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Preliminary Field Burns of RV Trailers with External Ignitions

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NIST TN 2292

Preliminary Field Burns of RV Trailers with External Ignitions

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Cover Photo
RV trailer burn #2 near peak heat release rate, approximately 17:37 (mm:ss) after ignition.

Abstract

Two recreational vehicle (RV) travel trailers were burned outdoors at the Austin Fire Department training campus in Austin, TX. The goal of these preliminary experiments was to observe and document the burning behavior of fully furnished RV trailers and to assess the feasibility of future instrumented burns in the National Fire Research Laboratory. Burning parcel-level combustibles can produce significant thermal exposures to surrounding combustibles, often leading to fire spread beyond the object of origin. In wildland-urban interface (WUI) fires, this scenario often perpetuates fire spread leading to destruction further into a community. For these field burns, the RV trailers were ignited from the exterior, representing a WUI fire scenario where a parcel-level combustible ignites and becomes an exposure source, producing an enhanced fire spread pathway to other nearby combustibles or primary structures. The RV trailers were 6.7 m (22 ft) long and were equipped with basic factory-installed furnishings. Videos of the burns were recorded from multiple angles to document visual observations of fire behavior and flame lengths. The primary burning period of each trailer ranged from 13 min to 17 min. Maximum flame lengths were approximately 10 m (30 ft). Observations from the field burns present some concerns about the size of the fire for potential indoor laboratory study. The burns were conducted in collaboration with the Austin Fire Department, U.S. Fire Administration, Federal Emergency Management Agency, and U.S. Consumer Product Safety Commission staff.

Keywords

disaster resilience; fire; hazard mitigation; recreational vehicle; travel trailer; vehicle fire; wildland-urban interface; WUI

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1. Introduction

Recreational vehicles (RVs) are a popular form of accommodation for camping, vacation, and travel. RVs come in a wide range of types and sizes, from small pop-up campers to large fifth-wheel trailers, and converted vans to coach bus-sized motorhomes. According to industry data, an average of nearly 480 000 new RV units were shipped annually in the U.S. between 2016 and 2022 [1]. The overwhelming majority, 90 %, were towable non-self-propelled units. RVs gained tremendous popularity in recent years, particularly since the start of the COVID-19 pandemic [2, 3]. In uses other than recreation, they may be inhabited more permanently as fixed residences or as temporary housing to support disaster relief, for example. They are also increasingly used as accommodations by those who cannot afford traditional fixed housing [4, 5].

Except for times when they are being transported, RVs are often occupied, parked, or stored in the vicinity of other combustibles or structures. In the event an RV catches fire, the radiative and convective exposures and potential firebrands can quickly spread fire to nearby fuels. The large fire exposures and enhanced fire spread pathway introduced by burning RVs presents a significant hazard, especially in the context of wildland-urban interface (WUI) fires. Post-fire research and observations of large WUI fires [6, 7] have identified that various parcel-level combustibles can increase the risk of fire spread on a parcel and throughout the greater community. RVs are one example of a parcel-level combustible that can generate significant fire exposures once ignited. The relatively lower ignition resistance of RV trailers compared to fire-hardened structures can introduce a large fuel package susceptible to ignition by firebrands or exterior flame contact. Once ignited, the resulting fire can then spread to a nearby structure that may have otherwise resisted ignition from the initial lower-intensity exposure [8].

In addition to WUI fires, an in-depth analysis of fire incident data submitted to the National Fire Incident Reporting System (NFIRS) shows an annual average of 5840 RV fires from 2008 to 2017 [9]. Data show that 33 % of fires were classified as structure fires (a 10-year average of 1920), with the remainder classified as vehicle fires.[1] External ignitions occur independent of WUI fires, as well. From the NFIRS data study [9], on average, 9 % of the documented RV fires had a reported area of origin on the exterior of the vehicle.[2] Similarly, the reported item first ignited included exterior components or surroundings 13 % of the time.[3] In 10 % of fires, exposures generated from another nearby fire were identified as a contributing factor, further demonstrating the exterior ignitability of RVs.

A brief review of incident data compiled by the U.S. Consumer Product Safety Commission (CPSC) identified common causes and outcomes of RV fires. Within the past 5 years (2019–2023), data indicate that space heaters were a common cause of ignition from inside RVs, starting 30 % of the incidents recorded in the database. The cause was unknown in 20 % of incidents. Unfortunately, fatalities are common, occurring in 25 % of the reported RV fire

[1] Data analysis differentiated between fires in RVs used as structures (NFIRS incident type code *122* – motor home, camper, or RV when used as a structure) and fires in RVs used as vehicles (NFIRS incident type codes *136* – self-propelled motor home when being used in transport mode, and *137* – non-self-propelled RV, including trailers, except when on blocks or used regularly as a fixed building).
[2] Categories including exterior surface of vehicle; exterior wall surface; and lawn, field, or open area.
[3] Categories including exterior wall covering or finish; tire; light vegetation; and exterior roof covering or finish.

incidents. See Appendix A for a description of the CPSC data, and Appendix B for brief examples of three incidents.

Whether an RV fire occurs as an external ignition such as a WUI fire (current study) or residential-type interior fire (potential future study), either on a residential parcel or in a campground or storage yard, burning RVs can produce hazardous fire exposures to surrounding combustibles and nearby structures. Even in non-WUI fire incidents, a search of relevant news stories yields hundreds of reports of RV fires that spread to nearby combustibles. A query of NFIRS data from 2002–2020, using the methods described by McNamara and Mell [10], identified 4119 exposure fire events including 5857 individual RV fire incidents.[4] An RV was the initial source exposure in at least 2330 of these incidents. Therefore, identification and quantification of the burning behavior are desired to develop guidance to mitigate the fire exposure hazards. The most straightforward and immediate solution is to provide appropriate spacing between parcel-level combustibles [8].

To better quantify the hazard of RV trailers and establish guidance for mitigation, there is interest among researchers and the fire service in measuring the heat release rate (HRR), flame exposures, and smoke products from burning RVs. This data would support guidance for safe separation distances between a parked RV trailer and a primary residential structure, or between RVs parked at a campground, for example, in order to limit fire spread.

With that goal in mind, two RV travel trailers were burned outdoors at the Austin Fire Department training campus to obtain preliminary observations of fire behavior. The burns were conducted to establish expectations for potential in-depth laboratory measurement and characterization of such fuels. The objective of these preliminary burns was to observe the fire behavior and assess the feasibility of further testing and measurements, including the potential for burns to be conducted indoors within NIST's National Fire Research Laboratory (NFRL). Initial concerns for burning the RVs inside the NFRL included safety of staff and exposure to the facility from aspects including:

1. the intensity and growth rate of the fire,
2. flame lengths,
3. smoke yield,
4. runoff/flow of melting components, and
5. residual debris removal.

[4] Exposure fires involving RVs were identified using NFIRS incident type codes 122, 136, and 137 (defined in footnote 1). A single exposure fire event may be comprised of multiple incidents if the fire spread to multiple targets.

2. Burn Configuration

The following sections describe the RV trailers, the burn site location, and burn procedure.

2.1. RV Trailer Specifications

The RVs were single-axle travel trailers with approximate overall dimensions of 6.7 m (22 ft) long, 2.4 m (8 ft) wide, and 3 m (10 ft) tall. The length of the cabin was 5.6 m (18.5 ft). The cabin was outfitted with stock manufacturer furniture, including a queen-sized bed in the front sleeping area and a twin-sized bunk in the driver's side rear. Foam pad mattresses (12 cm thick) were included. A kitchenette and booth-style dinette in the center of the cabin consisted of a table and two sofa benches with vinyl upholstery. Several cabinets made from wood-composites lined the interior walls. A bathroom in the passenger-side rear included a plastic toilet and shower. Flooring consisted of a plywood base with a vinyl covering. The cabin exterior was aluminum siding, and windows were tempered glass. No additional fuels typically found in RVs were added, such as clothing, bedding, or personal items. An exterior view of the trailer and a schematic of the interior configuration are shown in Fig. 1. Photos of the trailer interior are shown in Fig. 2.

The listed unloaded vehicle weight (UVW) was 1560 kg (3440 lb) with a gross vehicle weight rating (GVWR) of 2018 kg (4450 lb). The actual weight of each trailer was not measured, although is expected to be less than the UVW due to removal of several components for safety reasons. Hazardous materials and components including the refrigerator, propane tanks, pneumatic awning, batteries, cook top, and fire extinguisher were removed prior to the burns to comply with the requirements of NFPA 1403 (Standard on Live Fire Training Evolutions) and Austin Fire Department training procedures.

Throughout this report, the right side of the trailer refers to the side with the entry door, or the right side in the direction of travel (passenger side). The front of the trailer has the towing hitch.

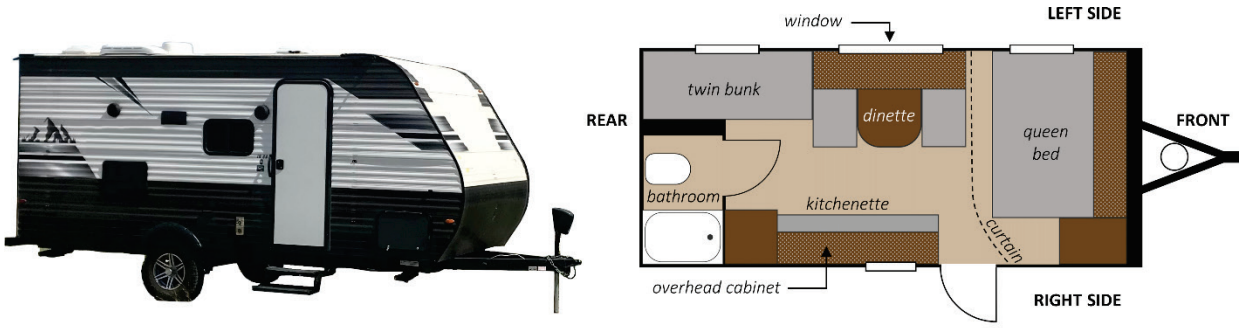


Fig. 1. Configuration of the RV trailers: a) photograph of the exterior of the trailer, b) diagram of interior layout.



Fig. 2. Photos of the cabin interior highlighting the following components: a) dinette, b) queen mattress, c) kitchenette, d) twin bunk, e) closet and cabinetry, f) vinyl flooring.

2.2. Burn Facility

The burns were conducted at the Austin Fire Department (AFD) training campus in Austin, TX. Figure 3 shows the overall configuration of the facility and the location of nearby structures and roads, the RV trailers, cameras, weather station, and observation area.

The burn site was a relatively flat grassy area surrounded on three sides by concrete roadways. A concrete-block constructed burn training building was located on the east side of the burn area, approximately 12 m (40 ft) from the RVs. Across the street on the west side, a portable classroom building, comparable to a mobile home, was located approximately 21 m (69 ft) away. A metal semi-truck trailer was parked north of the classroom building. While the positions of both RV trailers are indicated in Fig. 3, the second trailer was not moved into

position until after the first trailer was burned. Camera locations were static, as indicated by the blue circles, except for the west position which was modified for each burn according to the number shown (cameras were moved from position 1 to position 2). The dedicated observation area was 30 m (100 ft) from the trailers.

See Fig. 4 for a photograph of the site.

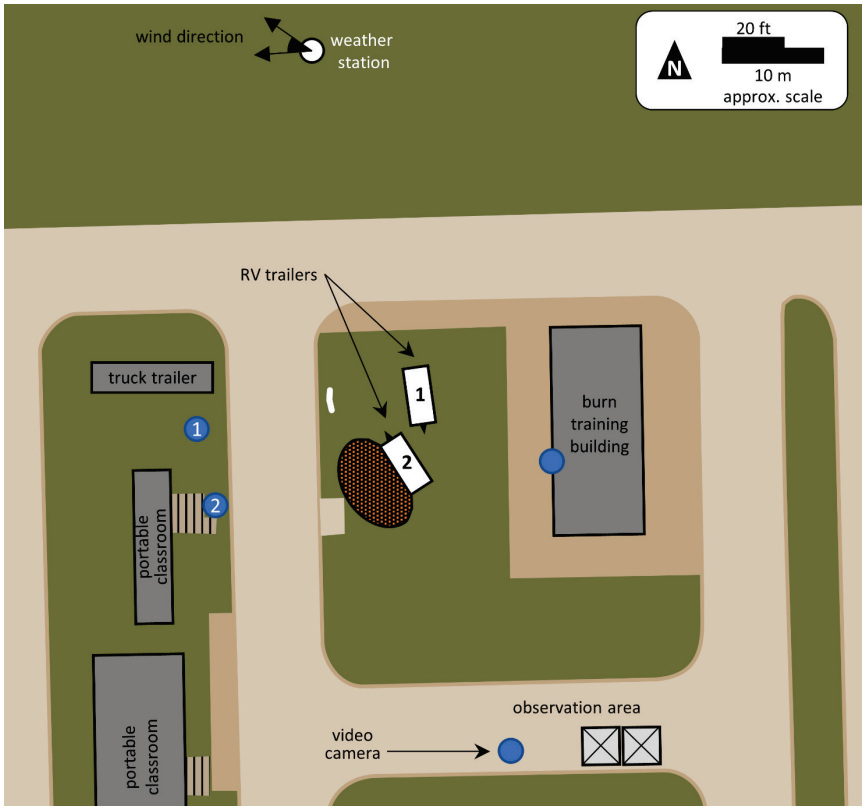


Fig. 3. Schematic of the AFD training facility showing the position of the trailers and the surrounding buildings, cameras, and observation area. The west cameras were repositioned for the second burn, as numbered.



Fig. 4. Photo of the site prior to the first burn showing the configuration and the layout of the nearby burn training building (right) and portable classroom building (left). View to the north.

2.3. Equipment

The burns were recorded using video cameras placed on tripods at the locations indicated by the blue circles in Fig. 3. Cameras at the west location were repositioned for the second burn to obtain a better viewing angle of the side of the RV, indicated by the numbers. Standard consumer-grade HD cameras were used at each location. Two modified 4K cameras were also utilized at the east and west locations. These cameras were converted to full spectrum sensitivity through removal of internal filters. External infrared filters were used to block wavelengths below 720 nm, resulting in images of near-infrared emissions that enhance visibility of flames and firebrands. Photos and videos were also recorded from the observation area using cellphone cameras.

Wind speed and direction, temperature, and relative humidity were recorded at a weather station located 40 m (130 ft) north of the burn site. Additional observations were obtained [11] from the Austin-Bergstrom International Airport (KAUS) weather station located 2.53 km (1.57 mi) east-southeast from the burn site.

2.4. Burn Procedure

Hazardous materials and components with potential to explode were removed from the trailers prior to the burns. Removed items included the refrigerator,[5] propane tank(s), pneumatic awning, batteries, cook top, and fire extinguisher. Caps to the water storage tanks were also removed; both tanks were empty. Tires were deflated prior to ignition for the first trailer.

AFD conducted a safety briefing for all personnel before the burns. Trailers were positioned and burned one at a time. After each trailer was positioned, cameras were adjusted for the desired

[5] The pressurized cooling unit contained hydrogen, ammonia, and sodium chromate.

viewing angle, zoom, and focus. NIST staff started camera recordings and returned to the designated viewing area prior to ignition.

The exterior ignition source consisted of a steel pan (approximately 50 cm × 30 cm × 15 cm) filled with a section of dry hay bale doused with between 1 L and 2 L of diesel fuel. The pan was positioned underneath the trailer at the desired ignition location. More specific descriptions are provided for each burn in Sec. 3.2 and 3.3, as ignition locations were different. Once all personnel were ready, firefighters ignited the hay/diesel using a propane torch.

The goal of the experiments was to observe the entire burning evolution of the RVs; however, firefighters were ready to suppress the fire at any time. Two fire engines were on site and hose lines were pre-deployed. Firefighters monitored exposures to the nearby buildings, watched for potential spot fires, and confirmed the smoke plume was not endangering traffic on the nearby public roadway just outside of the training campus. Flames were extinguished after the RV had burned down into a debris pile and the fire was in the decay phase.

When given the all-clear from the firefighters, staff returned to the cameras to stop recording. The second trailer was towed into place and cameras were adjusted as necessary before igniting the second burn.

Once post-fire photos and documentation were complete, the trailers and debris were cleaned up and disposed by a third-party contractor.

3. Burn Observations

The following sections describe the weather conditions and visual observations from the two burns.

3.1. Weather

Weather was generally overcast to mostly cloudy during the burns, with a steady temperature of 23 °C (73 °F). Relative humidity was above 90 % after it rained earlier in the morning. Heavy rain fell between 5:00 AM and 7:15 AM, stopping about 80 min before the first burn was ignited at 8:38 AM. Total rainfall reported at the airport (KAUS) was 1.6 cm (0.64 in). During the burns, winds were less than 4 m/s (9 mi/h) out of the east-southeast. The range of wind directions is indicated by the arrows at the weather station point at the top of Fig. 3.

The graph in Fig. 5 shows the time history of wind speed and direction recorded at the burn site (black lines) and at the airport (red lines). The time period of each burn is highlighted by the white background. Given their proximity, wind conditions were similar at both locations. Wind gusts measured at the burn site were comparable to the constant wind speeds measured at the airport and may be more representative of the true wind speed value at the burn site. Data values are listed in Table C-1 and Table C-2 in Appendix C.

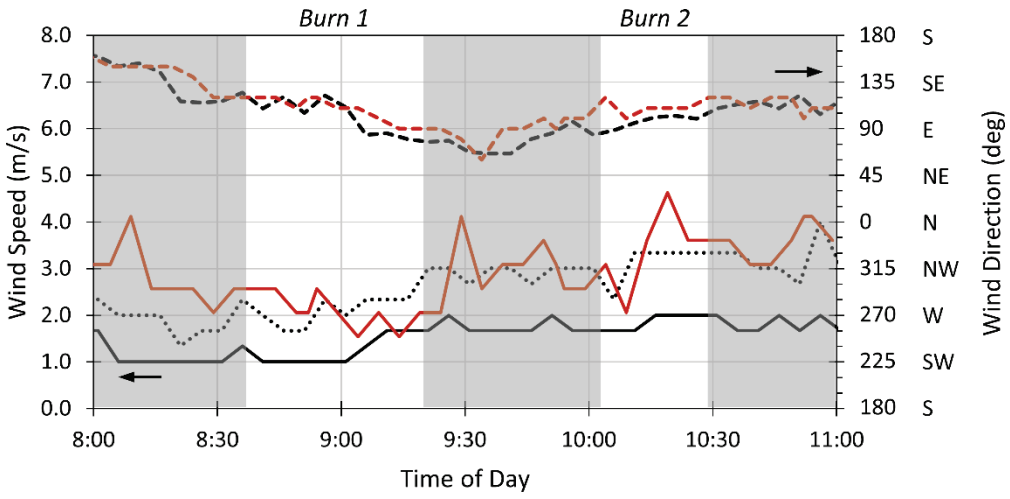


Fig. 5. Time history of observed wind speed and direction. The solid lines and dotted line represent wind speed and gusts, respectively (left axis). The upper dashed lines are wind direction (right axis). Black lines plot data recorded at the burn site. Red lines plot data from the airport. (1 m/s = 2.2 mi/h)

3.2. RV Trailer Burn 1

The first trailer was ignited from underneath, approximately 0.3 m (1 ft) in front of the left (driver side) wheel, shown in Fig. 6. The pan was placed on top of large rocks to raise the pan about 20 cm (7 in) off the ground to ensure flames would be in contact with the underside of the trailer.

Within 20 s, localized intermittent molten dripping was observed immediately above the ignition area. By 60 s, the dripping was constant and became a steady flow by 1 min 45 s (1:45) after ignition. The interior smoke alarm first sounded at 2:45 following ignition. Low-intensity flames and slow fire spread occurred for an extended period. At the 10:00 mark, the primary fuel burning still appeared to be only the underside corrugated plastic liner and was characterized by relatively short flame lengths (< 10 cm). The flames had spread approximately 1 m (3.6 ft) radially from the point of ignition. No flames were evident on the interior. Smoke output remained light.

There was no visible change in fire behavior during the first 16 min. Between 16:00 and 17:00 there was a noticeable increase in smoke production. Visible flames were still limited to the underside. By this time, flames had spread laterally along the axle and were near the right (passenger side) wheel.

By 18:00, more significant fire spread at the rear of the trailer near the water tank drains was observed, and the start of intense burning occurred approximately 19:00 after ignition. This was characterized by significant production of black smoke and rapid intensification of flames. Within one minute (20:00 after ignition), flames were extending from underneath the rear of the trailer and up the sidewall. At 21:45, flames were extending from the rear of the trailer and the right rear behind the axle, with flame lengths of 3 m (10 ft) reaching the top of the trailer. The front third of the trailer was still not involved. The fire appeared to intensify once the water storage tanks ignited and the bathroom area of the trailer became involved. The fire then spread to the rear bunks, and then forward into the dinette and queen bed areas.

The peak heat release rate appeared to occur between 29:00 and 32:00 based on qualitative observation of flame lengths, intensity, and coverage. This corresponds to between 10 min and 12 min after the fire took hold following the prolonged initial ignition period. A photograph of this period is shown in Fig. 7.

The cabin walls collapsed after 34:00, and the fire decayed as fuel was mostly consumed by this time. Suppression began after 43:00. The remains of the trailer are seen in Fig. 8, consisting of mostly non-combustible materials.

Table 1 includes a timeline of the observations along with the time after ignition. Due to the drawn-out ignition period compared to the second burn, an additional column indicating the time elapsed since the main fire activity began 19:00 after ignition is included to provide more relevant comparisons.

Winds remained light for the duration of the burn, approximately 2 m/s (4 mi/h) or less. No significant impact of wind was noted.

Additional photos of the burn progression are provided in Appendix D.



Fig. 6. Ignition of the first trailer was just in front of the left-side wheel.



Fig. 7. Burn 1 at 31:56 after ignition, near the time of presumptive peak heat release rate.



Fig. 8. Post-fire remains of the first trailer consisting primarily of the steel frame.

Table 1. Burn 1 summary timeline. Time 1 represents elapsed time after ignition. Time 2 represents elapsed time after the start of intense burning after transition beyond the underside of the trailer.

Time 1 (mm:ss)	Time 2 (mm:ss)	Observation
00:00	—	Ignition.
00:55	—	Molten dripping from underside.
01:10	—	Constant flow of melted burning underside liner.
02:45	—	Interior smoke alarm heard.
10:00	—	Continued low intensity fire spread along underside liner; melting and dripping.
17:00	—	Increase in smoke output.
19:00	00:00	Start of intense burning. Rolling black smoke. Intensifying flames on rear underside.
20:00	01:00	Gray smoke begins emitting from rear roof vent above bunks.
21:00	02:00	Flames wrap around the underside and intermittently reach halfway up the left rear exterior.
21:14	02:14	Persistent flame contact along the rear of the trailer.
21:21	02:21	Flames begin to wrap around onto the right rear wall.
21:45	02:45	Flames extend 3 m from the ground to the top of the trailer in the rear and right rear.
22:00	03:00	Flames at right rear extend 1 m out from the side of the trailer and 3.5 m (12 ft) high from the ground all the way up the wall.
22:00	03:00	Tires begin burning and a plume of dark gray smoke builds from underneath.
22:40	03:40	Flames are visible from the vents on the right-side wall. The right rear is fully involved.
24:30	05:30	White smoke begins flowing from front roof vent.
24:45	05:45	Overall flame lengths have reduced, but the rear and rear right exterior surfaces are burning. Flames extend 1 m outward to the sides and above the trailer.
25:00	06:00	The edge of the right rear roof ignites, producing intense flames up to 2.4 m (8 ft) long.
25:15	06:15	Smoke begins leaking from the seams of the left rear upper bunk window and from around the main door.
25:35	06:35	The exterior fire on the right rear intensifies and appears that the wall has opened up and the bathroom area interior is fully involved.
26:00	07:00	Smoke from the bunk window intensifies.
26:30	07:30	Radiation was noticeable from the observation area 30 m (100 ft) away from the trailer.
26:50	07:50	Smoke production from the main roof vent intensifies.
27:00	08:00	Smoke begins leaking from the dinette and queen bed windows.
27:17	08:17	Flames begin jetting out from the main roof vent reaching 2.7 m (9 ft) long.
27:52	08:52	Flames exit around the frame of the upper bunk window.
28:43	09:43	Flames appear from the top of the door.
29:06	10:06	The lower bunk window shatters and flames jet out.
30:27	11:27	The upper bunk window falls out. The aluminum siding begins burning through.

Time 1 (mm:ss)	Time 2 (mm:ss)	Observation
30:45	11:45	Fire burns through the door, and flames jet out.
31:20	12:20	Flames begin leaking out from the large dinette window.
31:30	12:30	One pane of the dinette window fails. Peak burning activity has progressed to the middle of the trailer as the rear fuel burns up.
31:55	12:55	Flames extend 2.7 m (9 ft) out from the doorway and up above the trailer.
32:00	13:00	Second pane of the dinette window melts.
32:26	13:26	Flames begin leaking from the queen bed window.
33:30	14:30	The rear half of the trailer is essentially all burned away.
33:40	14:40	One pane of the queen bed window melts.
34:12	15:12	The remainder of the queen bed window falls out.
34:15	15:15	Flames burn through the front exterior wall.
34:19	15:19	The right rear wall collapses.
35:00	16:00	Most of the burning is in the remaining front third of the trailer.
37:21	18:21	The left wall collapses.
38:00	19:00	The trailer is essentially a burning pile of debris. Flame lengths have reduced to 1 m.
43:28	24:28	Suppression begins.
47:20	28:20	Flames are extinguished.
62:00	43:00	A reignition in the debris pile was noticed and suppressed.

3.3. RV Trailer Burn 2

Based on the observations of the burning behavior from the first trailer, a different ignition location was used in the second burn with the goal of faster fire growth. The second trailer was also ignited from underneath; however, the pan was moved behind the axle near the center of the trailer, approximately 1 m (3 ft) from the rear.

Compared to the first trailer, the fire burned with higher intensity from the start. Sustained flaming began in the first two minutes, but the melt dripping was much faster than the first trailer. This led to enhanced fire growth, and within three minutes flames were wrapping from underneath and reaching up the rear left wall. Smoke from the interior began venting by 4:30, although the interior smoke alarm was not heard during the second burn.

The left tire ignited at 8:40 and contributed significantly to the fire growth; within 90 s the entire left rear wall was in contact with flames. Between 12:00 and 13:00 the left rear wall was intensely flaming. Intermittent views through the flames showed the wall had burned through and the interior was fully involved. Flames began jetting from the roof vent at 14:38.

The period of presumptive peak heat release rate began approximately 15:00 after ignition and lasted for approximately four minutes. The fire spread through the interior, and the main door burst into flames at 15:50. The right-side kitchenette window burst shortly after. The fire was past its peak by 19:00 and the trailer collapsed into a debris pile at 24:01. Table 2 provides a summary timeline of the second burn. Additional photos are included in Appendix D.

The wind during the second burn was slightly stronger and was perceived to increase during the burn. Measurements show an increase from 2 m/s to 4 m/s (4.5 mi/h to 9 mi/h), plotted in Fig. 5. The orientation of the trailer to the wind direction and the intense flaming on the rear corner of the lee side resulted in formation of large counter-rotating vortices downstream of the trailer visible between 13:50 and 17:30. The left vortex was a massive flame. Camera angles did not provide the best direct side view of the vortices, although the views were sufficient to estimate flame lengths extending 6 m to 8 m (20 ft to 26 ft) and ranging from 2.4 m to 3.6 m (8 ft to 12 ft) measured radially outward from the side of the trailer. Fig. 9 shows the view from the rear of the trailer at 14:20 after ignition with estimated flame lengths of 6 m (20 ft).

An additional difference of the second burn was that the tires were not deflated prior to the burn. The left tire ignited at 8:40 and ruptured at 10:40. A 2 m (6.5 ft) jetting flame was created while the tire deflated. The right tire ignited at approximately 11:29 and ruptured at 15:28. Neither tire exploded nor created any noticeable debris, although the trailer tilted with the different wheel heights (seen in Fig. 9) until the second tire deflated.



Fig. 9. Flame lengths exceeding 6 m (20 ft) were observed as a vortex formed on the left rear corner of the trailer, seen here approximately 14:20 after ignition.

The combination of wind direction, flame length, and radiation intensity on the left side of the trailer led firefighters to address exposures to nearby buildings. At 18:23, water was sprayed onto the surface of the nearby portable classroom building (22 m [75 ft] away from the trailer) to mitigate the thermal exposure. Firefighters reported the surface temperature had reached 52 °C (125 °F) when measured with an infrared thermometer.

Overall, a significantly larger number of debris and visible firebrands were produced during the second burn. This appeared to be primarily due to a perceived increase in fire intensity and occasional spalling or popping of materials during the burn. The slightly higher wind speed may have also contributed; however, the rear wall of the trailer remained intact during the burn, so the wind was largely blocked from directly fanning the base of the flames. No systematic survey or tracking of firebrands was conducted, although larger pieces included fabric-like materials and delaminated layers of plywood. Due to the force of the suppression stream, additional generation and transport of burned pieces makes interpretation of the scattered firebrands observed around the trailer after the burn unreliable.

An extensive area of grass burned along the left side of the trailer. The burned patch extended 5.5 m (18 ft) from the trailer and was 9.5 m (31 ft) long. The burned area is illustrated in Fig. 3 by the large black oval shape, and can be seen in the post-fire photo in Fig. 11.



Fig. 10. The second trailer approximately 16:40 after ignition, near the time of presumed peak heat release rate. This photo shows flame lengths extending radially 3 m (10 ft) from the left side and 2 m (6.5 ft) from the right side.



Fig. 11. Post-fire remains of the second trailer and the extent of the burned grassy area.

Table 2. Burn 2 summary timeline.

Time (mm:ss)	Observation
00:00	Ignition followed by dripping, burning melt from the underside.
01:10	Sustained flaming of underside is apparent; flame lengths 20 cm.
02:45	Flames begin wrapping around the left rear and up the wall.
04:30	It becomes apparent that smoke is coming from the rear roof vent.
08:40	Left tire ignites and flames intensify.
09:12	Steady flames reach halfway up the left wall and intermittently reach the top (3 m [10 ft]).
10:00	Flames are steady 3 m (10 ft) long, extending up the left rear wall.
10:18	Flames appear at the edge of the main dinette window.
10:40	Left tire ruptures. Flames jet 2 m (6.5 ft) out the side. Main flame lengths are 3.6 m (12 ft). The exterior wall ignites.
10:45	The flame intensity below the trailer increases and flames wrap around the right underside.
11:29	Large flames (2 m [6.5 ft]) jet out from underneath the right side. Right tire ignites seconds later.
11:39	Rear half of dinette window falls out.
12:00	Intermittent views through the flames show the left wall is burned through in the area above the wheel and the interior is fully involved.
12:30	Smoke begins venting from kitchenette vents (right side) and gaps around the main door.
12:55	The lower bunk window falls out.
13:15	The entire rear half of the left wall is intensely flaming.
13:50	A massive flame vortex forms off the left rear. Flame lengths exceed 6 m (20 ft).
14:06	The remaining dinette window falls out.
14:38	Flames jet from the front rooftop vent.
15:28	The right tire ruptures.
15:50	The exterior of the main door bursts into flames.
15:56	Half of the kitchenette window shatters. The remainder shatters 15 s later.
16:22	Flames appear around the edge of the queen bed window.
17:09	Heavy black smoke transitions to large flames from the rear bathroom roof vent.
17:22	Flames burn through the entire front wall almost simultaneously.
17:45	Half of the window above the queen bed melts open. The rest falls outward.
18:12	A gust of wind from the rear was noted in the field.
18:23	Firefighters spray water to protect the portable classroom building from radiative exposure.
19:20	Holes begin burning through the aluminum exterior on the right-side rear.
20:40	The remaining portion of the left front wall collapses.
24:01	The entire trailer collapses completely into a pile of debris. Flame lengths are reduced to 1 m. Suppression begins at 26:19.

3.4. Discussion

Overall, there was a significant difference in burning behavior between the two RV trailer burns. Table 3 provides a comparison of the timing and duration of different burning phases of the two trailers. Most noticeable was the difference in the ignition and fire growth period, where the first burn took 19 min to begin to spread beyond the underside of the trailer, compared to only 3 min in the second burn. Based on the observations during the first burn, the slower fire growth rate may have been primarily related to the ignition location. The pan was placed by the wheel near the steel frame of the trailer which may have acted as a heat sink and an area of lower fuel quantity. The cabin of the RV appeared to ignite after increased melting occurred underneath behind the axle near the plastic water storage tanks. This increased the fire intensity on the exterior, which then spread inside. It was hypothesized that an ignition in that area may lead to a shorter fire growth period, and the ignition location was adjusted for the second burn.

Table 3. Burn comparison overview.

	Burn 1			Burn 2		
Burn Phase	**Qualitative Intensity[A]**	**Time Period (min)**	**Duration (min)**	**Qualitative Intensity[A]**	**Time Period (min)**	**Duration (min)**
Underside ignition and slow growth	L	0 – 19	19	L	0 – 3	3
Transition from underside to structure	M	19 – 22	3	L	3 – 9	6
Intensification	M-H	22 – 29	7	M-H	9 – 14	5
Period of highest heat release rate	H	29 – 33	4	H	14 – 19	5
Post-peak burning	M	33 – 36	3	H-M	19 – 22	3
Decay to lower intensity rubble fire	L	36 – 40	4	L	22 – 24	2
Primary burning period		19 – 36	17		9 – 22	13

[A] Qualitative intensity is characterized relatively as low (L), moderate (M), or high (H). M-H and H-M indicate transitions in intensity within the identified period.

In addition to a much shorter period of underside ignition and slow fire growth compared to the first burn, the second trailer burned 4 min faster, taking only 75 % of the duration of the first burn. Once the structure of the cabin began burning, the first trailer burned progressively from the rear toward the front. However, the second trailer ignited more along the side and the tire, causing the middle and rear thirds of the trailer to burn at the same time. This difference in fire progression also accounts for the difference in burning duration, resulting in more extensive flames and higher heat release rate.

A second factor contributing to the increase in fire intensity may have been the higher wind speeds during the second burn. While still relatively light, up to 4 m/s (9 mi/h), particularly in the context of wind-driven fires and many catastrophic wildland/WUI fires, the increased wind was perceived in the field and is evident in the lean and dispersion of the flames and smoke plume and the development of the vortex flames. While a gust of wind was noted at 18:12 and

persisted through the end of the second burn, no significant change in fire behavior was discernable in the video recording. This may be because the RV was near the end of the period of peak heat release rate, or because the rear wall of the RV cabin was still intact and deflected much of the wind from the base of the flames.

A rough estimate of an average heat release rate (HRR) can be calculated using assumptions of total mass, heat of combustion, and burning time. A modification of the basic heat release rate equation $\dot{Q} = \Delta H_c \, \dot{m}$, using a heat of combustion ΔH_c and a mass loss rate $\dot{m}$, can be written as

$$\dot{Q} = \Delta H_c \, \beta \left(\frac{\alpha m_t}{t_b} \right) \quad (1)$$

where m_t is the total mass of the trailer, α is the mass fraction of the trailer that is combustible, and β is the fraction of the trailer that burned in time t_b. Estimates of these values, along with an estimated Type B uncertainty [12] for propagation of errors, are listed in Table 4.

Table 4. Estimated values and uncertainties for calculation of average heat release rate.

Parameter	Estimated Value	Estimated Uncertainty (±)
heat of combustion, ΔH_c	25 kJ/g	10 kJ/g
combustible mass fraction, α	0.8	0.1
fraction of combustibles burned, β	0.8	0.1
total mass of trailer, m_t	1500 kg	50 kg
burn duration, t_b	17 min, 13 min	2 min

The total mass of the trailer was obtained from the factory unloaded vehicle weight, and the assumption is that 80 % ±10 % of the mass was of combustible materials. Further, it was estimated that 80 % ±10 % of the combustible mass was burned within the burn duration, t_b. Materials within the trailers span a range of heats of combustion, from polyvinyl chloride (PVC) (16.9 kJ/g) and wood (18 kJ/g) to polyethylene (43.6 kJ/g) [13]. Based on these values, an effective heat of combustion was chosen as 25 kJ/g ±10 kJ/g. The result is an estimated average HRR of 24 MW ±11 MW for Burn 1, and 31 MW ±14 MW for Burn 2. This does not represent the peak HRR, which could be significantly higher depending on the fire progression. As expected, the uncertainty stems largely from the unknown effective heat of combustion of the trailers. However, this estimate provides context for discussion. The range in uncertainty highlights the value that a more detailed measurement would provide the fire science community.

Limited fire testing of modern vehicles has been conducted, with no measurement documentation found for RVs or RV travel trailers. Past measurements of heat release rates from vehicle burns conducted in the late 1990s into the 2000s have been compiled by Mohd Tohir and Spearpoint [14]. Data span a wide range of values, generally between 2 MW and 9 MW. Differences in ignition location, passenger compartment ventilation (i.e., windows), amount of fuel, and vehicle model all contribute to the variability. Li and Ingason [15] also present an overview of vehicle fires in the context of design fires for tunnels, including burns of

passenger cars, buses, heavy goods vehicle (HGV) trailers, and train carriages; however, many are loaded with cargo or were burned in tunnels, and are not directly comparable to this current work. Reference [15] presents a table of generalized values for vehicle fire heat release rates, which are also included in the explanatory materials in the appendix of NFPA 502 (Standard for Road Tunnels, Bridges, and Other Limited Access Highways) [16]. Examples include typical peak heat release rates for passenger car fires (5 MW to 10 MW), bus fires (25 MW to 34 MW), and HGV fires (20 MW to 200 MW). While the size, shape, construction, and materials of the current RV trailers are rather different from passenger vehicles and buses, the estimated range of heat release rate for the current work is in a reasonable range compared with the existing data.

While the change in ignition location between the two burns likely had a significant influence on the fire progression, this exterior ignition method only represents one controlled approach. Depending on the characteristics of the parking location, an exterior ignition could occur from a larger area of fire underneath the trailer (e.g., grass or other vegetation/debris), radiant or convective heat exposure to the walls from another large fire, or via firebrands landing in various locations. Aside from WUI fires, interior ignition of RV trailers is very common and may lead to more rapid fire spread since ignition of the primary fuels is not delayed by the exterior structure of the trailer. Different scenarios may lead to a range of fire progression and heat release rates.

Flame lengths of 8 m (26 ft) were observed during the second burn. In moderate to high density residential communities or in storage configurations, such flame lengths may easily extend to nearby structures. In wind-driven WUI fires, the burning intensity could increase and flame lengths could be stretched further.

3.5. Impact of Preliminary Findings

These preliminary burns confirm the potential hazard of RV fires. The large flame lengths of 8 m (26 ft) have implications in several contexts, including the spacing of trailers in RV parks and storage sites, post-disaster housing applications, and the positioning of RVs near other parcel-level combustibles and structures, particularly in high-density communities.

In relation to hazard mitigation within communities, these burns, and the numerous cases of RV fires spreading to nearby combustibles, suggest a need for implementation of best practices or regulations for the spacing and location of RVs in WUI communities, particularly in moderate and high-density communities where the consequence of such a large fire exposure can accelerate and propagate fire spread deeper into a community. Note that in many communities, existing spacing between homes is not sufficient to prevent fire spread from parcel to parcel when RVs or other combustibles that yield large flames are also present.

In more rural locations, the spacing guidance will still add value through reduction of collateral losses in the event of RV fires, during WUI fires or otherwise.

4. Considerations for Future Work

The overall observations of burning behavior, intensity, flame lengths, smoke yield, and debris provided insight for potential future burns. The variability and uncertainty of the estimated heat release rate suggests there would be value added to conduct future experiments under a calorimeter. Accompanying measurement of mass loss rate would allow the determination of an effective heat of combustion in conjunction with calorimetry measurements and would provide valuable information to fire protection engineers and support development and validation of fire modeling. In the absence of continuous mass loss rate, a mass measurement before and after burning would enable a refinement to the current heat release rate estimate. Quantitative measurements of thermal exposures to target structures via heat flux gauges would also provide information to support mitigation efforts.

However, the overall size of the fire as tested is a potential limitation for these experiments to be conducted indoors at the NFRL. For context, Fig. 12 shows a schematic of the NFRL laboratory space overlaid on top of the current experimental configuration. One potential path forward is to reduce the size of the trailer, although the exposures generated from a smaller class of trailers may not adequately represent the hazards presented by larger trailers or RVs. To alleviate concerns of structural damage, experiments could be conducted outdoors. This adds additional complications, particularly for large scale mass loss measurements in the presence of ambient wind and uneven ground, although these challenges might be overcome.

Outdoor experiments to measure heat release rate and smoke characteristics will be similarly challenging with any ambient wind, and calorimetry may be impossible. However, smoke characterization may be achievable with an adjustable and agile collection or sampling system that can be actively moved to the necessary location within the plume during the burn.

Each burn was accompanied by the initial melting of the corrugated plastic underlining and water storage tanks. This was observed as molten plastic dripping and flowing onto the ground. The uneven and porous nature of the dirt/gravel/grass ground covering prevented significant runoff and spread of the resulting pool fire. However, if burns are to be conducted in a lab setting, this behavior would need to be accounted for in the procedures.

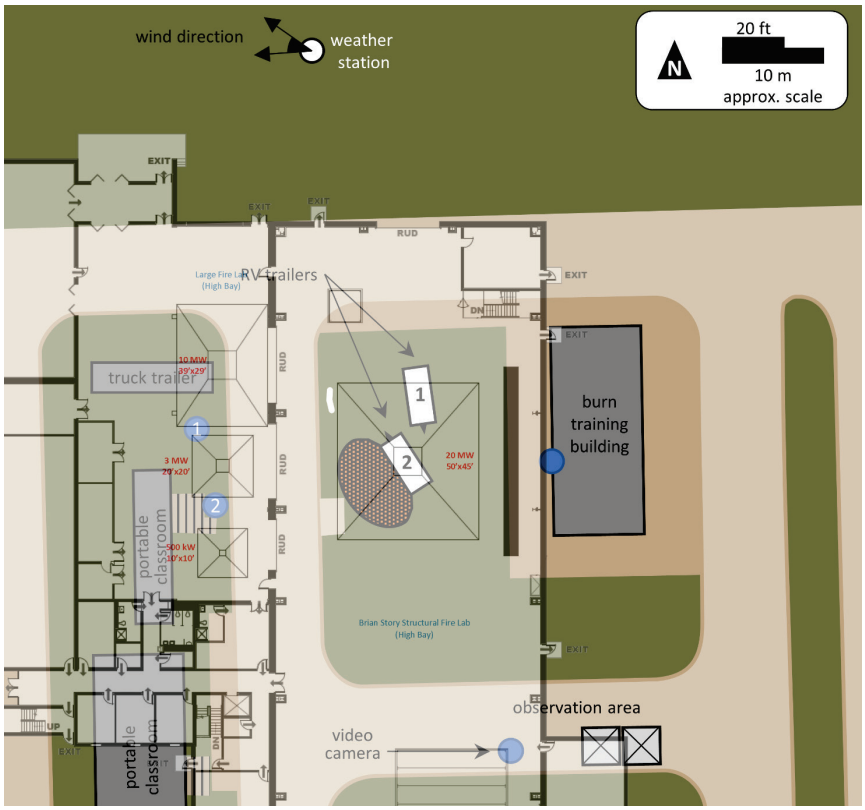


Fig. 12. Schematic of the NFRL laboratory space overlaid on burn configuration at AFD.

5. Summary

Two RV trailers (22 ft, single-axle models) were burned in an outdoor setting with an external ignition to resemble an ignition in a WUI fire. A wide range of burning intensity and fire behavior was observed between the two trailers, likely due to the difference in the ignition location. One trailer was characterized by an extended initial fire growth period, followed by a sequential burning of the trailer as fire progressed from the rear to the front. The bulk of the trailer burned within a period of 17 min. The second trailer ignited quicker, with approximately two-thirds of the trailer burning at the same time. This resulted in a shorter and more intense burning duration of approximately 13 min. Maximum flame lengths of 8 m (26 ft) were observed, with flames reaching 3.6 m (12 ft) radially out from the side of the trailer. Based on the burning duration and total mass, a basic estimate of heat release rate was calculated to be nominally 30 MW. These preliminary burns illustrate the potential hazard of radiation and flame contact that RV fires pose to surrounding combustibles, with implications for safe separation distances in WUI communities and other storage/parking applications. Further experiments and measurements would yield useful information for fire protection engineers and the fire service.

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Appendix A. RV Fire Incidence

Cursory analysis of fire incidence data from the U.S. Consumer Product Safety Commission (CPSC) show that RV trailer fires occurring independent of WUI fires are relatively common. Nearly 150 incidents between 2019 and 2023 were recorded in the CPSC databases, with 25 % of incidents resulting in civilian fatalities.[6] CPSC monitors fire incidents using two databases, the National Electronic Injury Surveillance System (NEISS) and the Consumer Product Safety Risk Management System (CPSRMS).

In 2000, CPSC, in partnership with the Centers for Disease Control (CDC), expanded NEISS into an all-injury system. The scope of NEISS was increased from a system collecting only consumer product related injury data to one that collects all injury data from first visits to hospital emergency departments regardless of product involvement, injury intent, or occurrence at work. The National Fire Incident Reporting System (NFIRS) collected by the U.S. Fire Administration collects information from fire departments regarding residential fires that they respond to. This can include products outside the jurisdiction of CPSC.

The Consumer Product Safety Risk Management System (CPSRMS), or CPSC 360, is an incident database maintained by the CPSC since 2011. It also contains anecdotal incident data involving consumer product-related incidents from older CPSC databases going back to the 1970s. The data comes from consumer complaints, news clips, medical examiner reports, compliance reports, retailer reporting, federal/state/local government referrals, in-depth investigations (IDIs), and more. The CPSC 360 database is a convenience sample and cannot be used to produce estimates, but it does provide detailed information about consumer product-related incidents, some of which include injuries or deaths.

Preliminary examination of the above databases indicate that the RV trailer fires often start from propane tank explosions, unattended cooking, and electrical fires from space heaters, overloaded extension cords, or generator malfunctions. Also common are fires starting from overheated heat tapes or embers from wood stoves. There are also several accounts of RV trailers catching fire at the gas station.

Typically, once a fire starts in an RV trailer, the trailer is quickly engulfed into flames and the entire structure is destroyed within minutes, often before firefighters arrive at the scene. Fire spread in the trailer is significantly faster when the ignition source is inside the trailer as opposed to an ignition source outside the trailer. This is primarily due to the high density of combustible materials in the trailer. The lightweight construction materials and furnishings of the RV trailers are flammable and have relatively high heats of combustion. For example, the lightweight wood-plastic composite materials commonly used to construct the cabinets in the trailers are highly flammable and have higher heats of combustion compared to solid wood.

CPSC incidence reports also indicate that a fire is likely to spread from the burning trailer to the adjacent combustible fuels including vegetation, homes, and parked vehicles. Civilian fatalities due to injuries sustained from RV trailer fires are also common.

[6] Disclaimer: CPSC does not guarantee the accuracy, completeness, or adequacy of the contents of the publicly available Consumer Product Safety Information Database on SaferProducts.gov, particularly with respect to information submitted by sources outside of CPSC.

Appendix B. RV Fire Examples

The following descriptions summarize three RV fire incidents that occurred near Austin, TX within the past three years. The three incidents span a range of possible scenarios and outcomes, including an RV trailer fire with no resulting exposure fire, and two fires that spread to nearby structures, with one incident resulting in a fatality. Information is included here with permission of Travis County Fire Rescue.

The first example is from an RV fire that occurred near Austin in Bastrop, TX in 2022. It was classified as a vehicle fire, NFIRS incident type code *137 – camper or RV fire*. The RV trailer involved was a large toy hauler trailer approximately 12.8 m (42 ft) in length. The back portion of the trailer was a cargo room holding a motorcycle. The trailer was located approximately 5 m (17 ft) from the corner of the primary residence. Figure B-1 shows a post-fire view of the configuration, while Fig. B-2 shows a pre-fire overview of the nearby parcels and structures.

In this incident, the trailer ignited from the interior. According to the fire department report, fire engines arrived 6 min after the alarm. On arrival, half of the trailer was on fire and the surrounding grass and vegetation was igniting. Firefighters attacked the fire and provided exposure protection to the nearby primary structure which was located approximately 5 m (17 ft) away, as seen in Fig. B-1. Mitigating factors in this exposure include the position of the trailer aligned corner-to-corner with the nearby structure rather than parallel to the wall, non-combustible brick exterior walls, and quick suppression actions. Despite the quick actions by firefighters, the amount of damage to the trailer shows how quickly the fire spread.



Fig. B-1. Aerial view of the burned toy hauler RV trailer.

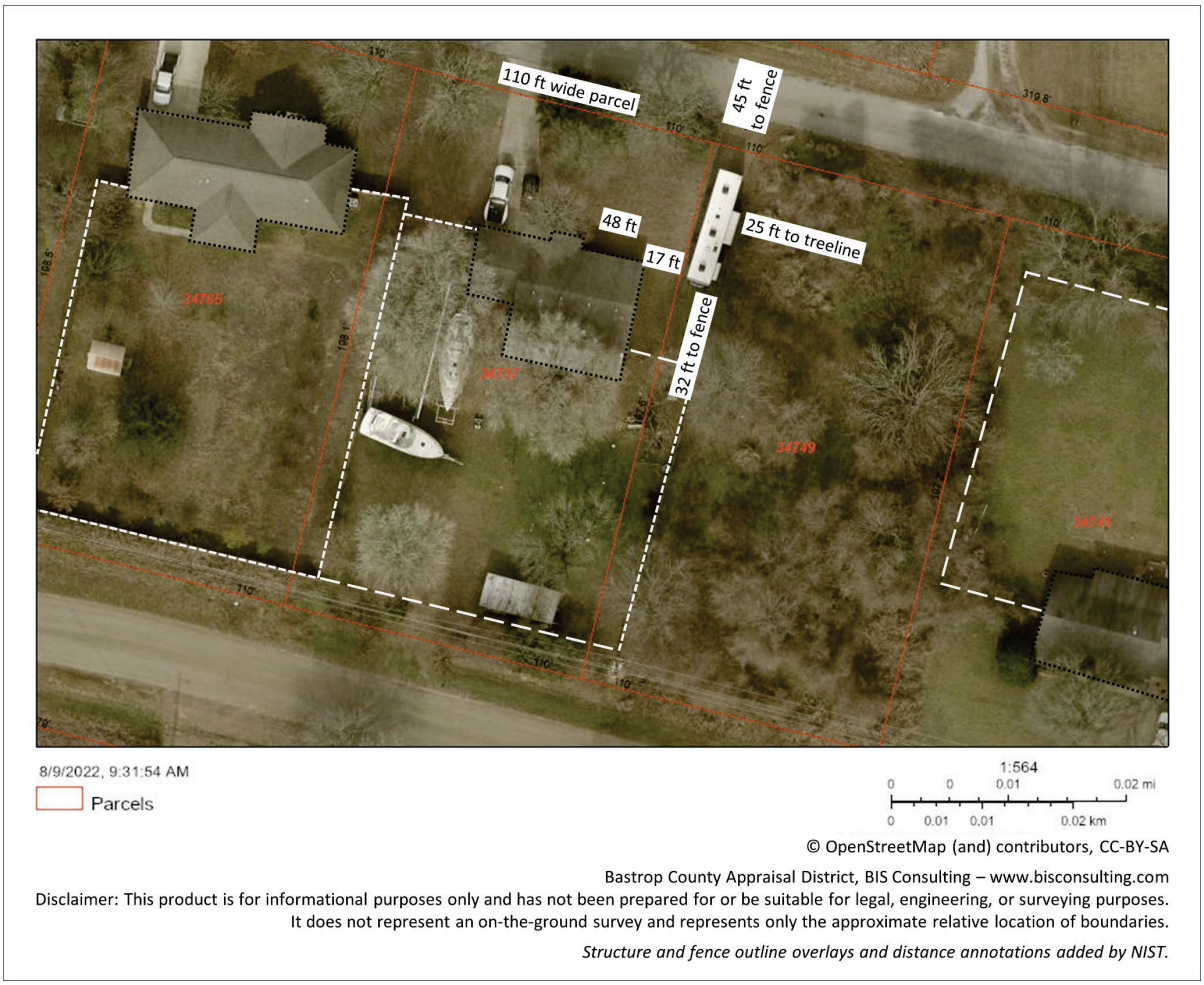


Fig. B-2. Aerial imagery showing the RV and surrounding parcels, vegetation, structures, and other objects.

In another example, a fire initially starting in an RV extended to a nearby mobile home. When the fire engine arrived, they found two RVs on fire threatening the mobile home. Firefighters began attacking the RV fire and protecting the exposure. After the main fire was extinguished, hot spots were observed on the mobile home and the trim and exterior paneling was removed to uncover a charred and glowing wall. The hot spots were extinguished, and the primary structure was saved. In this incident, the combination of exposure intensity and spacing between the trailer and mobile home resulted in the ignition of the neighboring structure, while the suppression action prevented additional losses. No additional specifics about the spacing or construction were available.

The final incident in this case review is a fire that started in an RV trailer and spread to a mobile home, subsequently resulting in a fatality and several injuries. An additional fifth-wheel trailer was parked on another side of the mobile home but did not ignite from the exposure of the mobile home fire. Specifics of the incident progression and the timing of firefighter suppression actions were not available to know if the fifth-wheel trailer was protected from the exposure. The mobile home was constructed of wooden studs with metal exterior siding and roof. Post-fire images show the frame of the RV trailer positioned parallel to the mobile home approximately 3 m (10 ft) away. The images in Fig. B-3, provided by Travis County Fire Rescue, show the destroyed mobile home after the fire. The remaining debris of the trailer is seen in the foreground with similar fuel consumption and appearance to the current burns.



a) b)

Fig. B-3. The mobile home and debris after the fire: a) the RV trailer was located in the white circle, b) the trailer frame is visible to the right of the image about 3 m (10 ft) away from the mobile home. Photos courtesy of Travis County Fire Rescue; circled annotations by NIST.

These three examples highlight different exposure scenarios from burning RV trailers and the influence of spatial configuration, structure construction, and fire suppression and defensive actions. The exposure fires generated by parcel-level fuels, such as RV trailers, introduce ignition hazards and increase the risk of fire spread through a parcel to nearby structures. In the context of WUI fires, when suppression resources are often outpaced by the number of ignitions, the accumulation of parcel-level fuels can exacerbate fire spread across parcels and through communities.

Appendix C. Weather Observation Data

Table C-1 includes the weather observations from the local on-site weather station located 40 m (130 ft) north of the burn site. Table C-2 includes the weather observations from Austin-Bergstrom International Airport (KAUS) [11]. Data was recorded at five-minute intervals at each station.

The data is plotted in Fig. 5 in the main text.

Table C-1. Weather observations at Austin Fire Department training campus.

Burn	Time (CDT)	Air Temp (°C)	RH (%)	Wind Speed (m/s)	Gust Speed (m/s)	Wind Dir (deg)	Wind Dir
	08:02	22.5	89.4	1.7	2.3	160	SSE
	08:07	22.5	89.7	1.0	2.0	150	SSE
	08:12	22.5	89.8	1.0	2.0	153	SSE
	08:17	22.5	89.8	1.0	2.0	145	SE
	08:22	22.5	89.8	1.0	1.3	117	ESE
	08:27	22.4	90.0	1.0	1.7	115	ESE
	08:32	22.4	90.1	1.0	1.7	117	ESE
1	08:37	22.4	90.3	1.3	2.3	125	SE
1	08:42	22.4	90.5	1.0	2.0	110	ESE
1	08:47	22.5	90.5	1.0	1.7	121	ESE
1	08:52	22.5	90.7	1.0	1.7	105	ESE
1	08:57	22.5	90.6	1.0	2.3	122	ESE
1	09:02	22.5	90.7	1.0	2.0	111	ESE
1	09:07	22.7	90.7	1.3	2.3	84	E
1	09:12	22.7	90.6	1.7	2.3	86	E
1	09:17	22.6	90.8	1.7	2.3	80	E
1	09:22	22.6	91.0	1.7	3.0	77	ENE
	09:27	22.5	91.2	2.0	3.0	79	ENE
	09:32	22.4	91.5	1.7	2.7	67	ENE
	09:37	22.4	91.8	1.7	3.0	66	ENE
	09:42	22.5	92.0	1.7	3.0	66	ENE
	09:47	22.5	92.1	1.7	2.7	80	E
	09:52	22.6	92.2	2.0	3.0	86	E
	09:57	22.5	92.4	1.7	3.0	97	E
	10:02	22.6	92.5	1.7	3.0	84	E
2	10:07	22.8	92.7	1.7	2.3	88	E
2	10:12	22.9	92.7	1.7	3.3	96	E
2	10:17	23.0	92.6	2.0	3.3	101	E
2	10:22	23.1	92.5	2.0	3.3	103	ESE
2	10:27	23.2	92.4	2.0	3.3	100	E
	10:32	23.2	92.3	2.0	3.3	110	ESE
	10:37	23.3	92.2	1.7	3.3	114	ESE
	10:42	23.5	91.9	1.7	3.0	117	ESE
	10:47	23.5	91.6	2.0	3.0	110	ESE
	10:52	23.6	91.1	1.7	2.7	122	ESE
	10:57	23.8	90.9	2.0	4.0	104	ESE
	11:02	23.7	90.5	1.7	3.0	118	ESE

Table C-2. Weather observations at KAUS.

Burn	Time (CDT)	Air Temp (°C)	Dew Point (°C)	RH (%)	Wind Speed (m/s)	Wind Dir (deg)	Wind Dir
	08:00	22.0	21.0	94.1	3.1	160	SSE
	08:05	22.0	21.0	94.1	3.1	150	SSE
	08:10	22.0	21.0	94.1	4.1	150	SSE
	08:15	22.0	21.0	94.1	2.6	150	SSE
	08:20	22.0	21.0	94.1	2.6	150	SSE
	08:25	23.0	22.0	94.1	2.6	140	SE
	08:30	23.0	22.0	94.1	2.1	120	ESE
	08:35	23.0	22.0	94.1	2.6	120	ESE
1	08:40	22.0	22.0	100.0	2.6	120	ESE
1	08:45	22.0	22.0	100.0	2.6	120	ESE
1	08:50	23.0	22.0	94.1	2.1	110	ESE
1	08:55	22.2	21.7	97.0	2.1	120	ESE
1	09:00	22.0	22.0	100.0	2.6	120	ESE
1	09:05	22.0	22.0	100.0	2.1	110	ESE
1	09:10	22.0	22.0	100.0	1.5	110	ESE
1	09:15	23.0	22.0	94.1	2.1	100	E
1	09:20	23.0	22.0	94.1	1.5	90	E
1	09:25	23.0	22.0	94.1	2.1	90	E
	09:30	23.0	22.0	94.1	2.1	90	E
	09:35	23.0	22.0	94.1	4.1	80	E
	09:40	23.0	22.0	94.1	2.6	60	ENE
	09:45	23.0	22.0	94.1	3.1	90	E
	09:50	23.0	22.0	94.1	3.1	90	E
	09:55	23.0	22.0	94.1	3.6	100	E
	10:00	22.8	22.2	96.4	3.1	90	E
2	10:05	23.0	22.0	94.1	2.6	100	E
2	10:10	23.0	23.0	100.0	2.6	100	E
2	10:15	23.0	23.0	100.0	3.1	120	ESE
2	10:20	23.0	23.0	100.0	2.1	100	E
2	10:25	23.0	23.0	100.0	3.6	110	ESE
2	10:30	23.0	23.0	100.0	4.6	110	ESE
	10:35	23.0	23.0	100.0	3.6	110	ESE
	10:40	23.0	23.0	100.0	3.6	120	ESE
	10:45	23.0	23.0	100.0	3.6	120	ESE
	10:50	24.0	23.0	94.2	3.1	110	ESE
	10:55	24.0	23.0	94.2	3.1	120	ESE
	11:00	24.0	23.0	94.2	3.6	120	ESE

Appendix D. Burn Photo Sequences

The following pages include snapshots from the video recordings at selected times to represent the overall progression of the burning behavior and to provide visual context to events listed in Tables 1 and 2. Images from the three HD video cameras were synchronized, and the time after ignition (mm:ss) is listed to the left of each row of images. Cameras were positioned as indicated in Fig. 3.

Burn 1
t = 00:00



Burn 1
t = 01:44



Burn 1
t = 10:00



Burn 1
t = 16:52



Burn 1
t = 19:22



Burn 1
t = 21:40



Burn 1
t = 22:40



Burn 1
t = 27:23



Burn 1
t = 30:30



Burn 1
t = 33:36



Burn 1
t = 37:30



Burn 1
t = 43:27



Burn 2
t = 00:00



Burn 2
t = 03:37



Burn 2
t = 07:44



Burn 2
t = 09:19



Burn 2
t = 11:30



Burn 2
t = 14:17



Burn 2
t = 15:57



Burn 2
t = 16:29



Burn 2
t = 18:23



Burn 2
t = 23:00

