.

The primary load path is the part of the seat structure that is structurally capable of carrying the passenger load according to the impact requirements outlined in CFR 25.562.

A.2.3 SPECIMEN SET.

A specimen set consists of three or more replicate test specimens of a particular magnesium alloy used in the construction of an aircraft seat primary-load-path structural component.

A.2.4 WEIGHT LOSS.

The specimen weight loss is the amount of weight a specimen loses during exposure to the burner flames, which includes any portion of the test specimen that melts and falls into the catch pan. Molten pieces of the test specimen must be retrieved from the catch pan following test completion once sufficient cooling has taken place. Molten/resolidified pieces of the test specimen must be blown off with compressed air to eliminate the inclusion of oxidized material or talc during the final weight measurement. The percentage weight loss for a specimen is defined as the pre-test weight of the specimen less the post-test weight of the specimen and any droppings, expressed as the percentage of the pre-test weight.

A.3 APPARATUS.

A.3.1 TEST SPECIMEN APPARATUS.

The test specimen apparatus is shown in figures A-1 and A-2. The test specimen apparatus must allow movement of the test specimen so it can be positioned in front of the burner at the proper distance.

A.3.1.1 Catch Pan.

The test specimen apparatus will include a suitable catch pan lined with a layer of dry talc powder, capable of preventing back-splashing of molten magnesium alloy. The talc should be filled to a depth of 0.25 inch, as measured from the highest point on the base of the catch pan. The catch pan should measure at least 8 inches wide by 16 inches long and at least 1.5 inches deep. A test specimen holder can be mounted directly to the sides of the catch pan.

A.3.1.2 Talc.

Talc is a magnesium-silicate-based mineral. Talc should be kept dry between test runs and renewed as appropriate. Storage in a sealed plastic bag is recommended to avoid moisture pick up.

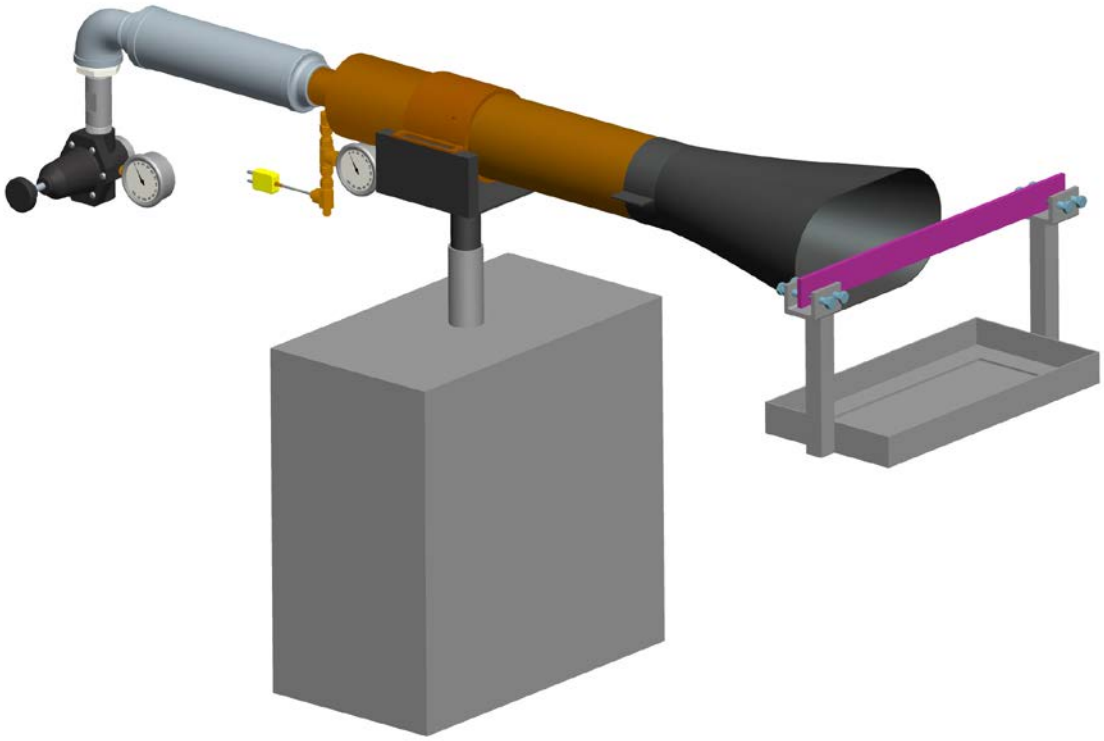


Figure A-1. Magnesium Alloy Test Apparatus

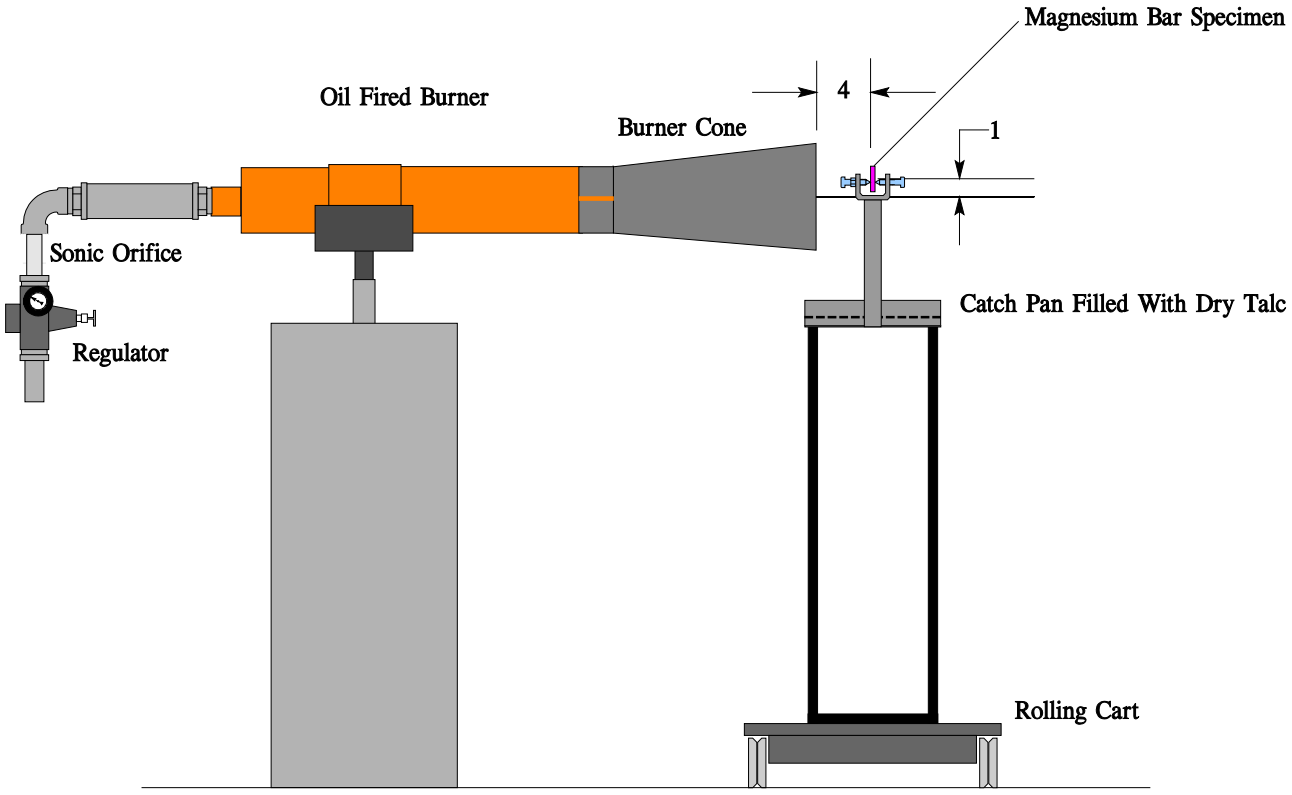


Figure A-2. Side View of Magnesium Alloy Test Apparatus

A.3.1.3 Test Specimen Stand and Holder.

A test specimen mounting stand and holder will be provided to rigidly mount the horizontal bar specimen in the proper position with respect to the test burner (figure A-3). A suitable U-shaped specimen holder can be fabricated from 2- by 2- by 0.250-inch-thick steel box tubing with one of the faces removed. The resulting U-shaped section can be drilled and tapped for insertion of the pointed mounting bolts (figure A-4).

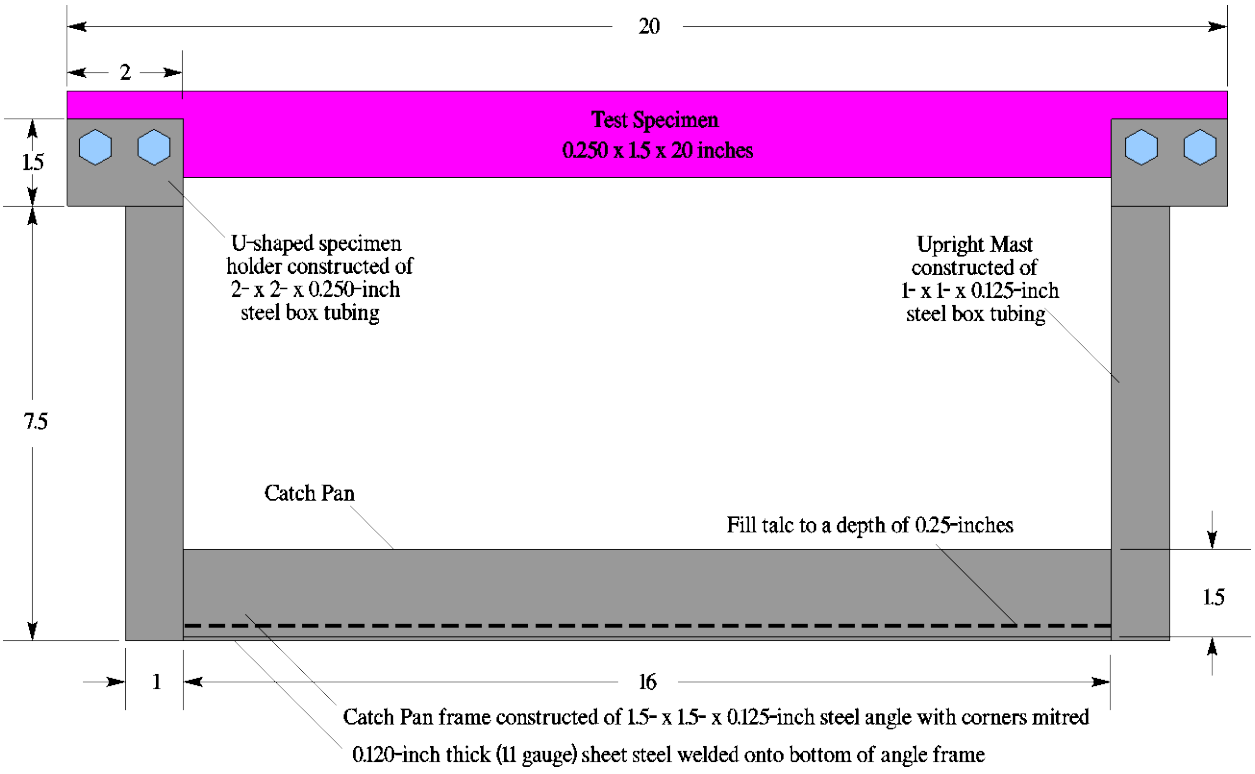


Figure A-3. Magnesium Alloy Test Specimen Mounting Stand and Holder (front)

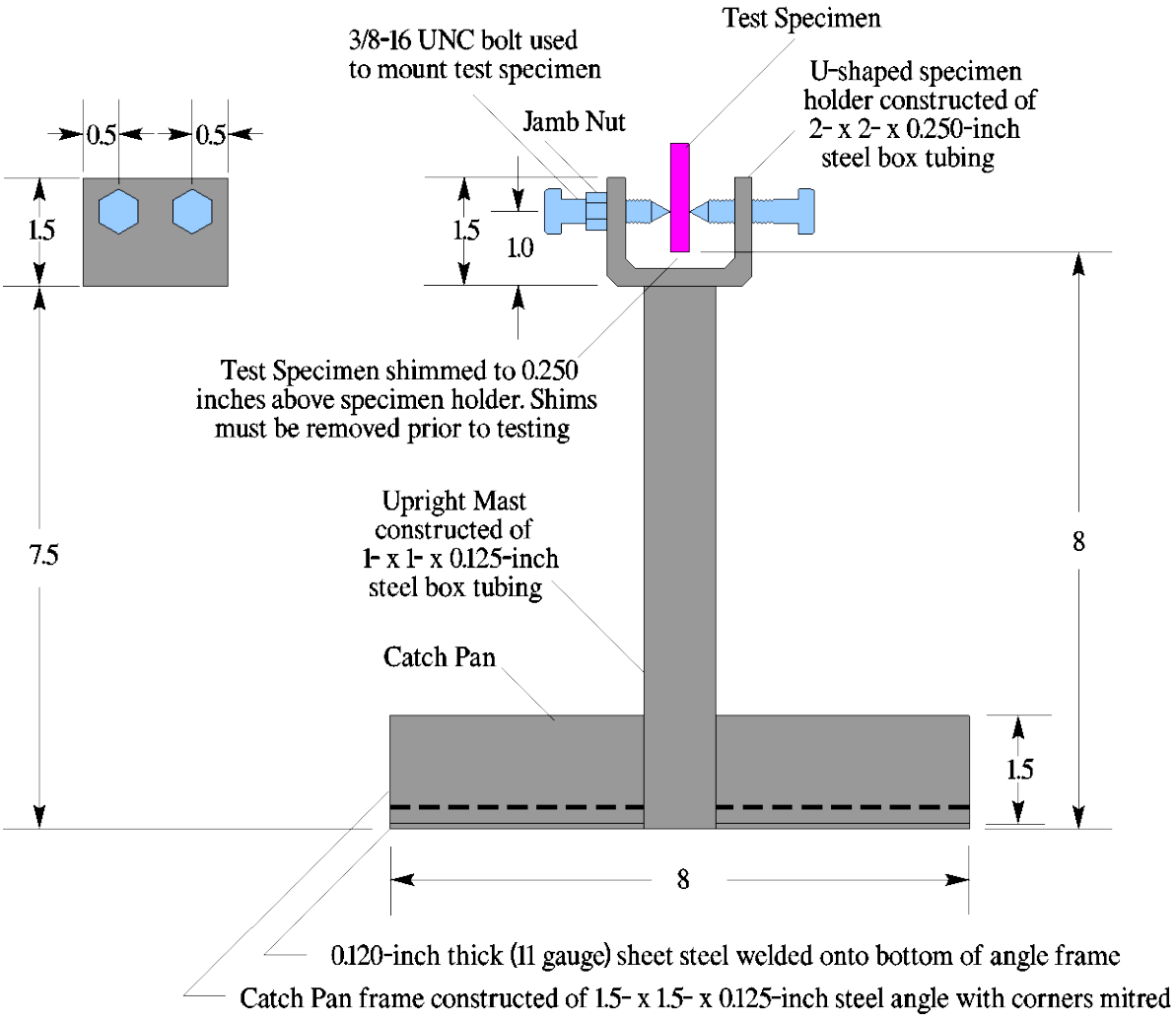


Figure A-4. Magnesium Alloy Test Specimen Mounting Stand and Holder (side)

A.3.2 TEST BURNER.

The test burner must be a gun-type, using a pressurized, sprayed kerosene-type fuel charge in conjunction with a ducted air source to produce the burner flames. An interchangeable, screw-in fuel nozzle will be used to produce the cone-shaped fuel charge from a pressurized fuel source. A pressurized air source controlled via a regulated sonic orifice will supply the combustion air. The combustion air will be ducted through a cylindrical draft tube containing a series of diffusing vanes. The diffused combustion air will mix with the sprayed fuel charge in a bell-shaped combustion cone. The fuel/air charge will be ignited by a high-voltage spark electrode pair positioned in the vicinity of the fuel spray nozzle. Flame characteristics can be adjusted by varying the pressure of the regulated air into the sonic orifice. Refer to appendix B, section B.3 for information on the components and construction of this burner.

A.3.2.1 Inlet Condition Measuring.

To obtain an accurate measurement of the conditions entering the burner, the fuel pressure and temperature, and air pressure and temperature measurements are made nearest to the burner inlet (see figure A-5). To minimize air-stream disruptions, the intake air temperature must be measured prior to the sonic orifice.

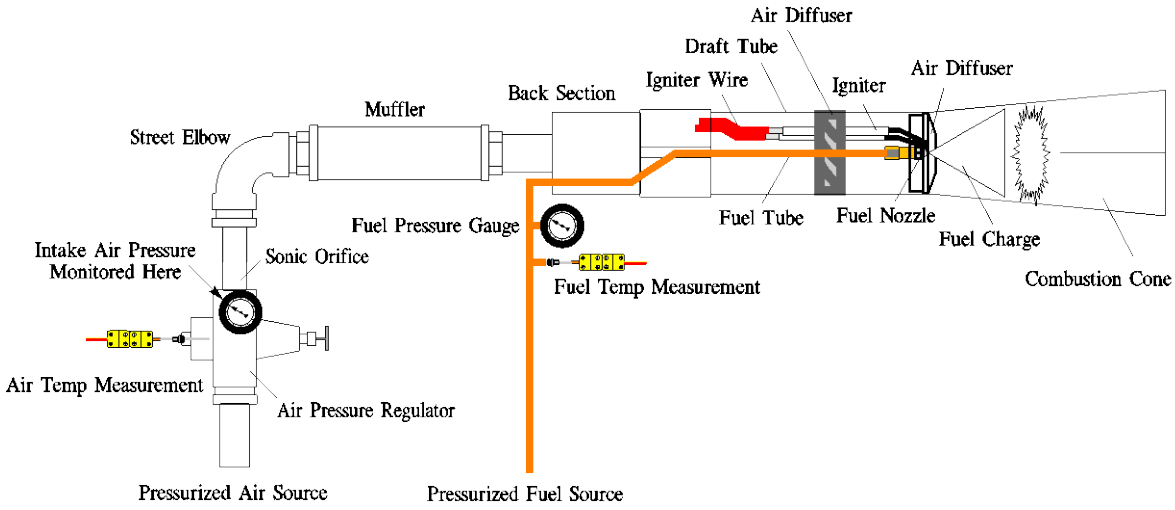


Figure A-5. Inlet-Condition Measurement Location (side view)

A.3.2.2 Fuel Nozzle.

A fuel nozzle will be required to maintain a fuel pressure that will yield a 2 ± 0.1 gallons/hour (0.126 L/min ± 0.0063 L/min) fuel flow. A nozzle with an 80-degree spray angle nominally rated at 2.0 gallons/hour (0.126 L/min) at 100 lb/in^2 (0.71 MPa) has been found to deliver the appropriate flow-rate and produce the proper flame pattern. Actual flow rate measurements may deviate from the advertised flow rate. The actual flow rate must be measured manually using a flexible tube, graduated cylinder, and timing device, as described in section A.6.4.6. The fuel pressure must then be adjusted accordingly to produce the required fuel flow of 2 ± 0.1 gallons/hour (0.126 L/min ± 0.0063 L/min). Refer to appendix B, section B.3.4.3 for additional details.

A.3.2.3 Fuel Pressure Regulation.

The fuel must be properly pressurized to deliver the proper fuel flow. Ideally, this pressure must be in the range of 80 to 140 lb/in^2 (0.55 to 0.97 MPa). Refer to appendix B, section B.3.4 for details on fuel pressurization and regulation.

A.3.2.4 Fuel Type.

A kerosene-type fuel is used in the burner equipment. Jet A and JP-8 (military equivalent to Jet A) fuel is recommended; however, other fuels are permissible if the flame temperature can be

maintained according to section A.7.1.3. Refer to appendix B, section B.3.4.4 for additional details.

A.3.2.5 Burner Cone.

A 12 ± 0.125-inch (305 ± 3-mm) burner extension cone is fitted to the end of the draft tube. The opening will be 6 ±0.125 inches (152 ± 3 mm) high and 11 ±0.125 inches (280 ± 3 mm) wide. Refer to appendix B, section B.3.7 for additional details.

A.3.3 THERMOCOUPLES.

The seven thermocouples to be used for calibration will be 0.125-inch (3.2-mm) ceramic-packed, metal-sheathed, type K (Chromel-Alumel), grounded-junction thermocouples with a nominal 24 AWG size conductor. The seven thermocouples will be attached to a steel mounting plate to form a thermocouple rake for placement in the test stand during burner calibration, as shown in figure A-6. The thermocouple mounting plate should be a minimum of 4 inches away from the tips of the thermocouples. Refer to appendix B, section B.4.5 for additional details.

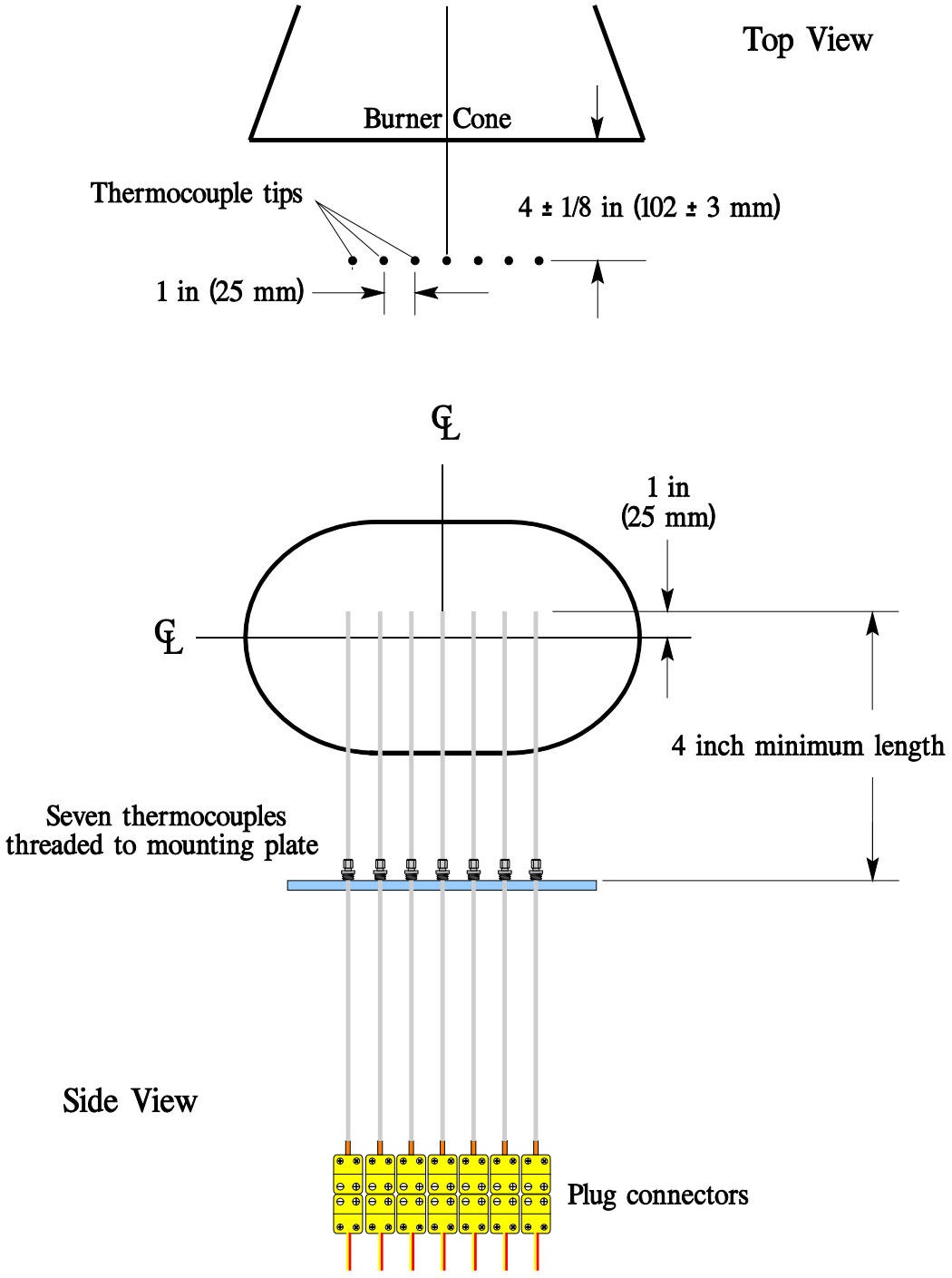


Figure A-6. Top and Side View of Thermocouple Rake Bracket

A.3.4 INSTRUMENTATION.

A.3.4.1 Data Acquisition.

A calibrated recording device or a computerized data-acquisition system with an appropriate range will be provided to measure and record the outputs of the thermocouples.

A.3.4.2 Timing Device.

A stopwatch or other device, accurate to within +/-1 second per 8 hours (+/-3 seconds/day), will be provided to measure the time of application of the burner flame and the test specimen ignition and extinguishment times.

A.3.4.3 Anemometer.

A handheld vane-type or hot wire-type air velocity sensing unit will be used to monitor the flow of air inside the test chamber when the ventilation hood is operating.

A.3.4.4 Digital Weight Scale.

A suitable weight scale will be used to determine the initial and final weights of the test specimen and weight of any molten /resolidified portions of the test specimen captured in the catch pan. The scale must have a resolution of 0.02 lb (0.01 kgs) and an accuracy of +/- 0.02 lb (+/- 0.01kgs).

A.4 TEST SPECIMENS.

A.4.1 SPECIMEN CONFIGURATION.

Test specimens representing the primary seat frame components (e.g., leg, spreader, cross tube, seat-back frame, and lower baggage bar) must be constructed of the identical magnesium alloy material to be used in service.

A.4.2 SPECIMEN SIZE.

The specimens to be tested will measure 1.5 ± .03 inches (38.10 ± 0.8 mm) height by 0.25 ± .0063 inches (6.35 ± 0.16 mm) thick by 20 ± .06 inches (508.0 ± 1.6 mm) in length. Test samples must be constructed according to the dimensions shown in figure A-7.

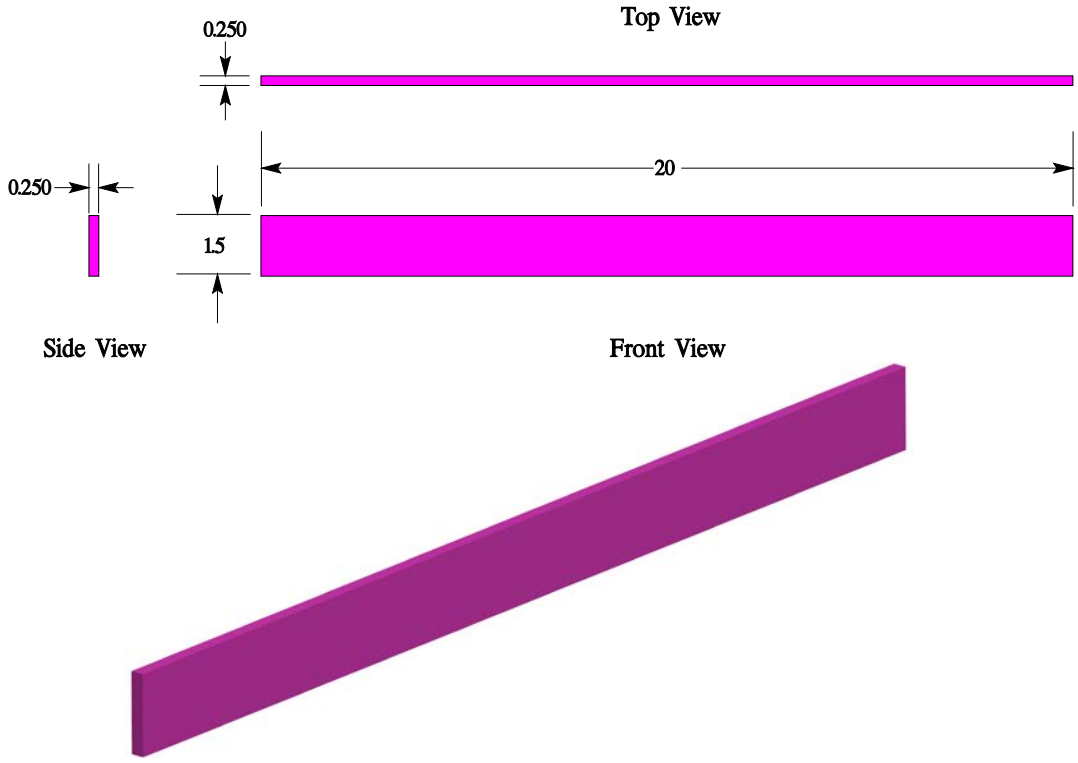


Figure A-7. Specimen Dimensions

A.4.3 SPECIMEN NUMBER.

A minimum of three specimens for each magnesium alloy type or design configuration must be prepared for testing. These specimens exclude any surface modifications, such as intumescent paints or coatings, or any anodizing processes.

A.4.4 SPECIMEN ORIENTATION.

The specimens are mounted horizontally, with the midpoint of the sample's face located 4 inches from the vertical exit plane of the burner cone and 1 inch above the burner centerline (refer to figure A-2).

A.4.5 SPECIMEN FINISH.

A machined surface finish to all faces is required for the test specimens (e.g., an average roughness value Ra of less than 1.75 μm and typically 0.9 μm).

A.4.6 SPECIMEN COATINGS.

If a finish coating, anodizing, or other surface treatment is used on the alloy in service, additional test specimens must also be prepared and tested with this treatment to ensure the surface treatment does not adversely affect specimen performance.

A.5 SPECIMEN CONDITIONING.

A.5.1 TEMERATURE AND HUMIDITY CONTROL.

The specimens must be conditioned at 70° ± 5°F (21° ± 2°C) and 55% ± 10 % relative humidity for a minimum of 24 hours prior to testing.

A.6 PREPARATION OF APPARATUS.

A.6.1 ALIGNMENT.

Level and center the specimen holder frame assembly to ensure alignment with the burner cone.

A.6.2 CHAMBER VENTILATION.

Turn on the ventilation hood for the test chamber. Do not turn on the pressurized burner air. Measure the airflow in the test chamber using a handheld vane-type anemometer or equivalent measuring device. The vertical air velocity within a 12-inch radius from any point on the horizontally positioned specimen must be less than 100 ft/min (50.8 cm/second). The horizontal air velocity within a 12-inch radius from any point on the specimen must be less than 50 ft/min (25.4 cm/second).

A.6.3 TEST CHAMBER AIR TEMPERATURE.

The temperature of the test chamber should be between 50°F and 100°F before the start of each test. The temperature should be measured at the same height as the center of the test sample, within 12 inches laterally.

A.6.4 SONIC BURNER.

A.6.4.1 Nozzle Location.

The tip of the fuel nozzle, or fuel exit plane, is located 0.1875 inch (4.8 mm) from the exit plane of the turbulator (figure A-7).

A.6.4.2 Stator Adjustment.

The stator is positioned by adjusting its translational position as well as its axial position on the fuel rod.

A.6.4.2.1 Stator Translational Position.

The front face of the stator is located 2.6875 inches (68.3 mm) from the exit plane of the turbulator (figure A-7).

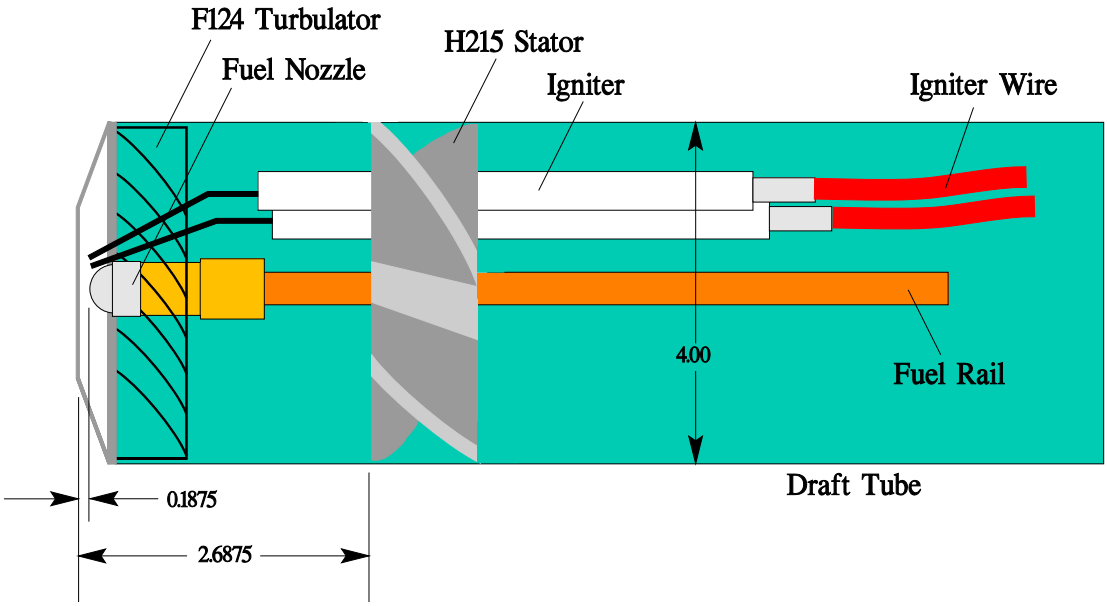


Figure A-7. Fuel Nozzle and Stator Locations

A.6.4.2.2 Stator Axial Position.

The midway point of the igniter pair (the line running midway between igniters and through the geometric center of stator) can be used as a reference for properly orienting the rotational position of the stator. The stator must be positioned so the igniter pair reference angle is 0^{o} from the zero position (figure A-8).

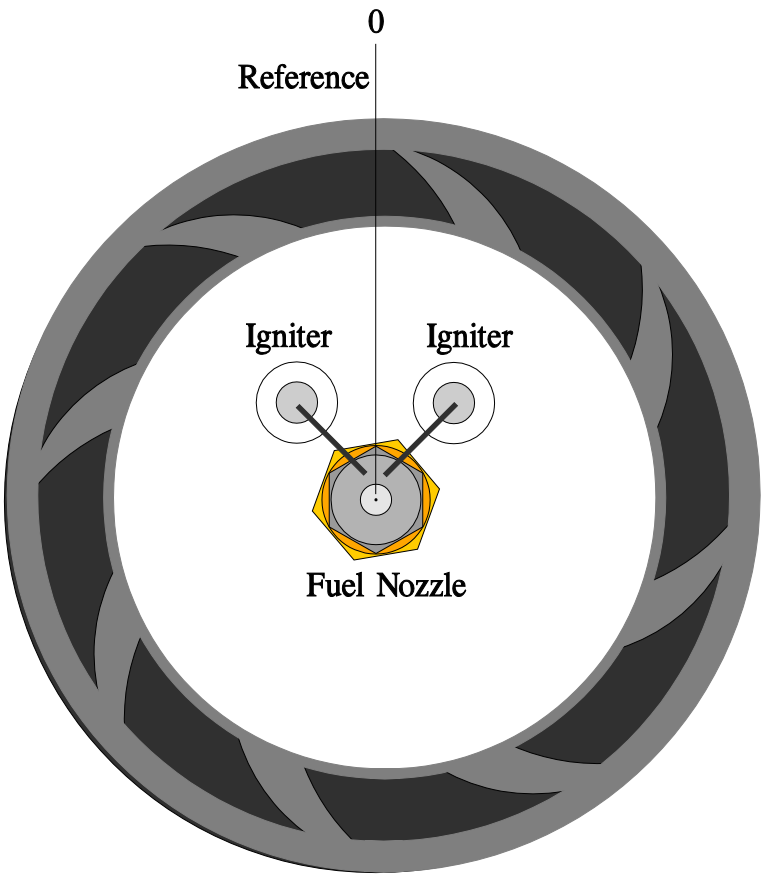


Figure A-8. Stator Rotational Position

A.6.4.3 Igniter Adjustment.

A.6.4.3.1 Igniter Height.

The igniter electrodes should protrude beyond the tip of the nozzle (exit plane of fuel spray) by 0.125 inch (3.2 mm) (figure A-9).

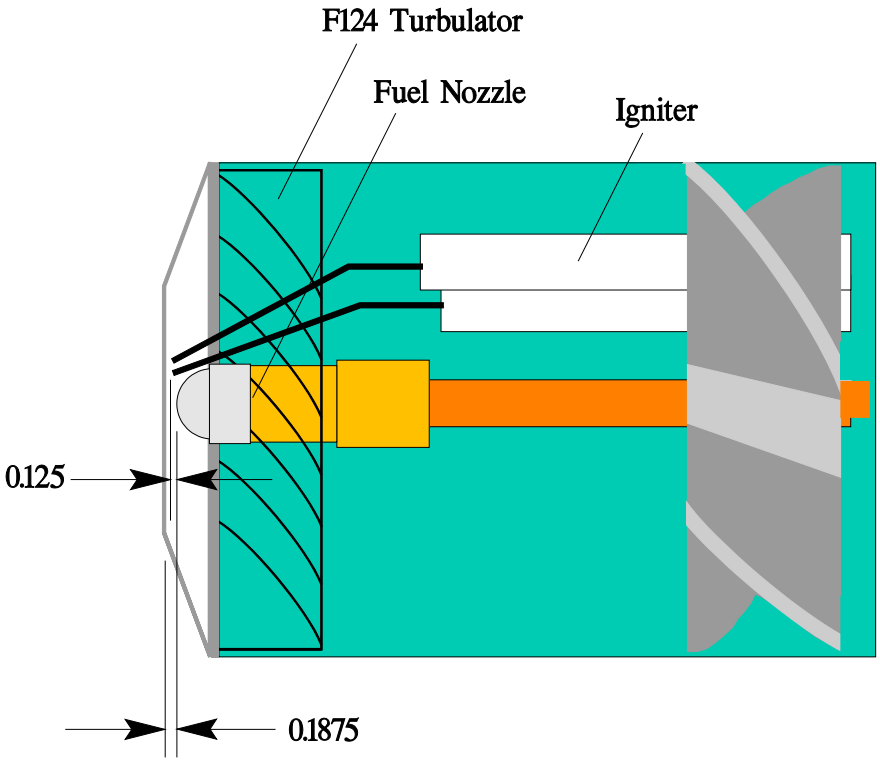


Figure A-9. Igniter Electrode Height Above Fuel Nozzle

A.6.4.3.2 Igniter Gap.

The gap (distance between) the two igniter electrodes must be 0.125 inch (3.2 mm), as shown in figure A-10.

A.6.4.3.3 Igniter Position.

The tips of each of the two igniter electrodes must be 0.250 inch (6.4 mm) from the geometric center of the fuel nozzle (figure A-10).

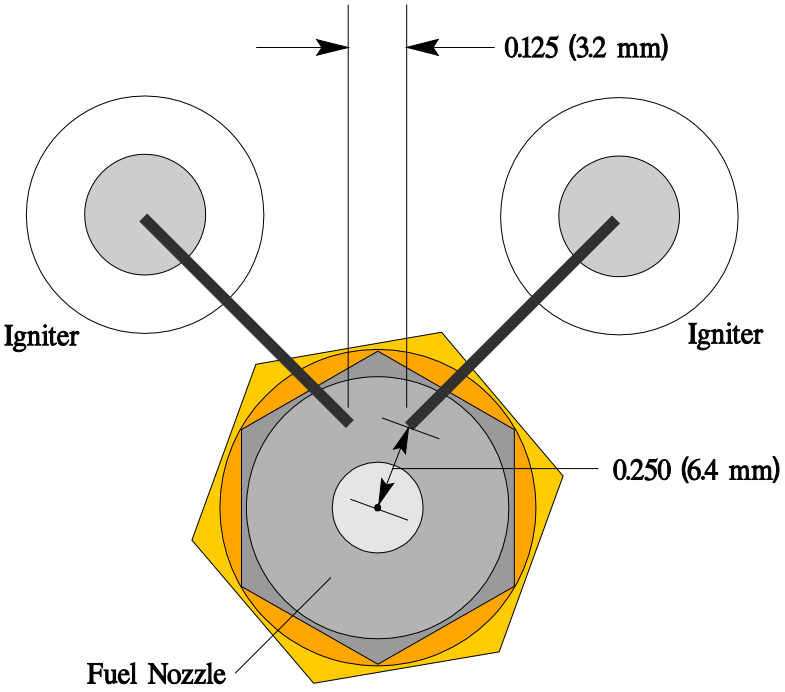


Figure A-10. Gap and Position of Igniter Electrodes

A.6.4.4 Ignition Wires.

The length and arrangement of the ignition wires within the burner tube are critical to allowing the proper airflow and pattern of air as it enters the combustion area. Small deviations or wire placement other than as described results in an uneven flame or prevent the burner from being properly calibrated. The wires should measure 13.25 inches +/- 0.25 inch (34.3 cm +/- 0.6 cm) in length from the point at which they enter the draft tube to the tip of the igniter terminal. This does not include the igniter terminal connecter. The wires must be orientated as shown in figure A-11 and should be pulled tight where they enter the burner draft tube. There should be no slack in the ignition wires between the igniter connecter and the points at which they penetrate the burner draft tube. The wires should remain tightly wrapped around the fuel rod to minimize their disruption of the air flow inside the burner.

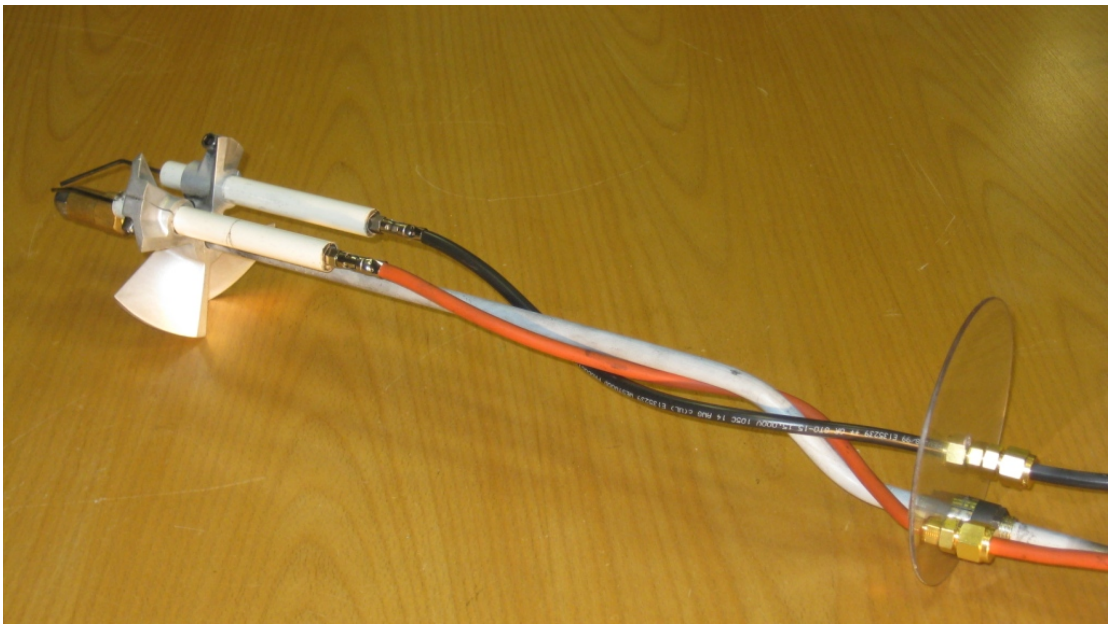


Figure A-11. Proper Routing of the Ignition Wires

A.6.4.5 Volumetric Air Flow Control.

The volumetric airflow is controlled via a regulated sonic orifice. Adjust the upstream supply air pressure to 45 lb/in^2. The intake air temperature must be maintained within the range of 40^{o}F to 60^{o}F. Refer to appendix B, sections B.3.2.1 and B.3.2.2 for additional details.

A.6.4.6 Fuel Flow Calibration.

If a calibrated flow meter is not available, measure the fuel flow directly using a length of Tygon® tubing and appropriately sized graduated cylinder. Slip the Tygon® tubing over the end of the fuel nozzle, making certain to establish a good seal. Direct the exit of the Tygon® tubing into a small bucket or other collection basin. Turn on the fuel solenoid, making sure the igniter system is off. After establishing a steady stream of fuel flow[A-1], simultaneously direct the tubing exit into the graduated cylinder while beginning the stopwatch or timing device. Collect the fuel for a 2-minute period, making certain to immediately direct the tubing exit away from the graduated cylinder at precisely 2 minutes. Calculate the flow rate and ensure that it is 2 ± 0.1 gallons/hour (0.126 ± 0.0063 L/min). If the flow rate is not within the tolerance, adjust the fuel pressure accordingly.

The temperature of the fuel must be maintained within the range of 32^{o}F to 52^{o}F.

[A-1] When collecting fuel, it is important to establish a steady stream of fuel before starting the measurement process. A 10-second period is recommended.

A.7 FLAME CALIBRATION.

A.7.1 SONIC BURNER.

The sonic burner used in the test must be checked to ensure the proper flame temperature is being produced for consistent and accurate test results.

A.7.1.1 Step 1.

Examine and clean the burner cone of any evidence of buildup of combustion, soot, etc. Soot buildup inside the cone may affect the flame characteristics and cause calibration difficulties. Because the burner cone may distort with time, dimensions should be checked periodically.

A.7.1.2 Step 2.

Mount the thermocouple rake on a rolling stand that is capable of being quickly moved into position in front of the burner. Move the rake into calibration position and check the distance of each of the seven thermocouples to ensure that they are located 4 ± 1/8 inch (102 ± 3.2 mm) from the vertical plane of the burner exit. Ensure that the horizontal centerline of the thermocouples are offset 1 ± 1/16 inch (25.4 ± 1.6 mm) above the horizontal centerline of the burner cone (see figure A-6). Place the center thermocouple (thermocouple number 4) in front of the center of the burner cone exit. Note that the thermocouple rake rolling stand must incorporate detents that ensure proper centering of the thermocouple rake with respect to the burner cone, so that rapid positioning of the rake can be achieved during the calibration procedure. Once the proper position is established, move the thermocouple rake away and move back into the calibration position to recheck distances. When all distances and positions are confirmed, move the thermocouple rake away from burner.

A.7.1.3 Step 3.

While the thermocouple rake is away from the burner, turn on the pressurized air and fuel flow, and light the burner. Allow the burner to warm up for a period of 2 minutes. After warmup, move the thermocouple rake into calibration position and allow 1 minute for thermocouple stabilization, then record the temperature of each of the seven thermocouples once every second for a period of 30 seconds. Remove thermocouple rake from the calibration position and turn off the burner. Calculate the average temperature of each thermocouple over this period and record. The average temperature of each of the seven thermocouples must be 1700°F (927°C) ± 100°F.

A.7.1.4 Step 4.

If the temperature of each of the seven thermocouples is not within the specified range, repeat sections A.7.1.1 through A.7.1.3 until all temperatures are within the calibration range. A slight adjustment of the internal stator orientation and distance from the end of the draft tube may be necessary to achieve the required temperatures.

A.7.1.5 Step 5.

Calibrate prior to each test until consistency has been demonstrated. After consistency has been confirmed, several tests can be performed with calibration conducted before and after the tests.

A.8 PROCEDURE.

A.8.1 STEP 1.

Examine and clean the cone of soot deposits and debris.

A.8.2 STEP 2.

Weigh the magnesium alloy test specimen and record this initial weight.

A.8.3 STEP 3.

Mount the magnesium alloy test specimen in the test frame specimen holder. Verify that the horizontal test specimen is level and that the center of the face of the specimen being exposed is at a distance of 4 ± 0.125 inch (102 ± 3.2 mm) from the vertical exit plane of the burner cone. Ensure that the horizontal centerline of the test specimen is offset 1 ± 0.0625 inch (25.4 ± 1.6 mm) above the horizontal centerline of the burner cone (see figure A-2).

A.8.4 STEP 4.

Move the test frame assembly away from the burner to the standby position so that the flame does not impinge on the test specimen during the warmup period. Turn on the burner and allow it to stabilize for a period of 2 minutes.

A.8.5 STEP 5.

Move the test frame assembly into the test position and start the timing device when the test frame is fully in the test position.

A.8.6 STEP 6.

Record the time for the sample to melt and the time of first sustained ignition (burning) of the sample.[A-2]

A.8.7 STEP 7.

Expose the test specimen to the flames for a period of 4 minutes, then move the test frame assembly away from the burner to the standby position and turn off the burner.

[A-2] Sustained ignition is defined as any ignition, including sparking, lasting for 3 consecutive seconds (i.e., an ignition lasting for more than 3 seconds shall be considered the beginning of the ignition period, in the event that ignition stops and then restarts).

A.8.8 STEP 8.

Continue to observe the test specimen remaining in the sample holder after removal from the burner position. If the sample is still burning, measure the time when ignition ends.

A.8.9 STEP 9.

When the test specimen has cooled sufficiently, loosen the retaining bolts and remove the specimen. Record the final weight. Also remove any specimen remnants located in the catch pan, and record these weights after first removing any residual oxidation and talc powder.[A-3]

To expedite the specimen mounting and testing process, several specimen holder/catch pans can be incorporated. The catch pan can use pins or other quick-release mechanisms to facilitate fast removal following each test. Once the test is complete, the entire specimen holder and catch pan, including talc and specimen remnants, can be removed from the testing area and a new specimen holder, catch pan, and test specimen replaced. Ensure that the new test specimen is properly aligned with the burner.

A.9 REPORT.

A.9.1 STEP 1.

Report a complete description of the material(s) being tested, including manufacturer, alloy content, trade name, etc.

A.9.2 STEP 2.

For each of the three specimens, report the time for the specimen to melt (visual observation when specimen center section separates from remaining test specimen). Also report the time of sustained ignition (burning) and the time when the specimen self-extinguishes.

A.9.3 STEP 3.

Calculate and record the weight percentage loss of each test specimen by combining the final weight of the specimen remaining in the holder and any additional remnants removed from the catch pan. Ensure that the remnant weight includes only metallic components and no oxidized material or talc. The combined weight of the tested specimen and remnants can be subtracted from the initial weight of the specimen. This value can then be divided by the initial weight and the value multiplied by 100 to determine the percentage weight loss.

[A-3] Residual oxidation and talc powder can be removed from the sample and retrieved molten/resolidified pieces by blowing them off with compressed air. This process should be completed within 1 hour of the end of the test.

A.9.4 STEP 4.

Record any observations regarding the behavior of the test specimen during flame exposure, such as popping, explosions, smoke, etc., and the time each event occurred.

A.9.5 STEP 5.

Provide a record of burner calibration.

A.10 REQUIREMENTS.

- None of the three specimens tested may ignite in less than 2 minutes of burner exposure.
- If ignition occurs in less than 4 minutes (but more than 2 minutes), all three samples must self-extinguish within 3 m inutes of the burner being turned off. It is important to continue monitoring the test specimen after its removal from the test burner, as it is not uncommon for a specimen to ignite spontaneously, or reignite after self-extinguishing.
- The calculated weight loss must not exceed 10%.
- If one or more samples fail to meet the above requirements, it is possible to run additional recovery tests if 80% or more of the total number of samples meet the requirements. For example, if one of the three original samples fails the test requirement, two additional passing tests can be conducted for a total of four passing tests in five opportunities (4/5 = 80%).

This recovery process is intended for materials that typically meet the test requirements, but failed for unexpected reasons. These failures, often referred to as rogue failures, are unanticipated and cannot be explained. The recovery process should not be viewed as a technique for meeting the requirement with inferior materials.

APPENDIX B—NEXT GENERATION FIRE TEST BURNER

B.1 SCOPE.

This chapter describes in detail the Federal Aviation Administration (FAA) Next Generation fire test burner, also known as the Sonic or the NexGen burner.

B.2 DESCRIPTION.

B.2.1 THE NEXGEN OR SONIC BURNER.

The NexGen fire test burner must be a gun-type, using a pressurized, sprayed fuel charge in conjunction with a ducted air source to produce the burner flames. An interchangeable, screw-in fuel nozzle is used to produce the cone-shaped fuel charge from a pressurized fuel source. A pressurized air source controlled via a regulated sonic orifice supplies the combustion air. The combustion air is ducted through a cylindrical draft tube containing a series of diffusing vanes. The diffused combustion air mixes with the sprayed fuel charge in a bell-shaped combustion cone. The fuel/air charge is ignited by a high-voltage spark electrode pair positioned in the vicinity of the fuel spray nozzle. Flame characteristics can be adjusted by varying the pressure of the regulated air into the sonic orifice. A schematic of the NexGen fire test burner is displayed in figure B-1. Note that the configuration of the burner components is test-method specific and described in section B.3.

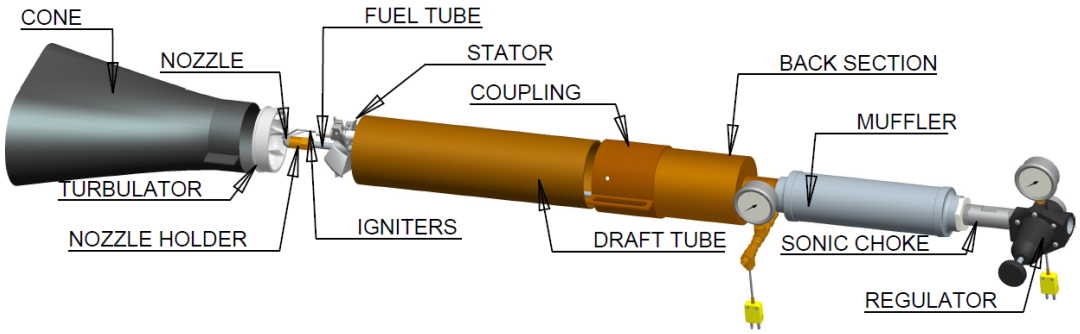


Figure B-1. The NexGen Burner - Exploded View

B.3 TEST APPARATUS COMPONENTS.

B.3.1 BURNER HOUSING.

The burner housing is comprised of three main sections: the draft tube, the coupling, and the back section. Figure B-2 shows the draft tube, which is constructed of 4-inch inner diameter mild-seam steel tubing with a wall thickness of 0.125-inch. The length of the draft tube is 15 inches, with 3 inches of the tube inserted into the coupling, resulting in a coupling-to-tip distance of 12 inches. Figure B-3 shows the coupling, which is constructed of 4.25-inch inner diameter mild-seam steel tubing that is 4 inches long with an outer diameter of 4.75 inches. Three set-screw holes are 120° apart and are drilled 1 inch from the edge to hold the draft tube in place.

The coupling has two mounting brackets welded to the sides for easy mounting and adjustment. Figure B-4 shows the back section, which is made of the same 4-inch tubing as the draft tube, but is 6 inches long, with 1 inch inserted into the coupling and welded in place. Figure B-5 shows the back plate, which is constructed of a 0.125-inch steel plate cut into a 4.25-inch diameter circle to cap the back section, with holes for the air inlet, fuel inlet, and two igniter wires. Figure B-6 shows a 1.5-inch NPT pipe nipple, which is cut to a length of 2.90 inches and welded into the recessed cut on the center of the back plate.

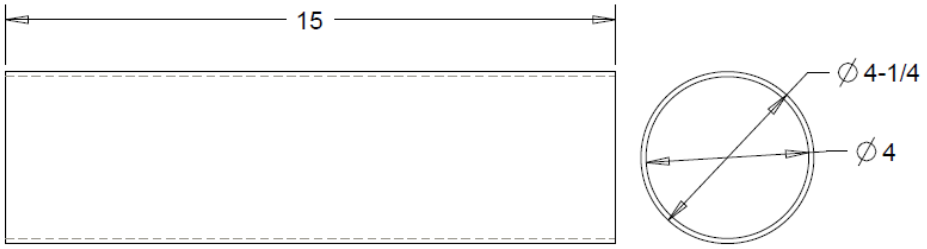


Figure B-2. Dimensioned Drawing of the Draft Tube

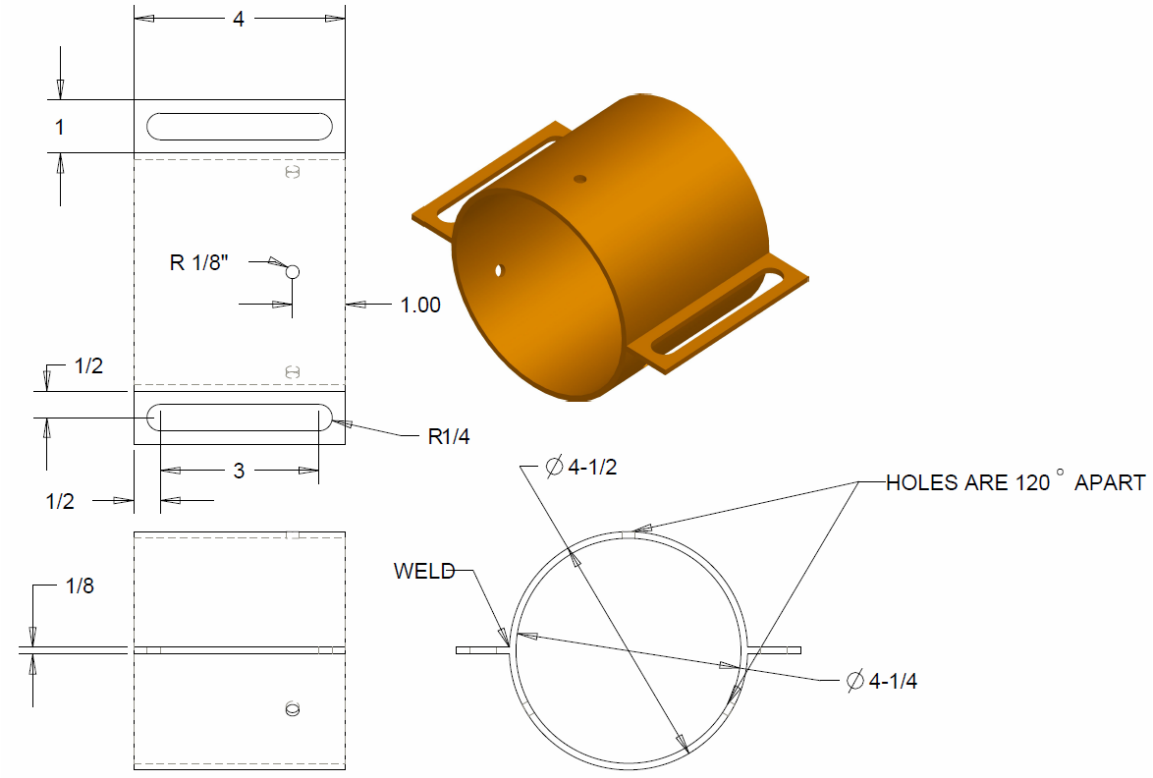


Figure B-3. Dimensioned Drawing of the Coupling

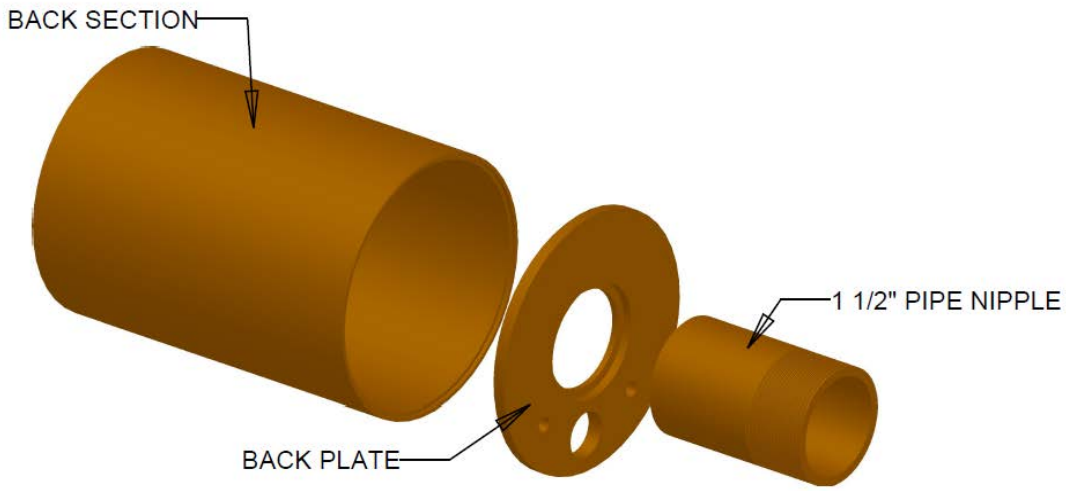


Figure B-4. Back Section Components—Exploded View

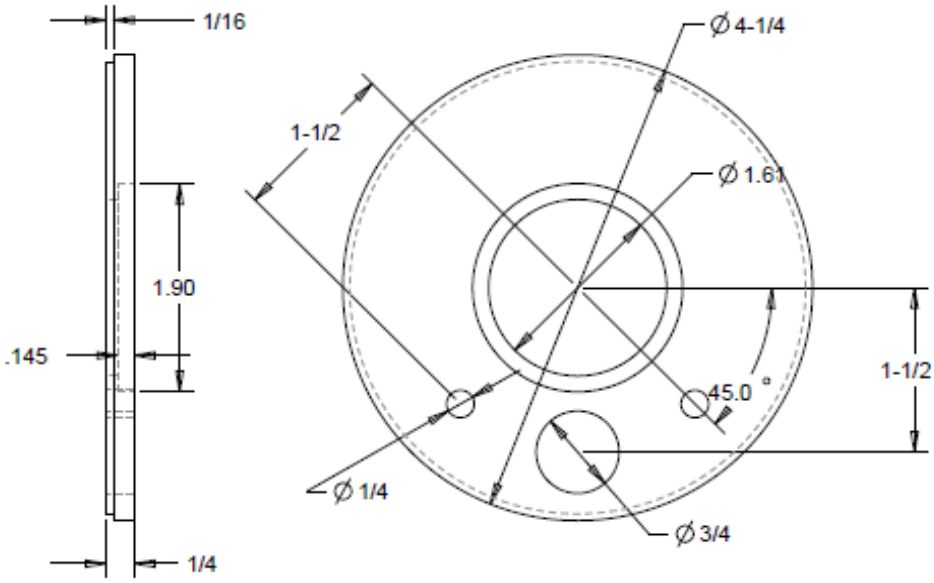


Figure B-5. Dimensioned Drawing of the Back Plate

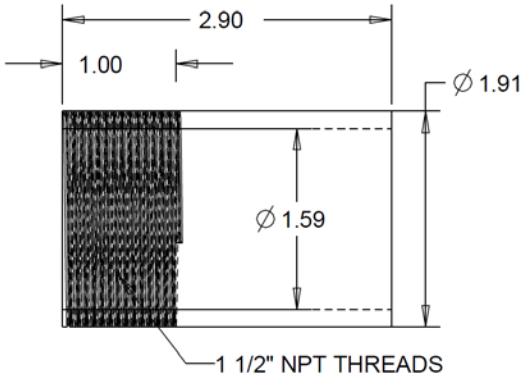


Figure B-6. Dimensioned Drawing of the Pipe Nipple

B.3.2 AIRFLOW.

B.3.2.1 Sonic Nozzle.

The NexGen burner airflow is regulated with a sonic nozzle, which delivers a constant mass flow rate depending on the supplied inlet air pressure. A schematic of the sonic nozzle is shown in figure B-7. The nozzle is constructed from stainless steel with 1-inch NPT male-thread ends. The throat diameter must be 1/4-inch, which will deliver a mass flow rate in standard cubic feet per minute as a function of inlet pressure, in pounds per square inch gauge, at a rate of

$$\dot{m} = 0.89 * P_i + 12.43 \qquad \text{(B-1)}$$

The exact inlet air pressure and mass flow rate is test-method specific and is described in section B.3.2.2. The nozzle that the FAA used to develop the NexGen burner was manufactured by Fox Venturi Products of Dover, New Jersey and is identified by part number 612021-8.

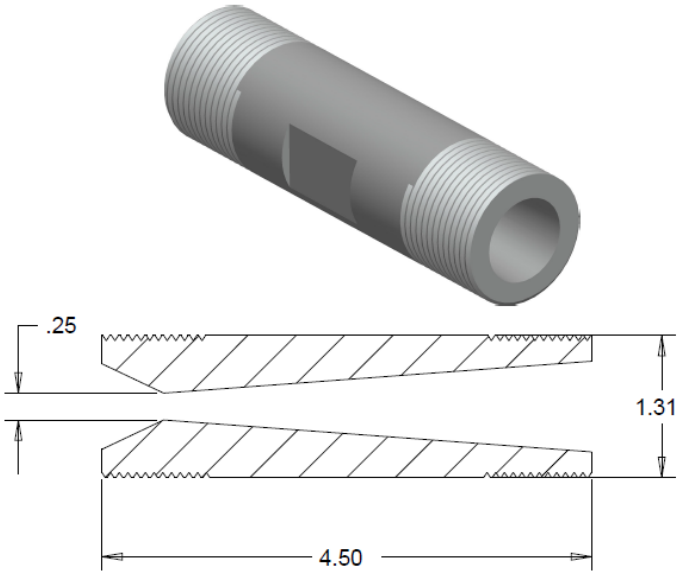


Figure B-7. The Sonic Nozzle With Cutaway View, Showing Converging and Diverging Interior Sections

B.3.2.2 Air Pressure Regulator.

The air pressure regulator is critical to maintaining the stability of the airflow supplied to the burner. The regulator must have 1-inch NPT female connections and at least one pressure tap for measurement of outlet pressure. It should also regulate over the range of 0-100 psig maintaining the desired pressure for the length of a test. A schematic of the air pressure regulator is shown in figure B-8. A suitable regulator is Ingersoll-Rand ARO 27364-000.

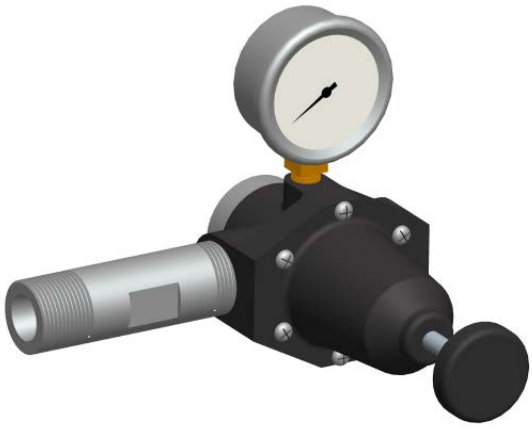


Figure B-8. Air Pressure Regulator With Sonic Nozzle Attached

B.3.2.3 Muffler.

An air flow muffler is used to reduce the high frequency noise created by the air expanding from the nozzle throat. The muffler has 1.5-inch NPT female-thread connections, is 3 inches in diameter, has an overall length of 12 inches, and has no internal baffles or tubes. A suitable muffler is McMaster-Carr part number 5889K73. Low pressure drop polyurethane foam can be used to further reduce the noise issuing from the burner. The foam can be cut into a 3-inch diameter by 12-inch-long cylinder and should have a density of approximately 1.20-1.50 lb/ft^3. A hex bushing (a 1.5-inch NPT male to a 1-inch NPT female) is used to connect one side of the muffler to the outlet side of the sonic nozzle.

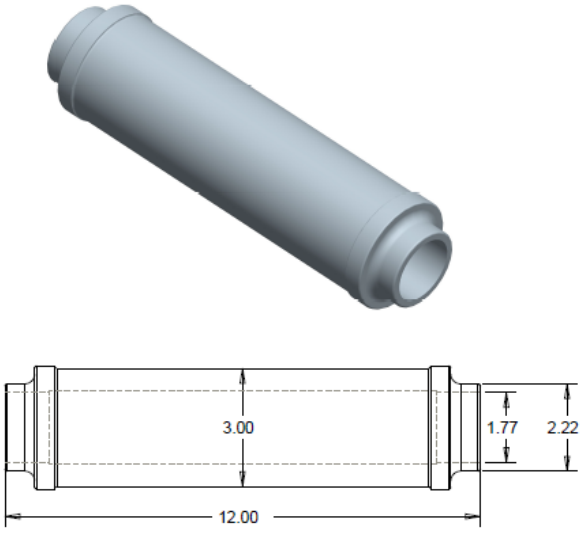


Figure B-9. Schematic of the Muffler

B.3.2.4 Air Temperature.

The air temperature must be maintained at 60 ±10°F for the duration of a test. This can be achieved by constructing a heat exchange system as described in section B.3.6.

B.3.3 STATOR AND TURBULATOR.

The stator and turbulator have been reverse-engineered from Monarch components used in the original Park oil burner. The components were dimensioned and corrected for irregularities, then drawn in three-dimensional (3D) modeling software. The 3D files can be downloaded from the Fire Safety Website:

http://www.fire.tc.faa.gov/materials/burnthru/nexgen.stm

These files can be used to make the components on a Computer Numerical Controlled mill.

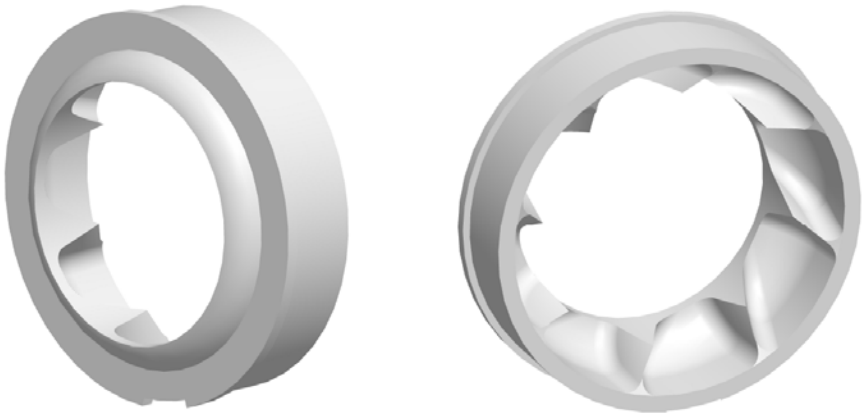
B.3.3.1 Stator.

Figure B-10 shows the stator, which is a four-vane internal component that creates a swirling flow while also holding the burner igniters and aligning the fuel tube with the center axis of the draft tube. The stator is 4 inches in diameter and should have a snug fit when placed inside the draft tube. A suitable stator is Marlin Engineering part number ME1500-101.

Figure B-10. Stator

B.3.3.2 Turbulator.

Figure B-11 shows the turbulator, which is a 4-inch diameter swirling device placed in the end of the draft tube. The center hole is 2.75 inches in diameter. A suitable turbulator is Marlin Engineering part number ME1500-103.



(a) (b)

Figure B-11. Turbulator: (a) Front and (b) Back

B.3.4 FUEL SYSTEM.

A method of fuel pressurization is required to deliver the proper amount of fuel to the spray nozzle for consistent atomization. The delivered fuel pressure must be in the range of 80-140 psig, and must maintain the desired pressure for the duration of a test. A suitable method of fuel

pressurization is a pressurized fuel tank; a fuel pump may also be used provided it can maintain the required pressure for the duration of a test with minimal fluctuation.

A schematic of the pressurized fuel tank system is shown in figure B-12. The headspace gas pressure is controlled by a precision regulator (figure B-8). Fuel pressure can also be measured at the back of the burner nearest to the fuel nozzle. A pressure vessel, such as McMaster-Carr part number 1584K7 that is 12 inches in diameter and 33 inches tall and has a 15-gallon capacity, can be used to contain the fuel. The tank has various fittings on the top, bottom, and sides to allow for connection of pipe fittings for filling, discharging, level and pressure measurement, pressurization, and venting. Nitrogen is used to pressurize the headspace of the fuel tank. Solenoid or manual valves can be used to start and stop the flow of fuel, nitrogen, and vent gas. A high-pressure translucent tube can be used to measure the fuel level in the tank.

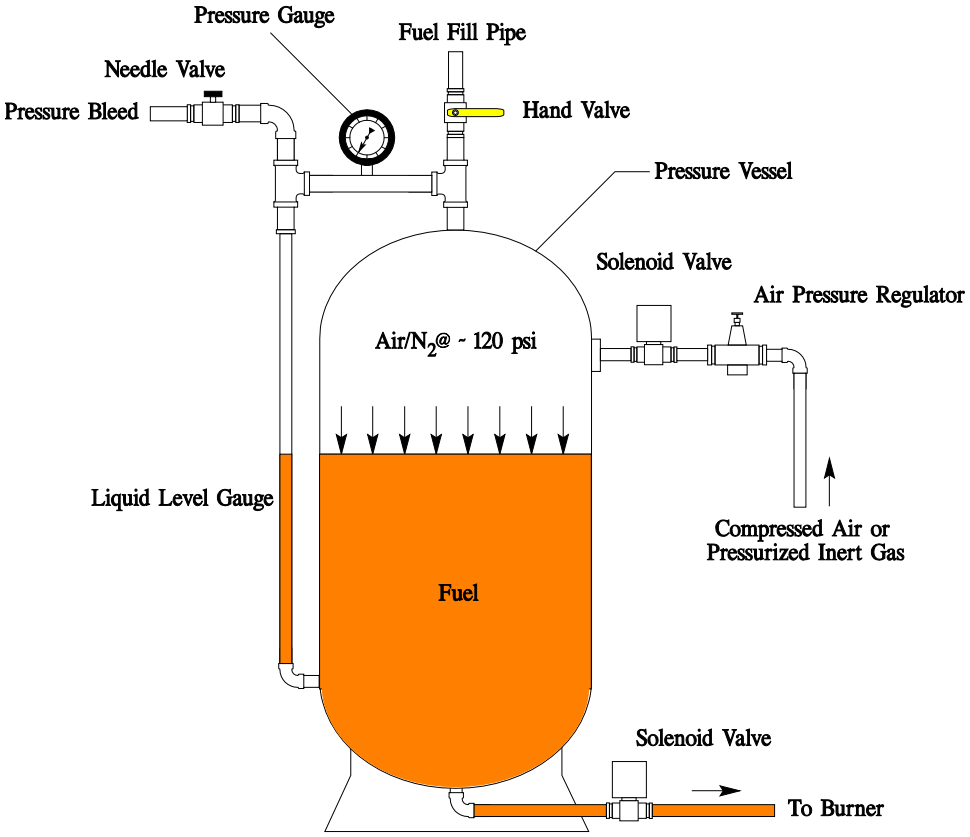


Figure B-12. Schematic of Fuel Tank

B.3.4.1 Fuel Temperature.

The fuel temperature must be maintained at 42 ± 10°F for the duration of a test. This can be achieved by constructing a heat exchange system as described in section B.3.6.

B.3.4.2 Fuel Tube.

Figure B-13 shows the fuel tube in the NexGen burner, which is designed to allow both the fuel nozzle and the airflow to be aligned with the axis of the draft tube. This is accomplished by creating two bends in the section of the fuel tube that enters the back of the burner. The tube is constructed from a 1/8-inch steel pipe with an outside diameter of 0.405 inch, an inside diameter of 0.215 inch, and a wall thickness of 0.095 inch. The pipe is cut to a length of approximately 21.5 inches; a section of the outer wall is removed on a lathe to fit the pipe through the keyless bushing that holds the tube in place. The outer diameter of the fuel tube is reduced to approximately 0.3750 inch for a length of 4 inches at one end. The tube is then shaped with a pipe bender according to the dimensions in figure B-13. A die is used to thread both ends of the tube with 1/8-inch NPT pipe threads. Heavy duty 0.004-inch-thick thread seal tape is wrapped on the pipe threads to prevent fuel leakage. A 1.375-inch-long brass fuel nozzle adapter is threaded onto the front end of the fuel tube where the fuel nozzle is attached. A keyless bushing (Fenner Drives p/n 6202109) is used to hold the back end of the fuel tube in place. A pipe fitting is attached to the back end of the fuel tube to connect the pressurized fuel system to the fuel tube.

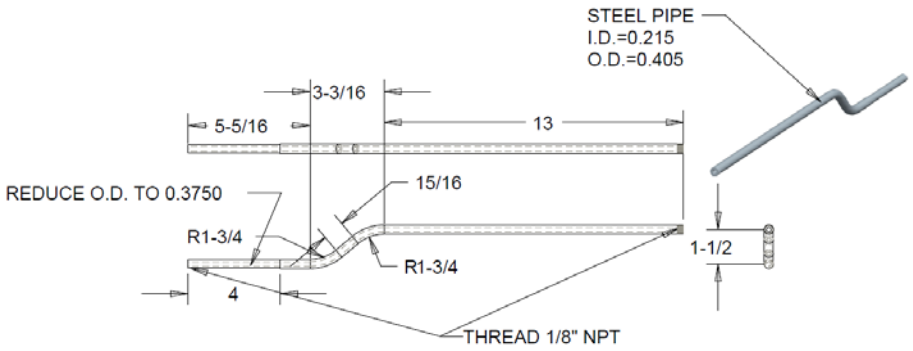


Figure B-13. The Fuel Tube

B.3.4.3 Fuel Nozzle.

The fuel nozzle and nozzle adapter are shown in figure B-14. The fuel nozzle for the NexGen burner should be an 80-degree conical spray pattern oil-burner nozzle. The nozzle flowrate depends on the test method. Favorable results have been achieved with Monarch brand fuel nozzles. The rated flow rate provided by the manufacturer is achieved when applying a 100-psig fuel pressure to the nozzle. If a different flow rate is desired, the pressure can be adjusted accordingly to achieve a wide range of flow rates. Generally speaking, the flow rate is related to the pressure by:

$$F_d = F_r \sqrt{P_d / P_r} \tag{B-2}$$

where F_d is the desired flow rate, F_r is the rated flow rate, P_d is the desired pressure, and P_r is the rated pressure, typically 100 psig. If the 5.5-gph-rated nozzle is operated at 120 psig, a flow rate

of 6.0 gph will be achieved. Other types of spray nozzles are currently being tested and may be considered acceptable if similar test results are achieved.

The fuel nozzle adapter is a brass fitting 1.375 inches in length with a 0.125-inch NPT thread on the inlet side and 0.5625-inch 24 UNF thread where the nozzle attaches.

Figure B-14. Fuel Nozzle and Nozzle Holder

B.3.4.4 Fuel.

Jet-A or JP-8 aviation kerosene are preferred, but other equivalent types, such as ASTM K2 fuel, can be used.

B.3.5 IGNITION.

A high-voltage oil burner ignition transformer with an output of 10 kilovolts is used to create an arc between a pair of ceramic insulated electrodes. The igniters have a 0.5625-inch diameter, 5-inch-long ceramic insulators with 3/32-inch diameter electrodes. The electrode tips are positioned at a depth of 5/32 inch from the exit plane of the turbulator. A suitable igniter pair is manufactured by Westwood Products, South River, NJ and is identified by part number E5-2M5.

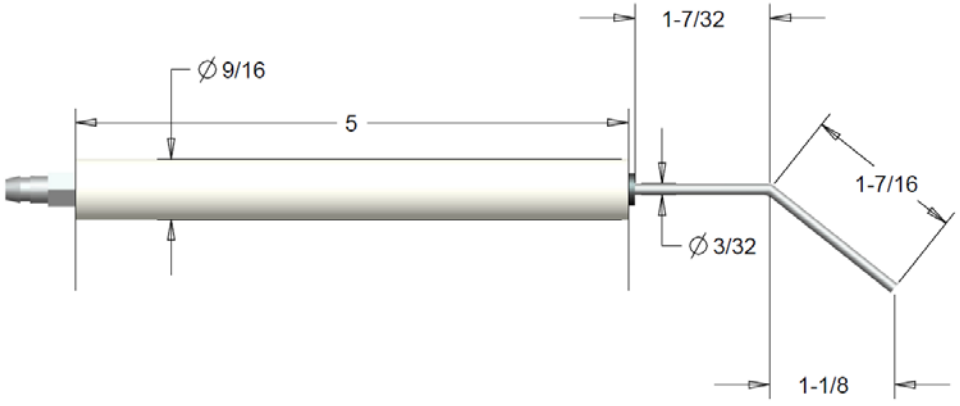


Figure B-15. Dimensioned Drawing of an Igniter

B.3.6 HEAT EXCHANGE SYSTEM.

A heat exchange system is used to regulate the temperature of the burner inlet air and fuel as the flow rate of each is dependent on the density of the air and fuel. Figure B-16 shows a schematic of a suitable heat exchange system. The ice bath can be constructed from an insulated cooler or a chest freezer with temperature-control capability. The fuel travels through coiled copper tubing in the ice bath and out to the burner. The air is cooled in a heat exchanger, such as McMaster-Carr part number 43865K78, which has ice water traveling through the outer shell, removing heat from the air. The ice water is circulated in a closed loop from the cooler to the heat exchanger by means of a submersible pump. The exact dimensions of the copper coils and the flowrate of the water pump is dependent on the particular conditions in the laboratory. Alternate methods, such as active heating and cooling systems, can be used and are more precise, but may be more costly.

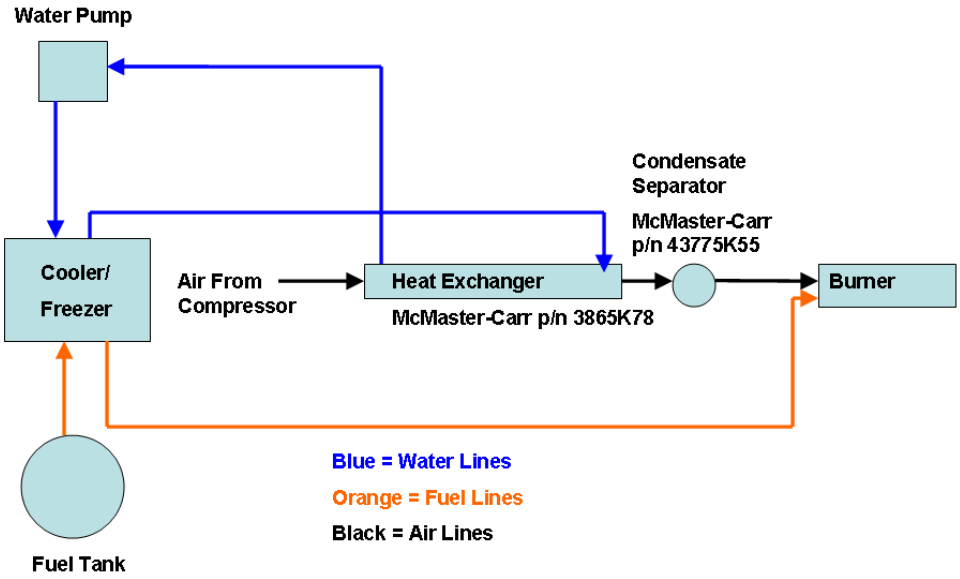
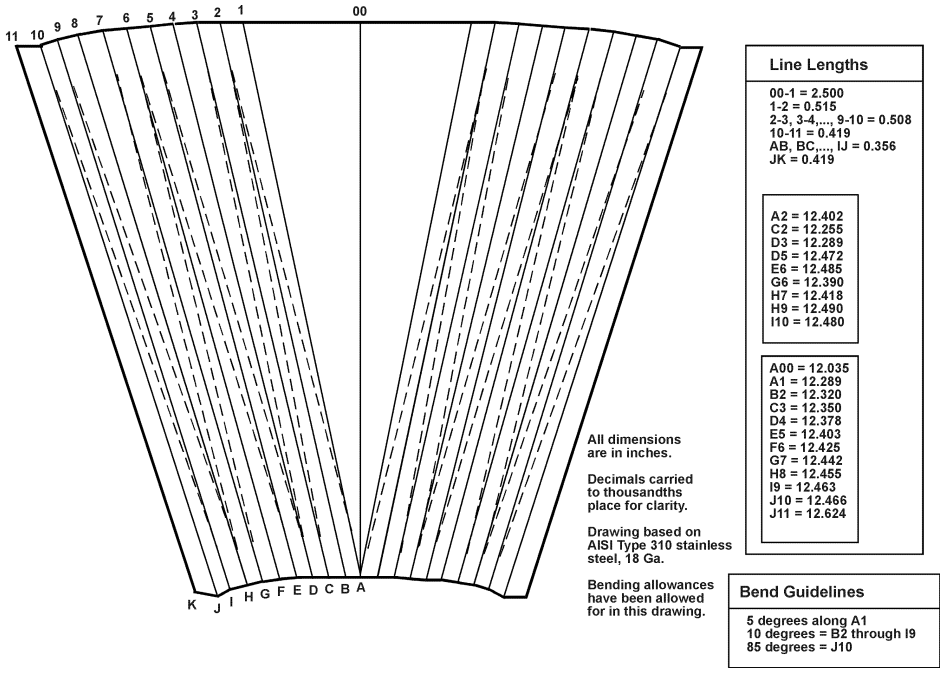


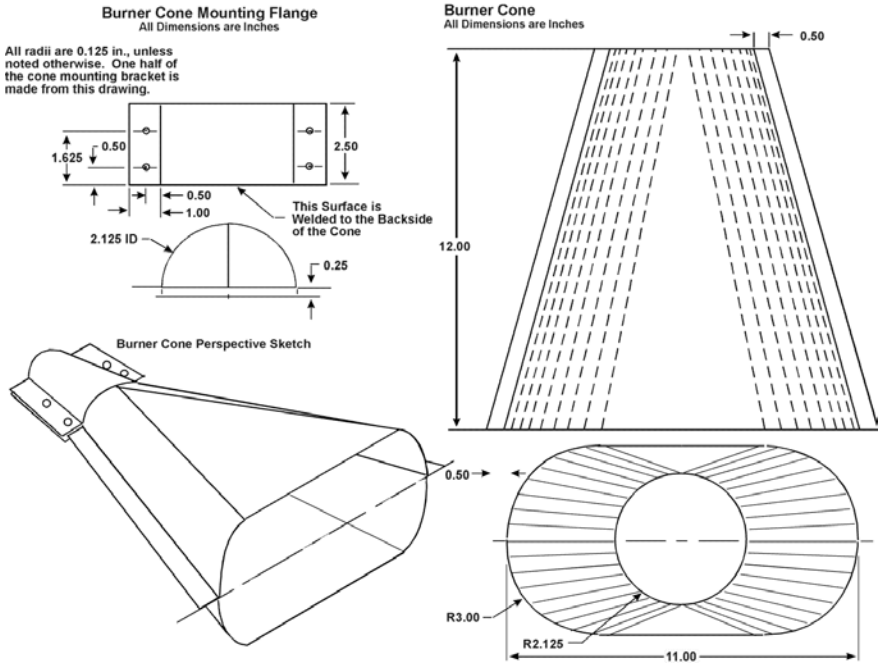
Figure B-16. Air/Fuel Heat Exchange System

B.3.7 BURNER CONE.

A 12 ± 1/8-inch (305 ± 3-mm) burner extension cone is fitted to the end of the draft tube. The cone is constructed from stainless steel or similar noncorrosive high-temperature metal, such as AISI type 310 18 gauge. The opening will be 6 ±0.125 inch (152 ± 3 mm) high and 11 ±0.125 inch (280 ± 3 mm), and the thickness should be 0.065 ± 0.015-inch (1.65 ±0.375 mm). See figures B-17 (a and b).



(a)



(b)

Figure B-17. Burner Cone: (a) Layout and Bending Pattern and (b) Details

B.4 BURNER MEASUREMENT.

B.4.1 AIR PRESSURE.

The sonic choke inlet pressure is measured with a suitable pressure gauge mounted just upstream of the sonic choke, preferably at the outlet pressure tap on the pressure regulator. The gauge should measure accurately in the range of 0-100 psig, with a resolution of 2 psig. Bourdon-type gauges and pressure transducers have proven to be suitable for this measurement.

B.4.2 AIR TEMPERATURE.

The burner air temperature is measured with a 0.125-inch K-type stainless steel-sheathed grounded junction thermocouple. The thermocouple should be inserted into the air stream just upstream of the sonic nozzle. In some testing situations, flame radiation may be incident on the inlet air lines, causing heating of the air and possible bursting of flexible hoses. It is important to shield all air lines with thermal wrapping to prevent an unsafe condition and maintain steady air temperature.

B.4.3 FUEL PRESSURE.

The burner fuel pressure is measured with a suitable pressure gauge mounted in a T-connection in the fuel inlet line near the back of the burner (figure B-19). It is important that the measurement location is as close to the back of the burner as possible to accurately measure the fuel pressure at the point it enters the burner.

B.4.4 FUEL TEMPERATURE.

The burner fuel temperature is measured with a 1/8-inch K-type stainless-steel-sheathed grounded junction thermocouple. The thermocouple should be mounted in a T-fitting such that the probe tip is located near the center of the fuel tube. In some testing situations, flame radiation may be incident on the inlet fuel lines, causing heating of the fuel and possible bursting of flexible hoses. It is important to shield all fuel lines with thermal wrapping to prevent an unsafe condition and maintain steady air temperature.

B.4.5 FLAME TEMPERATURE THERMOCOUPLES.

Seven 0.125-inch-diameter ceramic packed, 310 stainless-steel-sheathed, type K (Chromel-Alumel), grounded-junction thermocouples with a nominal 30 AWG size conductor are provided for calibration. The thermocouples are attached to a steel bracket to form a thermocouple rake for placement in the test stand during burner calibration.

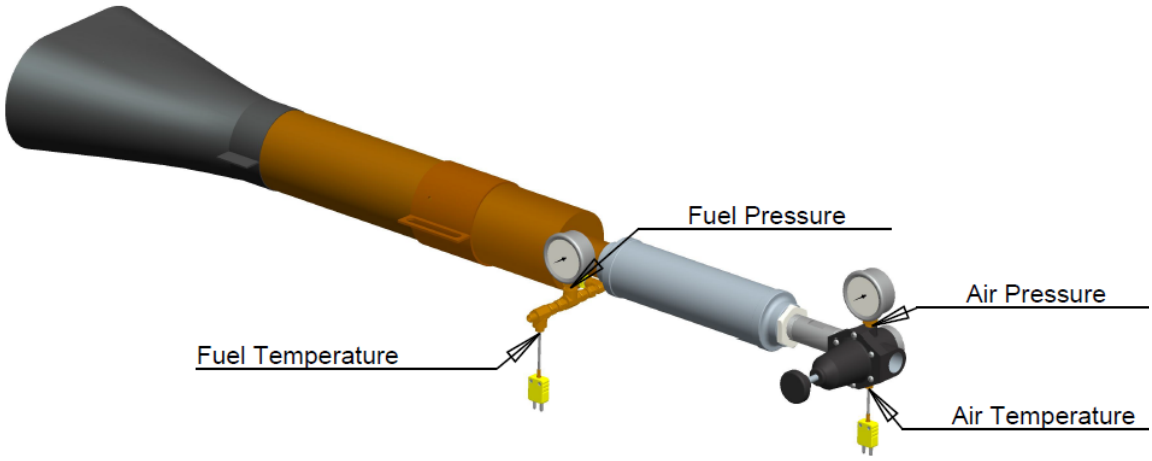


Figure B-18. Burner Schematic Showing Inlet Measurement Locations