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Spot Fire Ignition of Natural Fuels by Hot Aluminum Particles

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Abstract. The ignition of combustible material by contact with hot metal particles is an important pathway by which wildland and urban spot fires are started. This work examines how fuel characteristics such as density, morphology and chemical composition effect the ability of the fuel to be ignited by a hot metal particle. Fuels were prepared out of three materials: alpha-cellulose, a barley/wheat/oat grass blend, and pine needles. Each material was prepared as a powder and as larger, long pieces: strips of cellulose paper, loose grass, and pine needles. These fuels are representative of thermal insulation (cellulose strips), dry grasses (grass blend), forest litter (pine needles) and duff (powders). Aluminum particles ranging from 2 mm to 8 mm in diameter heated to temperatures between 575°C and 1100°C were dropped onto these fuels. The particle temperature required for ignition becomes higher as the particle size decreased. The results show that the required temperatures for ignition of powders were lower, with this trend particularly pronounced for the alpha-cellulose fuels. The biomass fuels required higher temperature particles to ignite, indicating that the presence of other ligno-cellulosic materials make ignition more difficult.

Keywords: Hot work, Conductor clashing, Spot ignition

1. Introduction

Wildland and wildland urban interface fires can be started when hot particles land on a fuel such as a dry grass, duff, litter, and others. These hot metal particles can be produced from hotwork, railroads, transmission lines and other sources. The process by which these hot metal particles ignite a solid fuel is called spot ignition. There are sources in the literature which have compiled lists of spot fires caused by metal particles [1–5], however there are many spot fires which remain unreferenced. Based on published data [2, 6], power lines, equipment, and railroads cause approximately 28,000 natural fuel fires annually in the United States. Some of these fires were catastrophic with extensive damage to land, property, and lives.

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In particular fires caused by clashing conductors have the potential to grow more rapidly than other fires because the conductor clashing is typically caused by high winds which causes the fire to spread faster [7]. In addition, research shows that fires caused by clashing conductors typically occur when the fire danger is higher from other factors such as ambient temperature, weather patterns, humidity, fuel moisture content, etc., not just high winds [8]. As an example, the Witch Creek and Guejito fires burned almost 200,000 acres and destroyed over 1100 homes during the 2007 California firestorm. According to reports by The California Department of Forestry and Fire Protection (CalFire) and NIST, both fires were allegedly ignited by hot metal particles generated by power line interactions [9, 10]. Another recent large fire at the wildland/urban fire is the Bastrop County Complex fire in Texas; the fire burned over 12,000 hectares in 2011 [4]. The fire allegedly started when power lines interacted with each other and nearby trees during high winds. The sparks produced by the powerline interactions fell on and ignited dried vegetation [4]. A more recent spot fire is the 2012 Taylor Bridge fire in the state of Washington; the fire was reportedly caused by spot ignitions of dry vegetation by sparks produced by rebar cutting and/or welding during construction of an underpass fell [11]. The fire eventually consumed in excess of 23,000 acres and destroyed approximately 60 homes and in excess of 200 outbuildings [11]. Spot fires have also occurred in other countries. In New Zealand 275 fires were ignited by embers, sparks, or flying brands between 2005 and 2010 [3]. In Australia, some of the wild fires of the Black Saturday fires of February 2009 were also allegedly started by sparks and the fires propagated extremely fast by ember spotting [12]. Particles and sparks produced by welding, grinding and various forms of hot work have also been involved in several other notable incidents, and the established literature discusses many potential hot particle sources [1, 5, 13–19].

The ignition of a fuel by thermal contact with a hot metal particle is a complex multi-step process. Once the hot particle comes into thermal contact with a solid fuel, energy is transferred from the particle to the fuel and ambient surroundings. If the particle has enough energy it can produce gaseous pyrolyzate. This pyrolyzate mixes with the air and may for a flammable gas mixture near the object. If the gas mixture is in contact with the hot particle it may experience heating or cooling depending on the relative temperatures. Then if heat generated by the gas phase chemical reactions is able to offset any heat losses gas phase ignition occurs. If gas phase ignition does not occur, the hot particle can initiate a self-sustained smolder in the fuel which might transition transition to a flame. This complex ignition process depends on several factors, the properties of the particle (size, temperature, phase, existence of oxidation reactions, etc.), the characteristics of the fuel (initial temperature, chemical composition, morphology, and fuel moisture content), the dynamics of the particle landing (fully or partially embedded on the fuel bed, bouncing, or splashing) and environmental conditions (temperature, humidity, or wind velocity). Obviously, a phenomenon of this level of complexity needs to parameterized into different studies.

There are a limited number of studies published on the ignition of fuels by hot metal particles [20–31]. Rowntree and Stokes [21], studied the ignition potential of barley grass by hot aluminum particles and found that smaller particles required higher temperatures to ignite the fuel. Tanaka, [23], studied the ignition of sawdust by welding spatter and found that some combination of higher temperatures and larger particle sizes to ignite sawdust when the fuel moisture content was increased. Hadden [20] studied the ability of stainless steel particles to smolder or flaming ignite powdered cellulose beds and showed that hot spot ignition theory qualitatively predicts the ignition behavior (in terms of particle diameter and temperature), but is not capable for quantitatively predicting ignition.

Zak et al. developed a statistical treatment of similar data with steel particles falling onto cellulose fuel beds [27]. Urban et al. studied the effect of different metal particle types (aluminum, brass, copper, and steel) igniting powdered cellulose fuel bed with a flame [24]. The results showed that the there were small differences between the different metal types with exception of aluminum which was molten for most of the conditions tested. The melting gave a molten aluminum particle at a given temperature more energy than a solid metal particle of different composition. Zak then modeled these experiments [29]. Later Urban et al. 2017 examined the process by which steel and aluminum particles ignite a smolder in a grass blend powder [25] and found that the energy from melting allowed aluminum particles to ignite a smolder at lower temperatures. The study also found that the smoldering ignition process by a hot metal particle at times can be limited by heat losses from the incipient smoldering front back to the particle which cools as it exchanges heat with its surroundings [25]. Recently Wang et al [30] studied the ignition (smoldering and flaming) of pine needles of various moisture contents by hot large stainless steel particles and smoldering to flaming transition. Previously, Wang et al. [32–34] studied the similar problem of hot metal particles landing on polymer foams.

This study seeks to investigate the flaming ignition boundaries (i.e. minimum conditions capable of ignition) for six ligno-cellulosic fuels. All the tests in this study were conducted with aluminum particles of sizes consistent with the sizes of particles found by welding [14] or powerline conductor clashing [17] and have plausible temperatures for particles produced by these processes, however higher temperature could be possible with these processes. The possibility of smoldering or the subsequent transition to flaming was not studied, and only flaming ignition event are reported. Smoldering Ignition events were thus recorded as No Ignition. As mentioned above this ignition process is complex and must be broken down into different studies to properly examine the different aspects of the problem.

2. Experimental Apparatus and Methods

2.1. Experimental Apparatus

A schematic of the experimental apparatus is shown in Fig. 1. The fuel bed holder is mounted in the bottom of a wind tunnel duct such that the sample surface flush with the bottom of the tunnel. The wind tunnel duct is 550 mm in length with a 130 mm by 80 mm cross section. The sample holder is 150 mm long, 100 mm wide and 50 mm deep and its leading edge is located 150 mm from the inlet of the tunnel duct. Laboratory air is flown through the wind tunnel with a centerline velocity of 0.5 m/s at the leading edge of the fuel bed holder. Changes in wind speed would effect the ignition process through mixing of the pyrolyzate and the air around the particles and potentially the rate of convective cooling on the surface of the particle as well as potentially even blow off of a flame.

The air flow velocity is a parameter of the problem that affects the rate at which the particle cools as well as the potential generation of a flammable mixture near the particle; in this study the air flow velocity was held constant at 0.5 m/s. The air velocity was chosen because it produces a more regular flow without disturbing the surface of the powdered fuels. Thus, the ignition data reported in this work may not be representative of those that would be obtained at higher air velocities. Flow uniformity is reduced when the tunnel top is open to introduce the particles. To overcome this complexity and ensure a uniform cross-flow velocity between tests, particles were only dropped on the leading half of the fuel bed. The mean and relative humidity and temperature of the air flow were measured daily and found to be on 16.2% ± 4.2% and 26.6°C ± 3.3°C respectively. Viewing windows in the sides of the tunnel allow optical access. A high temperature electrical furnace is used to heat the aluminum particles. A linear guide holds a ceramic crucible with a long handle approximately 140 mm above the fuel bed. This guide is collinear and concentric with the tube furnace such that the crucible can easily be inserted and removed from the furnace. A type K thermocouple is embedded in the crucible to provide a reliable measurement of the particle temperature. The aluminum particles are left in the oven until their temperature reaches equilibrium conditions as indicated by the thermocouple placed in the ceramic spoon. It should be noted that the particle temperature reported here is that of the particle in the oven, not at landing. The particle temperature at landing is obviously lower and dependent on the particle size, temperature, and emissivity. The temperature reduction during the particle drop was estimated to be less than 46°C for all tests performed. This was performed by treating the hot aluminum particle as thermally lumped and accounting for convective and radiative heat losses to the environment and considering a particle of the smallest size tested, 2.08 mm, at the highest temperature, 1100°C and using high speed photography to measure to drop time from the crucible.

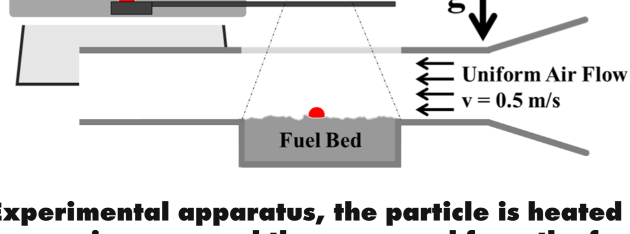

Figure 1. Experimental apparatus, the particle is heated in the tube furnace in a ceramic spoon and then removed from the furnace and dropped onto the fuel bed.

2.2. Fuel Beds

The fuels tests were composed of three different fuel materials (alpha-cellulose, a grass blend of barley/wheat/oat, and dead pine needles). These three fuel materials were prepared in two different morphologies for a total of six different fuels, which are shown in Fig. 2. The first morphology was a powder composed of particles small enough to pass through a 500-mesh sieve conforming to ASTM E-11 [35], this type of mesh allows particles that fit through 0.5 mm by 0.5 mm openings in a larger sieve to ensure a given particle size. The second morphology tested had a lighter bulk density than the powder morphology and the size of the individual pieces of the fuel were much larger in size. The cellulose strips, pine needles and the grass blend where cut to lengths between 37.5 and 87.5 mm and were typically $\sim$ 7.5 mm wide for the grass blend and $\sim$ 5 mm for the cellulose strips. The diameter of the pine needles was found to be $\sim$ 2 mm. The pine needles were collected from litter under a ponderosa pine (Pinus ponderosa) on the University of California Berkeley campus and then dried, cut to the specified length, and then conditioned in the laboratory. The grass blend was obtained commercially from Alfalfa King [36], and then cut to the specified length. The grass blend and its powder were dried in an oven and then allowed to reach an equilibrium moisture content comparable to the cellulose fuels ($\sim$7%). Rough values of expected compositions of the grass blend and pine needles were made by examining values reported in the literature for the oats, barley, and wheat grasses. Data for the moisture content and chemical compositions are shown in Table 1. The cellulose strips were cut uniformly to the same length range and had a thickness of 5mm and were cut from alpha cellulose ashless paper [37]. The different fuel compositions allow us to examine the effect of hemi-cellulose and lignin content which is

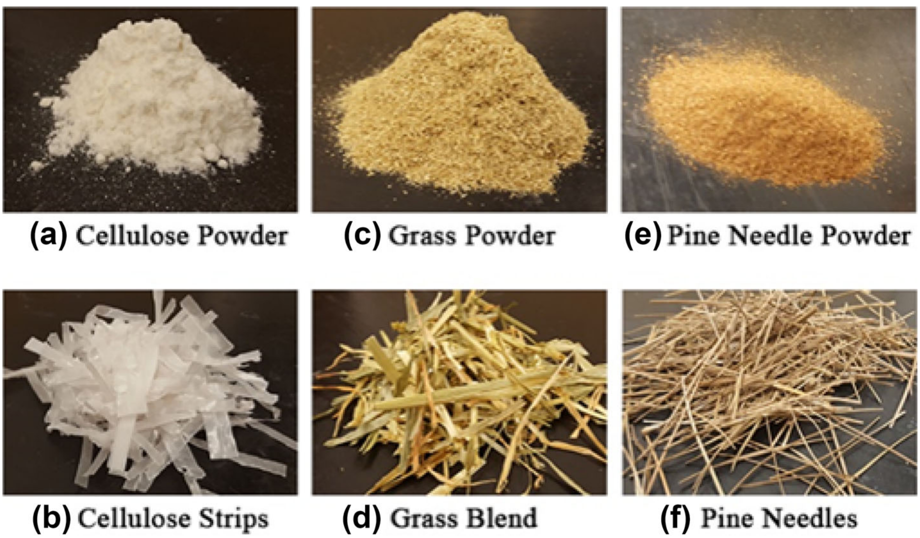

Figure 2. Photographs of the six fuels tested.

removed from the woody biomass to produce α-cellulose. The relevant fuel properties are shown below in Table 1.

The α-cellulose was chosen as a reference fuel bed material for its chemical homogeneity and because it is the largest component of woody biomass. The grass blend of barley, wheat, and oat grasses was chosen as representative of grassy fuels. The pine needles were chosen because they are representative of pine forest litter. In all experiments with powdered fuel beds, the settled volume was held constant. The settled volume refers to the minimum volume occupied by the fuel bed after vigorous vibration. The fuel beds were laboratory-conditioned and the moisture content of the fuel was measured each day tests were conducted. This involved drying laboratory-conditioned samples in an oven at 110°C ± 5°C for at least 4 hours. Each sample weighed at least 1.3 g initially and the mass was measured before and immediately after drying.

For this study, aluminum particles composed of aluminum alloy 1100, an alloy used for overhead power transmission in the United States, were heated in the tube furnace, and dropped onto the various fuels. The metal particles studied were either spherical or approximately spherical in shape. The particles ranged in size from 2 mm to 8 mm in diameter. The temperatures tested ranged from 525°C to 1100°C. Higher temperatures were not performed because 1100°C was the maximum operating temperature of the tube furnace. For the range of particles tested, no flaming ignition events were observed at 525°C, so additional tests were not conducted below that temperature. The relevant thermal properties for aluminum 1100 in both the solid and molten states are shown in Table 2.

The goal of these experiments was to provide a boundary where flaming ignition will occur. To achieve this, experiments focused on the boundaries where flaming ignition occurred and where it did not occur. Test conditions were chosen to focus on finding the lowest temperature where flaming ignition could occur for a given size particle and a given fuel bed. This was achieved by performing guess tests at increasing temperatures, in multiples of 25°C until an ignition event was observed. Then tests were performed at the temperature 25°C lower than the low-

Table 1
Fuel Bed Properties

Fuel	Density (kg/m^3)	MC (%)	Chemical composition	d_{char} (mm)
Cellulose powder	344 ± 36	7 ± 1	100% α-cellulose [37, 38]	0.4 [38]
Cellulose strips	42.5 ± 0.1	7 ± 1		5
Pine needle powder	370 ± 19	8 ± 1	30% α-cellulose	0.5
Pine needle	57 ± 1	8 ± 2	20% hemi-cellulose 26% lignin [39]	2
Grass blend powder	282 ± 1	7 ± 2	36–43% α-cellulose	0.5
Grass blend	75 ± 1	8 ± 2	23-28% hemi-cellulose 7–18% lignin [40, 41]	7.5

Table 2
Aluminum Particle Thermal Properties

Phase	Solid [42]	Molten [43–45]
Density (kg/m^3)	2710	2375
Specific heat (J/kg K)	900	1141
Thermal conductivity (W/m K)	220	90.7
Heat of melting (kJ/kg)	390	390
Thermal diffusivity (m^3/s)	9.02×10^{-5}	3.35×10^{-5}
Melting temperature (°C)	643–657	

est temperature where ignition was observed until either 5 tests were performed that did not result in ignition or an ignition event was observed. In this case the temperature was lowered by 25°C and the process was continued recursively until a temperature was found where none of the 5 tests performed resulted in flaming ignition. Further tests were done for temperatures were ignition was observed with at least 3 tests at each test condition.

For this study the tests only flaming ignition or no ignition outcomes are reported. Tests were designated flaming ignition if a flame was visible for at least one second. Flaming ignition happened in less than 1 second for all flaming ignition events observed. To minimize the effects of random variations in the fuel beds and the penetration of the particle into the fuel bed, the location where the particle was dropped was varied and no more than two tests were done on a single fuel bed on a given day. Although it is difficult to eliminate the randomness of the process, we feel that the experimental conditions were well controlled and that five tests were a good data sampling to provide an accurate measure of the ignition boundary. To quantify the uncertainty of the process the data is presented in terms of the observed probability of ignition as is shown in Fig. 3.

3. Results and Discussion

The results from the experiments and the flaming ignition boundaries for the six fuels tested are presented in Fig. 3. Each of the sub-figures (a–f) of Fig. 3 corresponds to the tests conducted with one of the six fuels. The circles correspond to sets of at least three tests for non-black circles and five for black circles and were colored based on the fraction of the experiments that resulted in a flaming ignition. Thus, black circles denote cases were FI was never observed and white circles to tests were flaming ignition occurred every time, intermediate values were colored per the colorbar at the right of the figure. The black circles were used to determine the ignition boundaries presented in Fig. 3. The flaming ignition boundaries denote a barrier separating conditions which can initiate a flame from those conditions which cannot. The ignition boundaries provide a good metric for comparing the ignition hazards of the different fuel relative to one another. It should be noted that in the case of the grass blend powder, many of the events that did not result in flaming ignition resulted in smoldering ignition, unlike the other fuels. The data regarding smoldering ignition is not presented here. Overall there are some common features among the results from the different fuels. The FI boundaries show monotonic rises in required particle temperature for ignition as the particle size decreases. While most of them have a similar hyperbolic shape, the ignition boundary for alpha-cellulose has a region that is relatively flat and causes changes in curvature in the curve. This occurs at the melting point of the aluminum alloy. The melting gives the particles additional energy equivalent to increasing a solid aluminum particle by $\sim$ 400°C.

The ignition boundaries for the six fuel beds are presented in Fig. 4 to facilitate direct comparison between themselves and results for the flaming ignition boundary for barley grass by contact with hot aluminum particles from another study [21]. In Fig. 4, the powder fuels and their non-powder counterparts are denoted by solid and dashed lines respectively. By comparing the different ignition boundaries we see that of the fuels tested, alpha cellulose were capable of being ignited by hot metal particles at considerably colder temperatures compared to the biomass fuels (pine needle fuels and grass blend fuels) which ignited under relatively similar conditions. It was also seen that the powder fuels were able to be ignited at lower temperatures than their non-powder counterparts.

The fact that the powder fuels were capable of ignition at lower temperatures indicates that some combination of smaller fuel particulate sizes and higher densi-

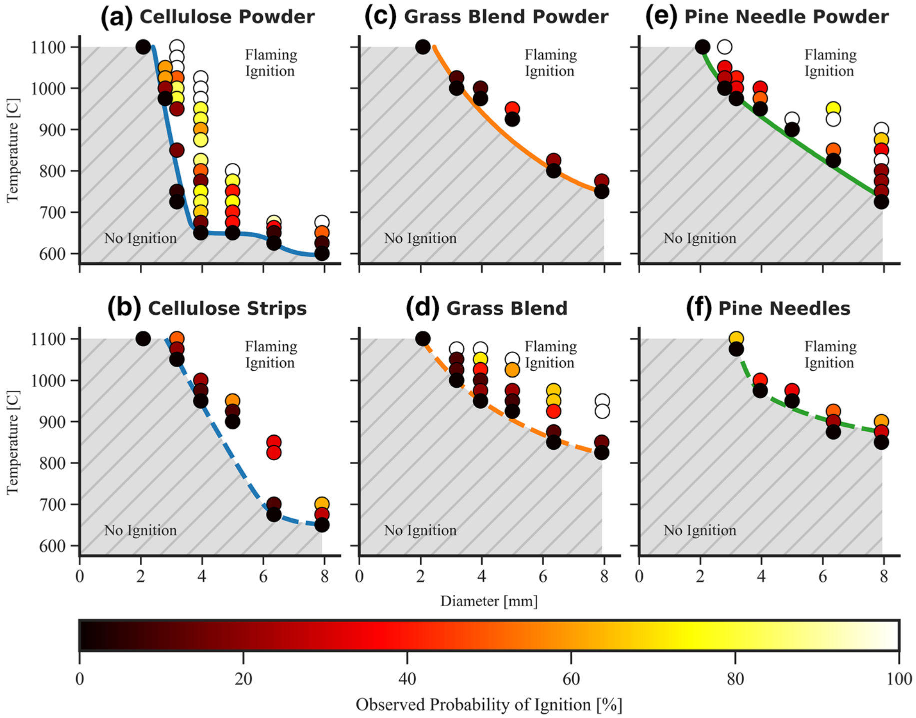

Figure 3. Ignition results for the six fuel beds. Circles were filled according to the colorbar to denote the fraction of tests that resulted in flaming ignition.

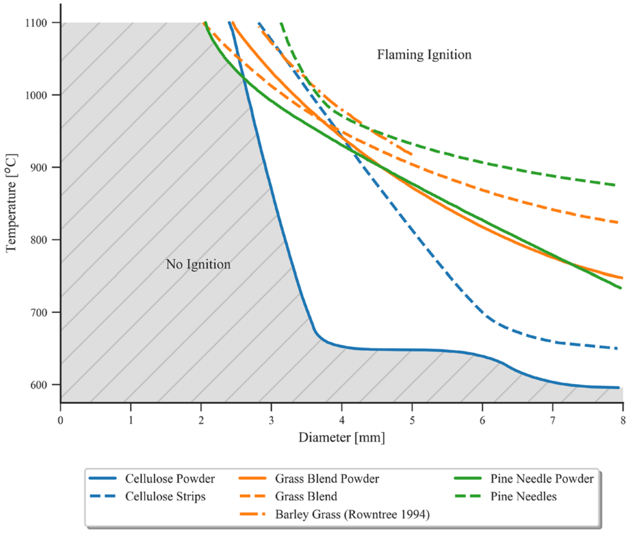

Figure 4. Comparison of the ignition boundaries for the six fuel beds. The data from Rowntree and Stokes [21] is also shown for comparison. For color figure please see the online version.

ties make ignition possible at lower temperatures. The lower flaming ignition boundaries for the alpha-cellulose strips and powder indicate that the components in the biomass fuels other than alpha-cellulose such as lignin, hemi-cellulose, proteins, and ash bearing components make the fuel require higher temperatures for ignition. Thus, both the morphology and chemical composition of the fuel effect the ignition process. Unfortunately, the lack of higher particle temperature data makes it difficult to determine whether there is a minimum particle size required for ignition and if that is dependent the fuel properties studied here. As mentioned earlier, our ability to investigate higher temperature particles was limited by the maximum operating temperature of the furnace used in the experiments.

The flaming ignition limits for the grass fuels agree well with the flaming ignition results from Rowntree and Stokes[21]. The difference between the ignition boundaries is attributed to different experimental conditions, apparatuses, and the different grasses used.

4. Conclusions

Experiments were performed investigating the flaming ignition of alpha-cellulose, a grass blend, and dead pine needles, each of these fuels were tested as powder and with larger fuel particle sizes with lower bulk densities (i.e. paper strips, blades of grass, and pine needles). For each fuel bed, the flaming ignition boundaries was determined by finding the lowest particle temperature where flaming ignition occurred. These ignition boundaries separate flaming ignition and non-flaming ignition conditions from each other, and thus which conditions are demonstrably hazardous. The results are consistent with similar studies of hot metal particles igniting fuels where larger particles were capable of igniting fuels at lower temperatures and smaller particles requiring higher temperatures. Thus, the smaller particles require a higher temperature to cause ignition.

It was found that the pure α-cellulose fuels ignite at lower temperatures than the biomass fuels (grass blend and pine needle fuels). This suggests that the additional components found in these fuels such as lignin, hemi-cellulose, other organic compounds as well as the inorganic compounds deter flaming ignition. It was also found that when the fuel is in powder form it is capable of ignition at lower temperature than in strip/grass/needle form confirming that the morphology of the fuel is also important for determining if ignition will occur, the effect was particularly pronounced for the alpha-cellulose fuels.

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