Most Probable Fire Scenarios in Spacecraft and Extraterrestrial Habitats - Why NASA's Current Test 1 Might Not Always Be Conservative

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NASA's current method of material screening determines fire resistance under conditions representing a worst-case for normal gravity flammability - the Upward Flame Propagation Test (Test 1[1]). Its simple pass-fail criteria eliminates materials that burn for more than 12 inches from a standardized ignition source. In addition, if a material drips burning pieces that ignite a flammable fabric below, it fails.

The applicability of Test 1 to fires in microgravity and extraterrestrial environments, however, is uncertain because the relationship between this buoyancy-dominated test and actual extraterrestrial fire hazards is not understood. There is compelling evidence that the Test 1 may not be the worst case for spacecraft fires, and we don't have enough information to assess if it is adequate at Lunar or Martian gravity levels.

Microgravity Flames do Strange Things

Flames in microgravity are known to preferentially spread upwind (ie opposed flow) [2], not downwind (i.e. concurrent flow) as in the normal gravity upward flammability screening Test 1. Over most of the range of air ventilation rates (5-20 cm/s) comparable to spacecraft ventilation, upstream flame spread was the only viable flame. Only when the flow becomes strong enough (estimated to be $\geq$ 10 cm/s), will at least a partial downstream flame become viable. Numerical and experimental results [7] predict an upstream flame only at 5.0 cm/s, an upstream flame and two localized edge flames propagating downstream at 10.0 cm/s, and both an upstream and downstream flame at 20.0 cm/s.

This propensity to spread upwind does not only occur for thin materials, but also occurs for thicker materials and other shapes. For example, experiments were conducted aboard the Mir space station using plastic cylinders. The intent was to burn them with a concurrent flame spread similar to that of Test 1. However, rather than spread along the rod, the flame stabilized at the front tip of the rod and burned like a candle flame at the end of a fat wick [3,4] ,

Under the right flow conditions in space, things will burn that won't burn on Earth. This is most clearly demonstrated by a flammability map [5,6]. In the opposed flow flame spread flammability map for a cellulose fuel, the LOI, or limiting oxygen index on Earth in opposed flow is 16.5% O_2. However, if the flow is on the order of spacecraft ventilation (5-20 cm/s), flames can be sustained even at 14 % O_2. Thus a normal gravity measure of flammability does not guarantee that the material won't burn in space.

Some preliminary work on independent opposed and concurrent flame spread was conducted in a glovebox experiment [8]. The flame spread results in the cabin air (~21% O2) show that the quenching region spans from +0.5 to -2 cm/s, so even correcting for the small spread rate, the concurrent flame has a higher flow flammability boundary than the opposed flow flame.

On the Moon or Mars (0.17g and 0.38 g, respectively), where buoyant flows will be greater than 20 cm/s, the concurrent flame spread will be viable simultaneously with any opposed flow flame. Experiments conducted aboard the KC-135 [9] demonstrate the faster burning of concurrent flames in partial gravity environments. These higher flow test conditions are on the blowoff side of the flammability boundary.

If a fire is initiated, and the crew takes steps to extinguish it, the first line of defense is to turn off the flow. As demonstrated by the data above, the flame cannot survive indefinitely without a supply of fresh oxygen. Once the fire is out, the crew would reactivate the flow to clean up any residual smoke.

However, experiments have shown that even a very slight air flow of a fraction of a cm/s [4] is sufficient to allow the flame to survive. These flames can become almost undetectable (small, non-luminous) and yet persist for many minutes [10, 11] for a fingering flame spread observed under very weak ventilation. The tiny flamelet (~6 mm x 2mm) spread steadily, albeit slowly, for 80 seconds. When the flow was turned up 100-fold to 50 cm/s, the flame did not blow out as one would expect, but flared up into a much larger spreading flame. The fingering behavior is unique to low gravity. The formation of these different flame structures is due to changes in lateral diffusive flux of oxygen from the outer flow to the flame, convective flow patterns and oxygen shadow caused by oxygen consumption at the upstream flamelet. These types of behaviors must be known and understood so that the crew can watch for them.

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The applicability of Test 1 to fires in microgravity and extraterrestrial environments, however, is uncertain because the relationship between this buoyancy-dominated test and actual extraterrestrial fire hazards is not understood. There is compelling evidence that the Test 1 may not be the worst case for spacecraft fires, or at Lunar or Martian gravity levels. This poster is a summary of what we know about the most likely forms a fire will take in space. (Please see reference list for cited works presented here).

Microgravity flames go the wrong way

Flames in microgravity are known to preferentially spread upwind (ie opposed flow) [2], not downwind (i.e. concurrent flow) as in the normal gravity upward flammability screening Test 1. Over most of the range of air ventilation rates (5-20 cm/s) comparable to spacecraft ventilation, upstream flame spread was the only viable flame. Figure 1 shows an image of a thin cellulose sample ignited in the middle. The blue half-dome flame is spreading upstream – into the fresh air. The downstream half of the dome is not viable because the oxygen has been consumed by the upstream side of the flame.

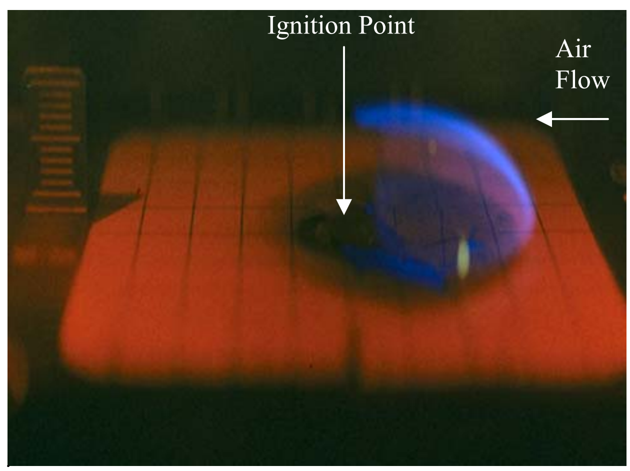

Figure 1: When ignited in the middle, the flame preferentially spreads upstream at low speed airflows

Only when the flow becomes strong enough (estimated to be ≥ 10 cm/s), will at least a partial downstream flame become viable. Numerical and experimental results [7]. predict an upstream flame only at 5.0 cm/s, an upstream flame and two localized edge flames propagating downstream at 10.0 cm/s, and both an upstream and downstream flame at 20.0 cm/s.

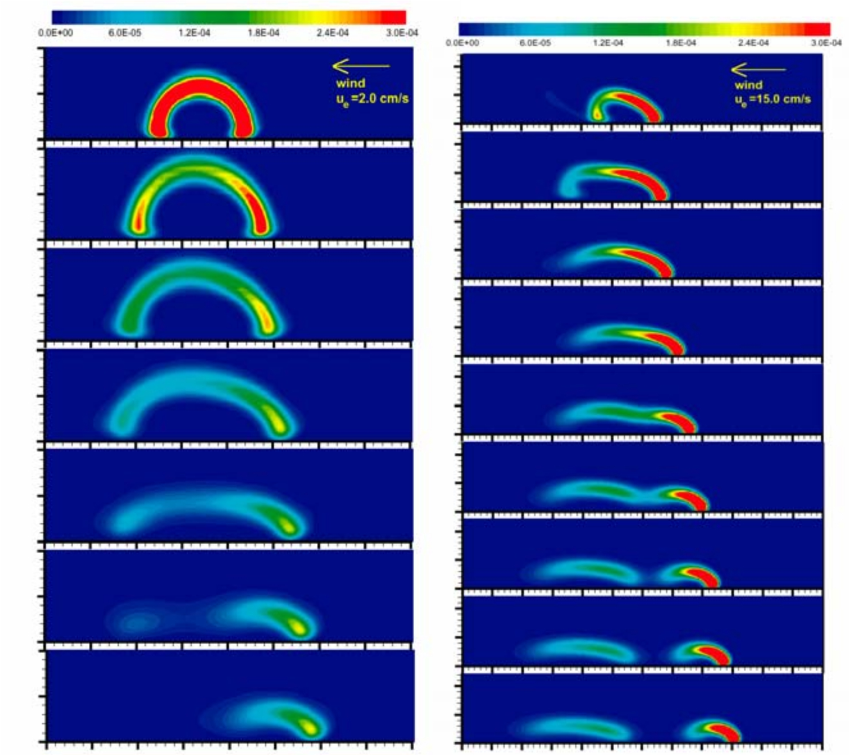

Figure 2: Computational Results of ignition and transition to flame spread for 5 cm/s (left) and 20 cm/s (right). The downstream flame is not viable at low wind velocities, but the two flames separate successfully at 20 cm/s as the thin fuel burns out in the middle. Notice even then how much weaker the downstream flame is. [7]

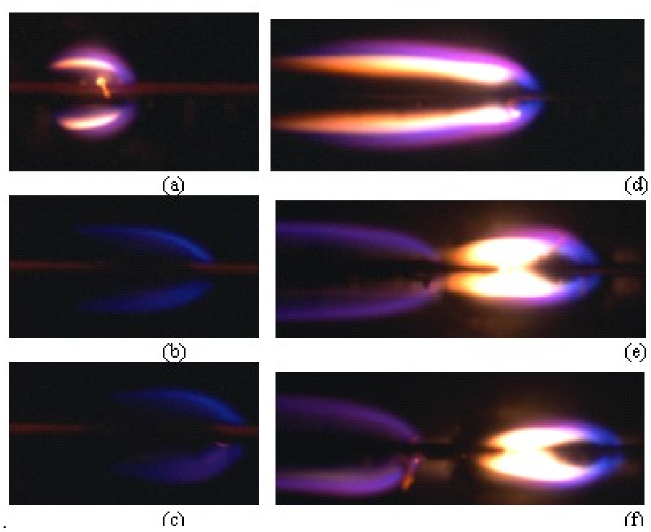

Figure 3: Color images of the edge view for flame spread in microgravity conditions obtained from the drop tower experiments. Figures 3. a, b and c are for an imposed flow velocity of 5 cm/s at t=2 s (a), 6.5 s (b) and 9.5 s (c) from the onset of external radiation. Figures 3. d, e and f are for an imposed flow velocity of 20 cm/s at t=4 s (a), 8 s (b) and 9.5 s (c) from the onset of external radiation. The flow is from right to left and the flames are propagating in air. Notice the similarities in the flame separation between these images and the computations of Figure 2.[7]

The computations and experimental results [7] at 5 cm/s and 20 cm/s are shown in Figures 2 and 3.

This propensity to spread upwind does not only occur for thin materials, but also occurs for thicker materials and other shapes. For example, experiments were conducted aboard the Mir space station using plastic cylinders. The intent was to burn them with a concurrent flame spread similar to that of Test 1. However, rather than spread along the rod, the flame stabilized at the front tip of the rod and burned like a candle flame at the end of a fat wick [3,4], as shown in Figure 4.

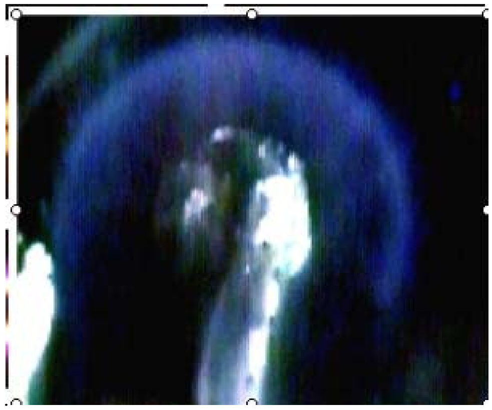

Figure 4: Candle-like flame burning at the upstream end of a plastic rod [4].

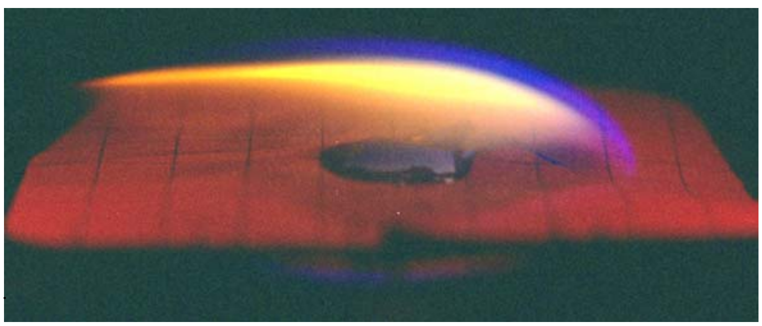

Figure 5: 3D flame spread with only upstream spread and a long downstream tail.

It is conceivable that a thermally thick sample would result in only one flame propagating upstream, with a long tail instead of the two flame structure for a thermally thin sample (because fuel burnout does not occur). [Takashi Kashiwagi, private communication]. Flame would look similar to Fig. 5.

<u>**Things burn in space that don't burn on Earth**</u>

Under the right flow conditions in space, things will burn that won't burn on Earth. This is most clearly demonstrated by a flammability map [5,6]. Figure 5 shows the opposed flow flame spread flammability map for a cellulose fuel. The LOI, or limiting oxygen index on Earth for this material in opposed flow is 16.5% O_2. **However, if the flow is on the order of spacecraft ventilation (5-20 cm/s), flames can be sustained even at 14 % O_2. Thus a normal gravity measure of flammability does not guarantee that the material won't burn in space.**

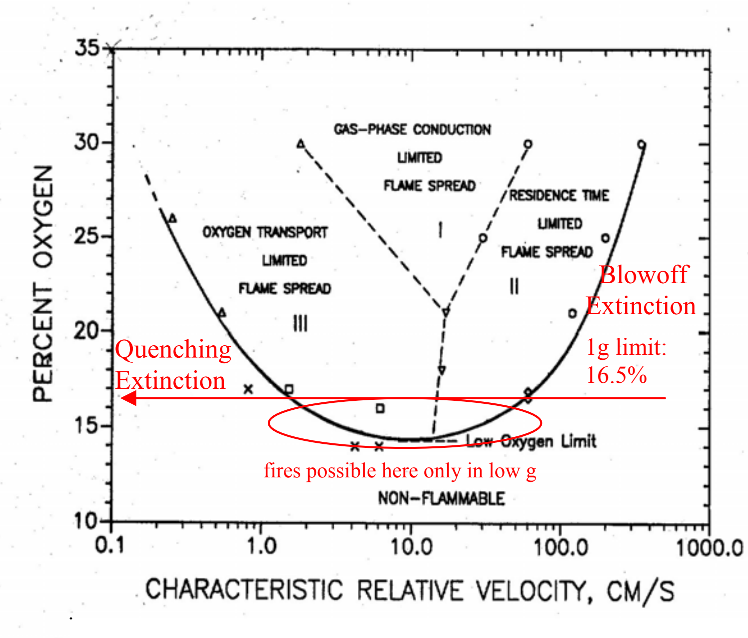

Figure 5: Experimentally-based flammability map for opposed flow flame spread over cellulose [5].

Shown in Figure 6 are 2D numerical predictions [6] of opposed flow vs concurrent flow flame spread (not simultaneous as described above).

As can be seen in Fig. 6, the fundamental LOI occurs at very low free stream velocities, which are in the range of spacecraft ventilation velocities (5-20 cm/s). Thus a 1g upward (concurrent) flame spread test, where buoyant flows are higher than 20 cm/s, is not conservative for these environments.

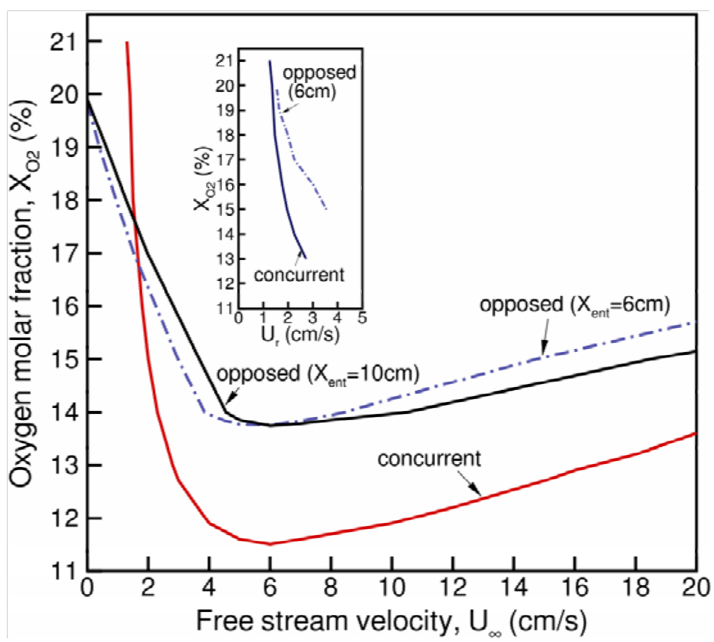

Figure 6: 2D theoretical flammability boundaries for independent opposed and concurrent flame spread. Notice the concurrent boundary extends to much lower oxygen concentrations than the opposed boundary except at very low speed forced flows, where the trend is reversed. [6]

These predictions show that oxygen limits (including the fundamental limit) are lower for the concurrent flame than for the opposed flames except in the very low velocity range. 3D computations are underway, and the extinction boundaries are expected to shift somewhat due to the importance of lateral oxygen transport, especially at low flows and low oxygen concentrations.

In the very low velocity range, oxygen supply is limiting. Therefore opposed spread, by moving against the oxygen flow, acquires a higher rate of oxygen transport into the flame, thus can have a lower oxygen limit. This point is illustrated further by plotting the flammability map using the relative velocity (between the flame and the flow) as the abscissa, shown in the inset of Fig. 6. Experiments are planned for ISS to measure the concurrent-only flame spread limits to verify these predictions.

Some preliminary work on independent opposed and concurrent flame spread was conducted in a glovebox experiment [8]. The flame spread results in the cabin air (~21% O2) are shown in Figure 7. The quenching region spans from +0.5 to -2 cm/s, so even correcting for the small spread rate, the concurrent flame has a higher flow flammability boundary than the opposed flow flame. This contradicts the inset of Figure 6, where the concurrent flame, once corrected for flame spread rate, has a comparable flammability limit.

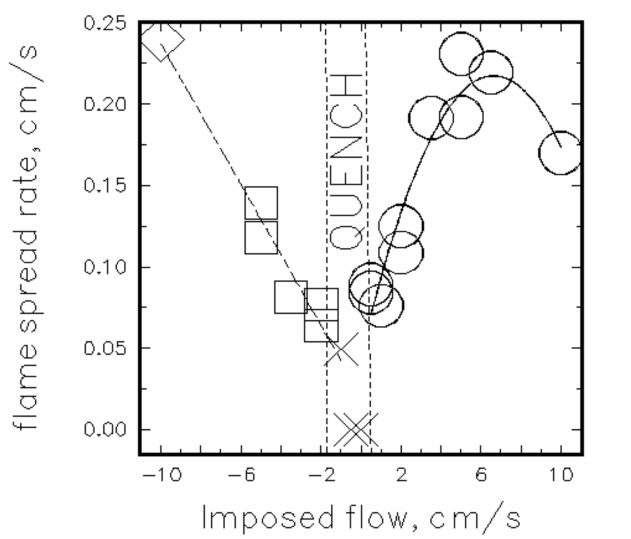

Figure 7: Flame spread rates in shuttle cabin air plotted against imposed flow. Negative flow is concurrent flow, whereas positive flow is opposed flow.

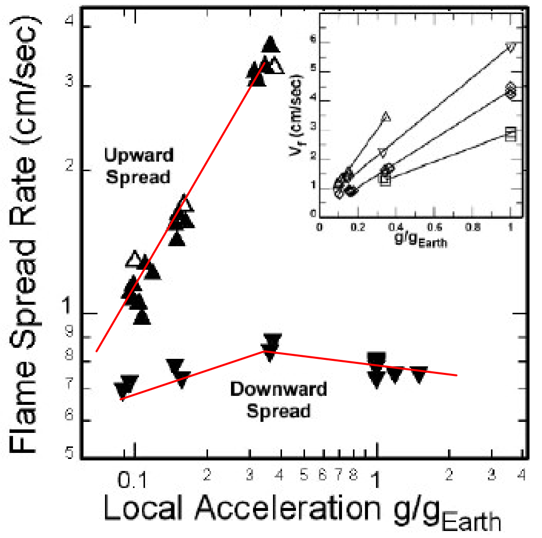

Figure 8: Upward and downward flame spread rates for narrow samples (2 cm) in low pressure (4 psia) air at various gravity levels. Closed symbols are experiments, open symbols are numerical simulations. Inset is 1 cm wide samples [9].

On the Moon or Mars (0.17g and 0.38 g, respectively), where buoyant flows will be greater than 20 cm/s, the concurrent flame spread will be viable simultaneously with any opposed flow flame. Experiments conducted aboard the KC-135 [9] demonstrate the faster burning of concurrent flames in partial gravity environments, as shown in Figure 8. These higher flow test conditions are on the blowoff side of the flammability boundary (Figure 5). Thus while upward burning here is worse than downward burning, the **normal gravity upward test is still not conservative because the minimum flammability is at low velocities only achievable in reduced gravity (Fig. 6).**

Flames Do Strange Things in Space

If a fire is initiated, and the crew takes steps to extinguish it, the first line of defense is to turn off the flow. As demonstrated by the data above, the flame cannot survive indefinitely without a supply of fresh oxygen. Once the fire is out, the crew would reactivate the flow to clean up any residual smoke.

Figure 9: A tiny flame at 0.5 cm/s flares up within seconds when the flow is suddenly increased. Flow enters from right.

However, experiments have shown that even a very slight air flow of a fraction of a cm/s [4] is sufficient to allow the flame to survive. **We cannot rely on quiescence to extinguish flames, because even the slightest flow *O*(mm/s) will support flames.** These flames, which near the limit will likely be flamelets, can become almost undetectable (small, non-luminous) and yet persist for many minutes[10], as shown in Figure 9 for a fingering flame spread observed under very weak ventilation (5 mm/s). The tiny flamelet (~6 mm x 2mm) spread steadily, albeit slowly, for 80 seconds. When the flow was turned up 100-fold to 50 cm/s, the flame did not blow out as one would expect, but flared up into a much larger spreading flame.

This fingering flamelet behavior, currently being studied as part of an ISS flight experiment, (Fig 10, 11) occurs near the quenching extinction boundary. The formation of these different flame structures is due to changes in lateral diffusive flux of oxygen from the outer flow to the flame, convective flow patterns and oxygen shadow caused by oxygen consumption at the upstream flamelet.

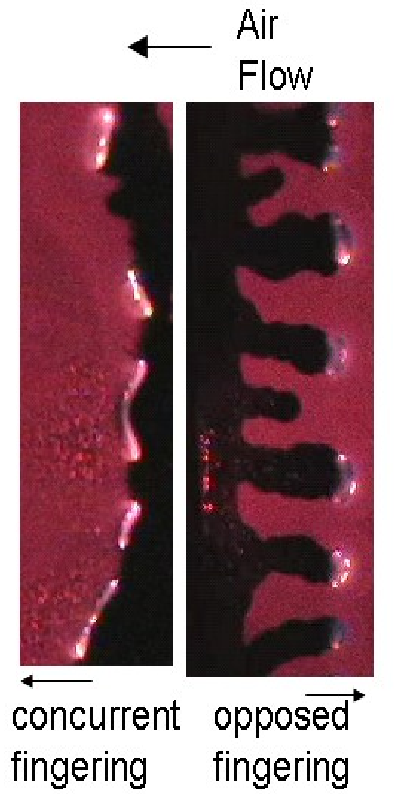

Figure 10: Concurrent flamelet fingering tends to travel along the edges of the unburned material like caterpillars eating a leaf, whereas opposed flamelet fingering tends to tunnel into the pristine fuel. While the concurrent flamelets spread more slowly than the opposed flamelets, overall, they consume more of the fuel. [10]

Flamelet fingering occurs in either opposed-flow spread (flame spreading against the wind) or concurrent spread (with the wind) under weak ventilation conditions. The fingering nature of the two spread modes is different, however, as shown in Figure 10.

If ignited in the middle of the fuel, the predominant mode is opposed flow spread, because the upstream-most flame will consume the oxygen and any downstream reactions are unable to survive in the vitiated air [7]. However, if ignited at the upstream edge, then concurrent flamelets can survive since the fresh oxidizer reaches them directly. However, they stabilize on the edge of the burning material and cannot tunnel into the material very far before turning back upstream toward the fresh oxidizer.

Figure 11: Smoldering fingering [11] has also been seen in microgravity. 1 cm grid. Flow enters from right. Large circle is ignition point.

These types of flaming and smoldering must be better understood so that we can gain confidence that we can detect these hard-to-detect fires and fully-extinguish them so that they do not flare up into a large fire.

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