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Ignition from High Heat Flux for Flat Versus Complex Geometry

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ABSTRACT

Ignition of solid materials from radiative heat flux has been well studied, as it relates to common fire instantiation and propagation. Conventional testing involves a small (~10 cm) flat sample in a test apparatus such as a cone calorimeter exposed to fluxes in the range of 25-100 kW/m^2. Higher heat flux ignition has been less-well studied, and the majority of scientific data come from similarly scaled experiments mostly on flat surfaces. High heat flux ignition is less well studied because it has a more limited application space given that fewer fire scenarios involve high (> 200 kW/m^2) fluxes. We have been performing experimental investigations of the behavior of a variety of materials exposed to concentrated solar power with peak flux in excess of 2 MW/m^2. Dozens of materials at a variety of flux conditions with varying scales and configurations have been tested thus far. While we have found good correlation in our new data to historical data and model constructs, some of our data are not well predicted by existing models and correlations. Present results suggest ignition on flat materials is not necessarily a good predictor of other materials and configurations, and that future testing would benefit from an increased emphasis on the geometry of exposed materials.

KEYWORDS: Ignition, High Heat Flux

INTRODUCTION

Ignition from an incident radiative flux is well characterized for many materials under flux conditions typical of conventional hydrocarbon fires (25-100 kW/m^2). Standards such as ASTM E1740-15 and ASTM E1354 govern this type of testing. We are focused on ignitions and fire behavior from much higher fluxes (100-10,000,000 kW/m^2), which may be obtained from metal fires, propellants, lightning, directed energy, space exploration, etc.

Historical data on ignition from high heat fluxes are not as plentiful. Notable compilations of data in this flux regime include Glasstone and Dolan (1977) [1] and Martin and collaborators [2-3]. Glasstone and Dolan correlated ignition for a variety of materials to the yield and distance from a nuclear weapon, a construct that is not particularly useful in other applications. Martin et al. represented their ignition data in terms of scaled flux and fluence, a more useful construct for extensibility. The Martin datasets are dominated by cellulose paper data and exposure areas of around 10 cm^2, the primary focus of their efforts. They found various behavioral regimes characterized by different parameters. At low fluxes, the sample thickness and imposed energy were most significant. At higher fluxes, the incident energy was the dominant parameter. At even higher fluxes, the imposed energy and the flux magnitude had comparable significance. Different types of ignition were observed (glowing, sustained flaming, transient flaming). Transient flaming was defined by flaming that occurred only as the heat flux was incident on the object. Sustained flaming lasted beyond the exposure.

We have been adding to the body of work on high-heat flux ignition by testing materials under high flux (> 200 kW/m^2) conditions using concentrated solar energy. Work began with a focus on flat materials with an objective to reach-back to the majority of the historical data [2-3], but has included enough geometric variation to begin to deduce the important role geometry has in the ignition

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behavior. Our prior reporting of this work illustrates the significant role of scale in the fire behavior [4], a new approach to the ignition and damage threshold modelling [5], and the effect of wind and gas phase radiation attenuation on the fire response of materials [6].

Evaluations of the recent data suggest an additional significant feature of the materials that appears to affect the outcome of the event. The shape of the samples appears to affect the resultant ignition behavior. The effect of shape is not systematically studied in any of the historical datasets, and consequently is ignored in prior models and inferences derived therefrom. More complex shapes may tend to more easily ignite and sustain ignition. This paper examines the evidence for this statement in the context of the recent concentrated solar ignition tests. The purpose and value of this paper is in the identification of the important role that shape has on the propensity for sustained ignition from high heat flux events. The objective is to help motivate an increased exploration of the shape as an important factor leading to high heat flux ignition to better characterize a broader range of material response.

METHODS

The National Solar Thermal Test Facility at Sandia National Labs in Albuquerque has two main facilities that concentrate solar energy. One is the Solar Tower, that uses a heliostat field (an array of large mirrors with fine motor control that actively track the sun to maintain a relatively constant target location for the rays) to achieve a concentration factor greater than 2000 suns (1 sun is approximately 1 kW/m^2), and a power of 6 MW at length scales of 0.3-1 m. The other is the smaller Solar Furnace that uses a single heliostat and a parabolic dish for smaller length scale testing (5-7 cm). Several hundred high flux ignition tests have been conducted at these facilities including varying material types, thicknesses and shapes, while also varying flux, fluence, length-scale, wind, and ambient temperature.

Tests were conducted in test phases. A Solar Furnace test phase involved approximately 50 test shots, while the solar tower test phase involved about 30 shots. The test matrix for each test was determined by a panel of researchers. Materials were selected from a list of relevant materials. Test and environment conditions were controlled as well as could reasonably be done for the facilities available. Test objectives were manifold, so the test programs were not apparently targeted in their approach to specific objectives. Rather, a wide variety of materials and test conditions were employed with the outcome of the tests being the identification of prospective subsequent tests to explore interesting observations from prior test phases. The three main objectives were:

1. To produce quality datasets with sufficient repeatability to employ for validating 3D computational models of fire and related phenomena.
2. To explore environmental factors with the intent of reach-back to historical datasets to understand material dynamics under various conditions.
3. To explore practical or unique ignitions that are under-represented in the body of historical testing.

Tests were split roughly evenly between the above three objective areas. The reason for testing in phases while incorporating multiple objectives is because of the uncertainties in funding cycles and the desire to have broad impact rather than narrowly focused program results. A negative consequence of this method is that it may take multiple test phases to achieve sufficient data to quantitatively resolve phenomenology from the tests. An advantage of the method is that a targeted assessment is made after each phase of testing, and the subsequent plans are formulated after gaining insight from the results from prior phases.

For this analysis, the test results are grouped by cellulosic and polymeric sources. Cellulosic materials include cellulose, papers, biomass (plant materials), and cotton fabrics. Polymeric sources include polyethylene, polystyrene, synthetic rubber, polymethyl-methacrylate (PMMA), polypropylene, vinyl and other petroleum product polymers. L-shaped samples consisted of two chairs, photographs of which are shown in Fig. 1. A polypropylene patio chair and a wood/foam/fabric office chair were used. Chairs were oriented differently during the tests, polypropylene chairs were upright with the back of the seat back exposed to the flux, and the fabric chairs were on their side with the front of the seat back in direct exposure.

Fig. 1. Pre-test photographs of the polypropylene (left) and wood/foam/fabric chairs (right).

Instrumentation

A variety of instrumentation was deployed for the tests, the details of which may be found in the test series documentation. For this paper, highlights of the instrumentation are outlined only. Details on the instrumentation are available in the corresponding test phase documentation [3-6]. Each test included the following:

1. Flux measurements to confirm the imposed thermal environment, and characterization of the day, time, and configuration of the flux source
2. Multiple angle fiducially accurate video imagery from standard, high-speed, and filtered optical cameras
3. Atmospheric data from a weather station to confirm the ambient conditions
4. Pre- and post-test photography
5. A temporal fiducial to allow post-test synchronization of instrumentation results from various sources
6. Controls output containing data on the temporal sequence for each test

Tests mostly included:

7. Pre- and post-test weight of samples

Some tests included:

8. Strategically mounted thermocouples for temperature measurements
9. IR camera imagery for thermal response
10. Witness strings as local air flow indicators

11. Post-test 3D scanning for digital re-construction of the thermal crater

Ignition and burn times are key to the analysis presented in this paper. These were deduced through post-test analysis of the video imagery. Ignition was often discernable through the observed flames in the video output. In some tests, the pyrolysis gases obscured direct views of the ignition. The ignition event usually included a rapid increase in the motion of the pyrolysis gases, in which case the flames were not directly observed but inferred based on the motion of the opaque gases and the presence of flaming later in the video.

Characterization of Environment

Tests were conducted within a few hours of solar noon on clear (cloudless) days. The environment was characterized using pre- and post-test analysis of heat flux instrumentation to verify the test conditions. Because of the response time of the test facility hardware, the imposed flux was a ramp to a constant hold, and a ramp back down to ambient.

Fluence (defined as flux integrated with time) magnitude was a target condition, which explains the regularity of intervals in some of the fluence data. Fluence targets were usually round numbers, however post-analysis sometimes adjusted these away from the target values. For this paper, exposures are simplified to a fluence condition.

Tests were conducted at different times of the year in an outdoor environment. Ambient temperatures for two Solar Furnace test series conducted in July/August were 20-35ºC. The second Solar Furnace phase was conducted in February/March, and mid-day ambient temperatures were between 5-25ºC. The Solar Tower tests were conducted from August-November, and ambient temperatures varied between 10-30ºC. Post-processing of the data has not suggested a significant effect of the initial ambient temperature on any resultant parameters over the range of variation.

RESULTS AND DISCUSSION

We grouped materials in a few categories for this analysis. The first main grouping is by material type. Cellulosic materials (plant matter, paper, wood, fabrics, etc.) are grouped, as cellulose constitutes a significant fraction of these materials. Synthetic polymers are also grouped. The second grouping consists of the shape of the test objects. Flat objects are primarily surfaces exposed to the flux, and represent the traditional way of assessing ignition at high heat flux. A few of the samples consisted of significant L-shapes, and these are termed L-shaped materials. Some materials were round (tires and trash cans). They differ from the flat materials because there were no significant flat surfaces, and the curves were the dominant shape of the exposed surfaces. These are termed circular. Irregular shapes are generally biomass materials that are characterized by high surface area compared to the volume.

The test series involved more tests than are exhibited here. Tests omitted include ones that defied characterization by the shape parameters (flat, circular, L and irregular), those that did not fit the material type categorization, as well as those that did not achieve flaming ignition.

Combining the duration of burn results with the fluence imposed on the samples, a picture emerges suggesting a significant role that shape plays in the duration of burn. For convenience in plotting, burn durations greater than 1000 seconds have been truncated to 1000, and durations below 1 second have been increased to 1. While this is not a hard rule, it turns out that tests that involved transient flaming all are below 10 s burn time, and the sustained flaming tests all fall at or above 10 seconds. Figure 2 shows a plot of cellulosic materials on the fluence/burn duration plot. There is a very clear stratification between the data by shape. The few L-shaped tests show generally higher burn durations than other tests. The irregular shaped objects tend to have higher burn durations. The flat materials exhibit generally lower burn durations. There were no ‘circular’ samples for the cellulosic materials.

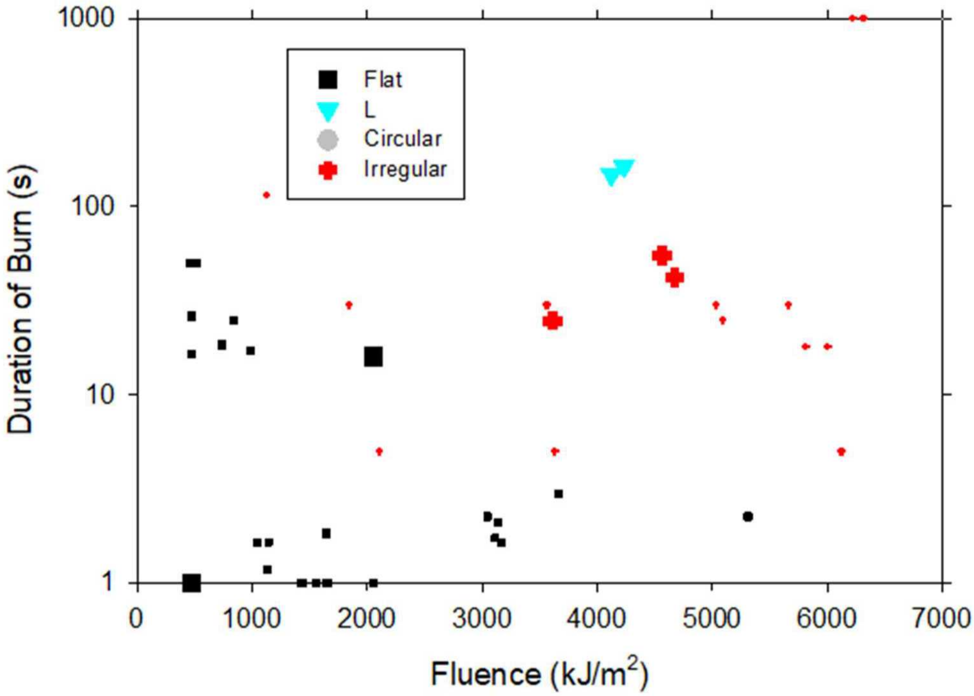

Fig. 2. Duration of burn versus fluence for cellulosic samples. Solar Tower experiments are differentiated from Solar Furnace tests, having larger data points in the plot.

Because the tests were not systematically varied specifically for this parameterization, there is a need to interpret the meaning of these results in the context of a more representative evaluation including the other variabilities. The flat materials generally did not result in sustained burning. The general exception to this is flat materials that were sufficiently thin that the imposed radiant energy pyrolyzed the sample completely through. Figure 3 illustrates some sustained ignition of thin materials fitting the just described behavioral description. The fire was initially (post-exposure) localized to edges on the sample, typically a circular ring at the center of the sample. Thicker samples pyrolyzed, but would not sustain flaming if they ignited. The flat materials that sustained flaming were all sufficiently thin to burn in this manner. It is not a particular surprise to see the irregular shaped materials generally exhibiting longer burn times. When burning solid materials, the surface area to volume is widely recognized to be a very significant parameter. The three irregular samples that fall below 10 s burn duration were a mix of green and dry needles. The green needles alone did not ignite, and the dry needles alone generally burned profusely. The large-scale (Solar Tower) and some of the small-scale tests were green plant materials. The trees at the Solar Tower were cut within 30 minutes of their exposure, and were well watered. Even with the high moisture content that normally is expected to inhibit flaming, the irregular materials appear to result in much greater burn times than was typical of the flat samples. This suggests a more significant effect of shape as compared to moisture.

Fig. 3. Two thin rectangular Solar Furnace samples exhibiting sustained flaming at/within the rim of the hole. The left figure is a walnut veneer at 3.5 seconds, and the right figure is black polystyrene at 3.5 seconds.

A similar plot of burn duration versus fluence for the synthetic polymer samples is shown in Fig. 4. These data lacked samples that could be considered 'irregular', however included a number of samples that could be considered circular. The response of flat synthetic polymer samples was observed to be similar to that of cellulosics in that the tests tended to produce transient flaming results unless the samples were thin and holes were formed in the material at the center of the exposure. The L-shaped chairs exhibited the longest flaming, and this was surprising. The same polypropylene chair seats had been cut and tested at the Solar Furnace as flat panels at higher fluxes. They did not ignite, even with a higher flux/fluence condition. The differing ignition/non-ignition behavior was not particularly surprising, as PMMA flat panels behaved similarly with scale changes. What was surprising was that the flaming was sustained for a very long time without the immediate burn-through that seemed to be the contributing factor for flat materials to exhibit sustained burning. There were multiple L-shapes on the polypropylene chairs. The seat/back formed L's. But the legs and seat also had smaller L-shaped structural members. It was at these that flaming was sustained. The chair back melted and sloughed during the exposure and was not able to maintain the L-shape through to the end of the exposure. The seat was made of thicker and more rigid material, and was oriented less orthogonal to the incident flux. The seat and legs remained mostly rigid during the test (one leg burned through long after the exposure).

The circular materials were only tested at the Solar Tower, and resulted in transient flaming, consistent with flat surfaces. There was postulation ahead of the testing that the trash can with a circular cavity might augment ignition and burn prospects due to the ability of the material to retain more energy by radiating within the cavity. The tests did not suggest that this was a significant effect. The circular materials generally agreed with the flat materials in terms of burn duration.

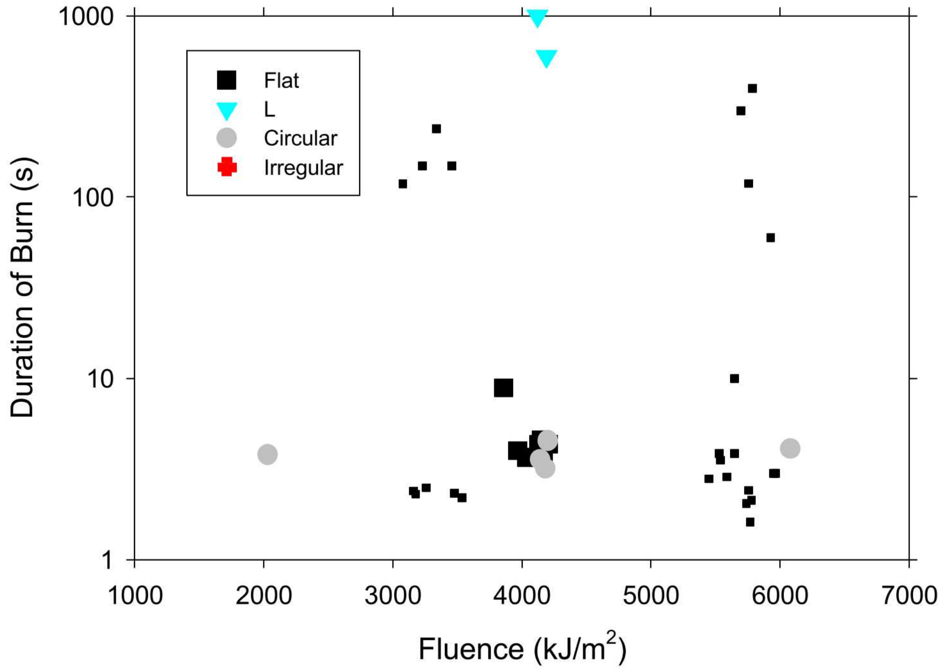

Fig. 4. Duration of burn versus fluence for synthetic polymer samples. Solar Tower experiments are differentiated from Solar Furnace tests, having larger data points in the plot.

Because the burn duration relates to the size of the samples in the sense that full burn-out limits the potential for longer burn durations, there is a desire to filter the data to differentiate on this effect. It is also desirable to differentiate the comparatively thick samples that classically are only ignite the transient mode. The normalization of the fluence is done by Martin et al. by the heat capacity of the material. The resultant parameter is not fully non-dimensionalized, as the scaled parameter retains units of temperature. Martin et al. found for cellulose that sustained flaming was generally attained when the scaled fluence was greater than 1000 K. Below 1000 K there was either no flaming or transient flaming depending on the magnitude of the scaled flux. The relation for the scaled fluence is:

$$Scaled\ Fluence = \frac{\alpha q''}{\rho C_P L} \tag{1}$$

Here α is the absorptivity, q'' is the imposed fluence (J-m^{-2}), ρ is the bulk material density (kg-m^{-3}), Cp is the specific heat of the solid (J-kg^{-1}-K^{-1}), and L is the characteristic length (m), which is the primary thickness of the samples. Thermal properties were estimated from measurements (typically density, absorptivity, fluence, and thickness) and common literature sources (specific heat and select others), and are expected to be accurate to within at least 10%. This accuracy is believed adequate for the purposes of this analysis.

We re-cast the burn duration data in terms of the scaled fluence in Figs. 5 and 6. The cellulosic materials in Fig. 5 show a reasonably consistent trend with the expected transition to sustained flaming above 1000 K. Some transient flaming is observed for materials with higher scaled fluence than 1000 K. These flat materials were mostly the wood veneers. The irregular materials that fit this category included the mix of dry and green needles. Transient flaming below 100 K scaled fluence were a stack of 50 copy paper pages, and ignited because the scaled flux was relatively high. Some sustained flaming was observed for samples with lower scaled fluence than 1000 K. This included most notably the solar tower fabric test. The L-shaped chairs had noticeably high burn duration compared to other samples at the same scaled flux, but were in a regime where ignition was not unexpected.

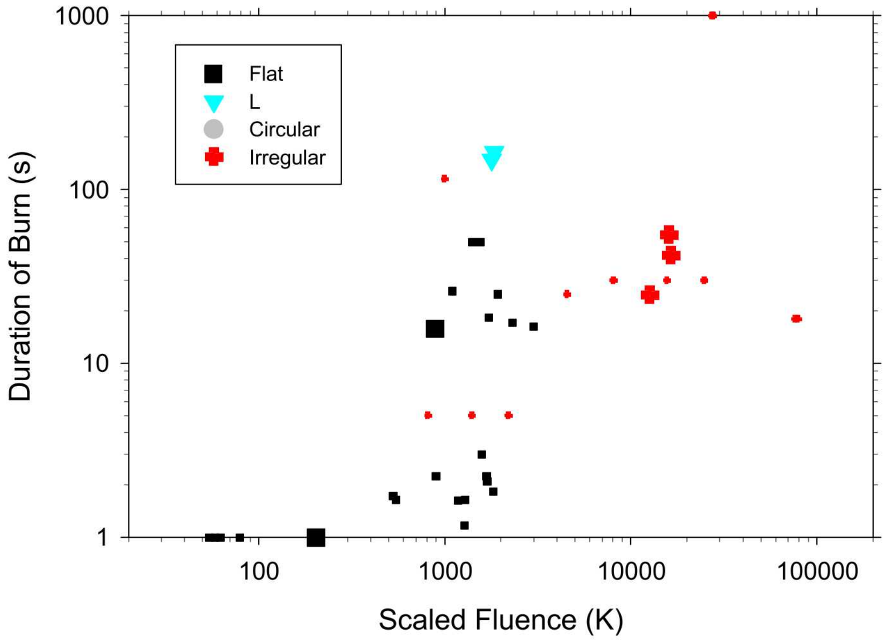

Fig. 5. Duration of burn versus scaled fluence for cellulosic samples. Solar Tower experiments are differentiated from Solar Furnace tests, having larger data points in the plot.

Even though Martin et al. imply that scaled fluence ignition thresholds for different materials might be different, we have generally found the cellulose scaled ignition data to roughly coincide with the data from the common polymer samples we have been testing thus far. The synthetic polymer data in Fig. 6 might also be expected to transition between transient and sustained flaming at about 1000 K on the scaled fluence axis. The L shaped polypropylene chairs are a notable exception. They are moderately below the threshold, yet exhibited the greatest burn duration. This is added evidence for the significance of the L-shape to the ignition and burn duration. A cluster of flat materials had scaled fluence around 2000 K but did not sustain ignition. These are solid vinyl and thicker polystyrene samples. The circular samples that did not sustain ignition all fall below 1000 K, suggesting that they were not necessarily expected to. All flat samples that sustained ignition had scaled fluence above 1000 K. These were mostly burn-through scenarios involving comparatively thin materials.

GENERAL DISCUSSION

The results presented herein point to a significant effect of the shape parameter on the burn duration and on the ignition of a variety of materials. The fact that what we have called irregular shaped materials are more prone to longer burn durations is not a particularly surprising or novel conclusion. The basis for this expectation is in conventional fire starting where kindling is often used to initiate larger fires. The surface area compared to the volume is augmented, reducing the thermal sink and augmenting the fraction of energy that results in pyrolysis. One would assume the same behavior and sensitivity might be applicable to high flux conditions as well. The more significant finding is that the chairs that have been characterized as L-shaped are significantly more prone to ignition and sustained burning. The mechanism differentiating L-shaped and flat materials is likely quite different than that between the irregular and flat materials. From a surface area to volume ratio perspective, the L-shaped materials are much more closely related to the flat materials than the irregular materials. L-shaped materials may have two different features that contribute to augmenting the propensity for fire. First, they have the ability of the surfaces to emit or reflect radiation from one to the other, a feature not available to flat surfaces. Second, they create a different flow pattern for the product gases and will interact differently with ambient winds.

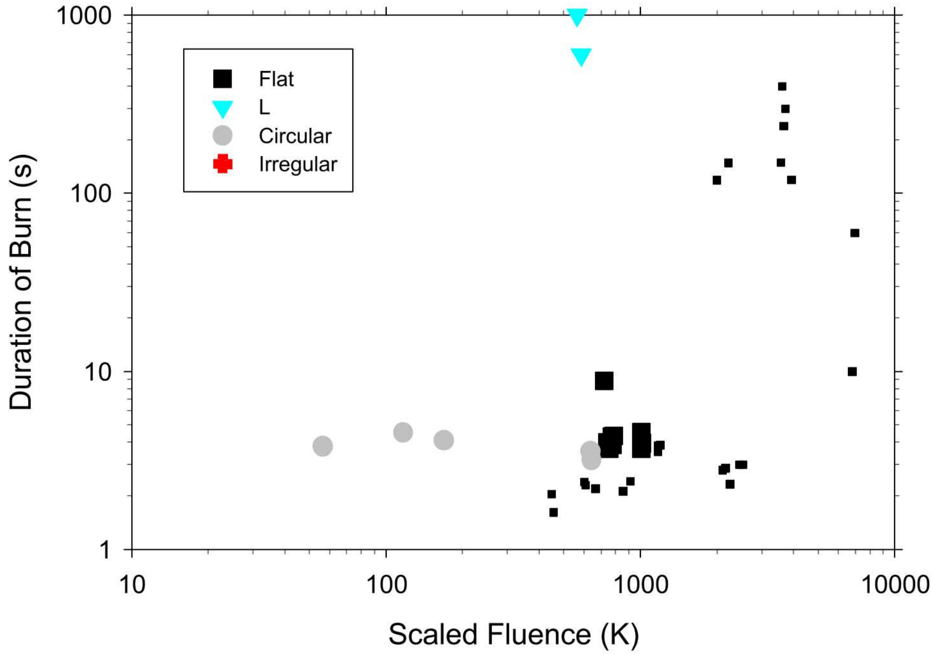

Fig. 6. Duration of burn versus fluence for synthetic polymer samples. Solar Tower experiments are differentiated from Solar Furnace tests, having larger data points in the plot.

Prior to testing these materials, the radiation (first) mechanism was anticipated to be the dominant mechanism that might augment the prospects of burning and ignition. Imposed radiative flux from the concentrated solar panels at these high flux conditions is expected to dwarf any reasonably expected convective heat flux. Post-test, there is reason to attribute greater relative significance to the convective (second) mechanism. Fig. 7 shows images from two chair fire tests. The polypropylene chair illustrated had sustained burning on one of the two symmetrically similar chair legs. Because the radiation flux was relatively symmetric as well, we conjecture that the wind direction was the contributing factor to the continuing burn. The fabric chairs exhibited significant vortical motion in the volume between the seat and seat back. This is best observed in the video results, but the image showing the narrow elongated plume from the chair fire helps illustrate presence of significant vortical flow originating at the fire. The fact that circular geometries with cavities did not sustain ignition also lends to the argument, but the cavity also has the effect of limiting oxygen while the L-shape provides better exhaust pathways for product gases.

There was a noticeable edge effect for flat samples when they experienced burn-through that appears to relate significantly to the sustainability of the fire. Because high flux ignitions involve large energy input, the majority of the historical tests were either similar to the Solar Furnace tests where the samples were much larger than the exposure, or had a mask that eliminated edge effects. This may not be representative of many fire scenarios of interest, in which case there may be reason in the future to examine offset ignitions on samples that contain pre-existing edges in the exposure. On larger-scaled tests, the flames often would originate or be obviously influenced by the sample edges.

Fig. 7. Post-exposure flaming of the polypropylene chair (left) and the fabric chair (right)

CONCLUSIONS

Major findings of this study of ignition from high incident heat fluxes include:

- Sustained ignition appears to be augmented for L-shaped and irregular geometries. Two different chairs exhibited long-term sustained burning in the solar tower tests with long-term flames localized to the internal cavity regions and edges. Irregular shapes like plant material (needles, trees, shrubs, grasses) also exhibited prolonged sustained burning.
- Circular geometries (tires and plastic trash cans) were not as prone to sustained ignition as irregular and L-shaped geometries.
- Flat geometries are more heavily tested historically, but may be poorly representative of more practical (complex) geometries with respect to sustained ignition.
- Flat geometries tend not to exhibit sustained ignition unless they develop (via burn-through) or include exposed irradiated edges.

We consequently recommend increasing the experimental focus on non-planar samples and samples with edges in subsequent testing to better capture the ignitability of a broader range of materials and configurations.

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