Failure of Fractional Horsepower Ventilation Fan Motors

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Abstract. Fractional horsepower motors are used to power exhaust fans such as those found in bathrooms and oven hoods. There was an increase in fires attributed to these motors shortly after the year 2000. Still, many argue that these motors cannot cause fires because they contain a thermal cutoff (TCO) unit that shuts off electrical current when the TCO reaches a specific temperature. In this paper we describe an unsafe failure mode that can occur after extended use. As fans age, the bearings wear out, resulting in heating of the coil wires. Excessive heating results in breakdown of the wire insulation, which can lead to a short between wires and create an autotransformer configuration. An autotransformer can support high current in only part of the wiring, resulting in resistive heating sufficient for ignition. With the low thermal conductivity of the coil (0.0162 \text{W/(cm°C)}) and the poor performance of the TCO (no cutoff up to 260°C), a large temperature gradient is possible. The gradient allows for ignition in one part of the motor without activating the TCO. We experimentally validated the proposed mechanism in an isolated motor and a complete fan assembly resulting in ignition after 18 s and 23 s. The assembled fan burned for more than 6 minutes before we extinguished the flames for safety reasons. Our results are consistent with field results from actual fires.

Keywords: Ventilation fan, Shaded-pole motor, Thermal protection device, Arcing, Ignition

1. Introduction

Fractional horsepower motors provide the mechanical power for small exhaust fans such as those found in bathrooms and oven hoods. These motors can cause fires if an electrical short causes high current to flow through the motor wires resulting in non-uniform or localized heating. Apart from electrical distribution and lightning equipment, which account for 48% of all household electrical fires, fans are the next largest cause of electrical fires at 6% with 2770 fires reported between 2007 and 2011 [1]. Damage from household fires caused by fans between 2006 and 2010 included 13 deaths, 130 injuries and $77 million in direct property damage [2]. Many of these fans have fractional horsepower motors. For example, half of all stationary fan fires started in a bathroom, which would use fractional horsepower motors [2]. One of the highest mortality fires attributed by some to a fractional horsepower motor happened recently resulting in seven deaths [3].

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Though deaths are not common in fires, certain populations are significantly more at-risk of dying in a fire, including children, the elderly, the disabled, minorities and those with lower incomes [4, 5]. Because of the risk of fire and potential consequences, protection from excess current must be built in to fan motors to prevent fires in the case of a motor failure [6]. In general, fractional horsepower motors fail safely, resulting in the current being cut off. Around the year 2000 however, more and more fires occurred and were attributed to these motors [7]. Such fires were reported in residential and commercial buildings with damage ranging from a burned fan to entirely destroyed buildings. We have investigated more than 50 such fires concluding that the fan was the cause of the fire and other investigators have reported similar numbers [7]. Fire fighters have taken notice and have warned of the potential fire hazard of such fractional horsepower fans [8, 9].

Manufacturers of the fans implicated in the fires argue that because the fans contain a thermal-cutoff unit (TCO) and pass Underwriters Laboratory (UL) testing they cannot start fires. One explanation they argue as to why many damaged motors have been found in fires is that the fire started elsewhere and advanced on the fan. However, the heat patterns found in numerous motors from such fires is consistent with internal heating. Many theories have been proposed for how internal heating could happen in fractional horsepower motors and how they could start fires, but few have demonstrated a fire experimentally. In this paper we outline normal operation of these motors, how they are intended to fail safely and how they can fail unsafely resulting in fire. We show experimental results validating our explanation and demonstrate an unsafe failure resulting in fire. Our results are consistent with numerous fire investigations.

2. Background

2.1. Normal Operation

Many single room exhaust fans are composed of a fractional horsepower motor connected to an impeller inside a housing. For fire safety there is a thermal safety device on the motor to prevent the motor from becoming too hot in case the unit fails. A thermal cutoff unit (TCO) is often used that cuts off power when it exceeds a specified temperature, which should protect the fan from overheating electrically. We provide further details on the motor and TCO below and their normal operation.

2.1.1. Motor When power is applied, current through the coil around the motor stator, or stationary part of the motor, produces a magnetic field which is coupled to the rotor, or rotating part of the motor. That magnetic field induces a current in the rotor windings that generates a magnetic field surrounding the rotor. The magnetic field from the stator interacts with the magnetic field from the rotor and produces a torque causing the rotor to turn. A single-phase induction motor has zero torque at zero speed so it needs an auxiliary mechanism to start the motor turning.
Many small single-phase induction motors use “shading” coils for starting, which are a set of copper windings to create a short-circuit on the stator magnetic structure [10]. The stator magnetic field induces a voltage in the shading coils which in turn produces a current. The instantaneous voltage is proportional to the time rate-of-change of the stator field (according to Faraday’s Law) and the subsequent current and magnetic field are out of phase with the stator magnetic field. The out of phase magnetic field provides the asymmetry needed to start the motor. This type of motor is called a shaded pole motor and is convenient because of the simple design and because it utilizes AC power directly. A shaded pole motor can only produce a fraction of a horsepower, but that is all that is needed for small loads like an exhaust fan.

Figure 1 shows the diagram of a shaded pole fractional horsepower induction motor next to a photograph of an actual motor from an exhaust fan. Current flows through the primary coil, which is a wire wrapped many hundreds or even thousands of times around the stator. The time-varying AC current in the primary coil induces magnetic flux in the stator, creating an electromagnet that is confined by the magnetic properties of the stator. The rotor sits in the stator with the magnetic field alternating poles as the alternating current varies. The shading coils cause the magnetic flux lines to be arranged at an angle to the rotor allowing it to start rotating. Once rotating, the rotor magnetic field attempts to line up with the stator magnetic lines of force, but because they are constantly changing, the rotor chases the stator field and continues to rotate [10].

The same motor from Fig. 1 is shown disassembled in Fig. 2. The top left photo shows the primary coil removed from the stator and the top right shows the primary coil with the wiring exposed. The bottom left shows a close up of the coil windings with the TCO visible. The bottom right shows the stator windings from the side around the core.

Figure 3 shows a diagram of the cross-section of the coil windings magnified. A copper or aluminum wire with an insulator coating is wrapped approximately 1000 to 1200 times. The magnetic core is part of the stator that is in the middle of the bobbin.
2.1.2. Thermal Cutoff

The thermal cutoff (TCO) is a safety device that interrupts electrical current when the TCO reaches a specific temperature. Without electrical current, the motor cannot heat internally and therefore cannot ignite a fire.

**Figure 2.** Disassembly of shaded pole motor with close-up photos of the motor coil.

**Figure 3.** Cutaway diagram of motor coil.

2.1.2. Thermal Cutoff The thermal cutoff (TCO) is a safety device that interrupts electrical current when the TCO reaches a specific temperature. Without electrical current, the motor cannot heat internally and therefore cannot ignite a fire. The
thermal cutoff used in motors of many of the fires we have investigated has a cut-off temperature of 136°C (277°F), which has also been reported by others [7]. Figure 4 shows the previous picture of the motor windings with the TCO outlined in yellow along with a diagram of the TCO. There is an alloy connecting the two leads inside the case that should melt when the specified temperature is reached, thus preventing electrical current from flowing. Figure 5 shows an x-ray of a TCO before and after it was heated showing that the metal was disconnected after heating.

If the TCO works as specified, it only ensures that current will stop if the TCO reaches the specified temperature. It is still possible that the TCO is a different temperature from other parts of the motor. The heat is generated by the current through the conductor. According to the second law of thermodynamics, heat will only flow away from the heat source. For the TCO to prevent coil wires from overheating, one of two assumptions must be true.

The first assumption is that the temperature differential between the TCO and all parts of the coil is small. The temperature differential depends on the physical distance and the thermal conductivity. If the TCO is far away from the coil, one would not expect the temperatures to be the same. Similarly, if there is a thermal insulator between the TCO and the coil, the temperatures will be different. In many cases, the TCO is placed next to the outer wraps of the coil. The difference in temperature is governed by Fourier’s law [11, 12]

$$q = -kA \frac{dT}{dx}$$
where \( q \) is heat flux or intensity, \( k \) is the thermal conductivity, \( A \) is the cross-sectional area of the material, \( \Delta T \) is the temperature difference and \( \Delta x \) is the distance. The relationship indicates how quickly heat \((q)\) is transferred when there is a temperature difference \((\Delta T)\) over some distance \((\Delta x)\). A large \( q \) means heat is transferred quickly and will prevent the temperature difference from becoming large.

There are two paths the heat can travel, one is along the path of the copper or aluminum wiring and the other is the shortest path through wiring, insulation and air. For the first path, the thermal conductivity of the wiring \((k)\) is very large compared to the wire insulation and air, but because the wire is wrapped approximately a thousand times, the distance \((\Delta x)\) is large, resulting in a small \( q \). For the second path, the distance \((\Delta x)\) is small, but air and insulation have low thermal conductivity \((k)\) resulting in a small \( q \). In either case the heat transfer is relatively small.

The second assumption is that resistive heating in the coil is equal to the resistive heating in the TCO. Resistive heating is proportional to the electrical current squared and the electrical resistance of the material according to Joule’s law

\[
H \propto i^2Rt
\]

where \( H \) is heat, \( i \) is current, \( R \) is electrical resistance and \( t \) is time. The resistive heating in the two locations would be the same if the current and resistances were the same for each. The resistance of the coil wire and the TCO are different because they are made of different materials and are different sizes. The current through each will be the same if there are no electrical nodes or branches anywhere between the two according to Kirchhoff’s current law. If there was a node, which could be caused by a short between turns in the wiring, then the current in part of the wiring and the current in the TCO will be very different.

If one of the above assumptions hold, then the TCO could stop the wiring from overheating. However, there are reasons to believe that both assumptions can be false, in which case the TCO would not prevent overheating and consequently not prevent ignition.

### 2.2. Assumed Failure Mode

It is known that motors may fail, which is why the TCO is required. It is known that a common way for motors to fail is for the rotor to be locked or at least impeded from full speed rotation. In this case, not all of the electrical energy is converted into mechanical energy and instead some is converted to heat. Additionally the current drawn by the motor increases. We measured an increase in current of 30–40% in test motors during a locked rotor test compared to a typical load. Figure 21 in the Appendix shows the temperature increase when the rotor is locked and when the TCO operates properly. Small exhaust fans did not have a TCO until 1994 when the UL locked rotor test increased to 14-days. In UL testing the TCO activates when the motor gets too hot and the current is interrupted. Given these tests, some have proposed it is impossible to start a fire from heating
within the coil. The problem with this reasoning is that UL tests are performed on new, previously unused fans whereas the vast majority of fires have been reported from fans that have been in use for years. It is not likely that a rotor suddenly locks, as in the case of the UL tests, but that the rotor gradually slows down over time leading to an unsafe failure mode.

One reason that rotors slow is because bearings wear out, which results in increased current and eventually burnout of the motor windings [10]. It is common for bearings to wear over time due to vibrations, misalignment, harsh environments or many other factors. It is estimated that bearing failures cause up to one-half of all motor burnouts [10]. As the temperature in the coil goes up, the insulation in the coil wears down. It has been estimated that every 10°C a motor is operated above its rating, the insulation life of the motor is halved [10]. If the insulation between windings breaks down there can be short-circuit current between the windings. A short circuit causes high current to flow because the resistance is low and leads to localized heating. The TCO in theory would prevent overheating in this case and prevent a fire. We show in the next section several examples of field examples of exhaust fans with motors that started to fail and exhibited localized heating and in some cases ignition.

3. Localized Heating in Field Examples

The Guide for Fire and Explosion Investigations (NFPA 921) explains that if current flow increases in a motor, the motor windings can become hot enough to ignite insulation or plastics that are part of the motor or housing construction [13]. An increase in current can happen if the rotor is stopped while the motor is still energized. Shaded pole motors are specifically mentioned because “they are often of open construction, and could ignite combustibles that are in contact with them if the windings get hot enough [13]”.

The Guide recommends examining motor windings to determine if they were heated. Unheated motor windings with fire damage around the motor would indicate the motor was not the cause. On the other hand, “if the windings are thoroughly baked, with oxidized strands all through, but materials around the motor are not so thoroughly heated, that indicates that the windings overheated”. If the fire burned everything in the area of the exhaust fan, the guide suggests it would be difficult to know whether the fire started in the fan or not. We found it is possible to identify damage from internal versus external heating by identifying changes of different materials in the motor.

Changes to materials at specific temperatures, such as melting, provide evidence of the minimum temperature a material has reached. Table 1 lists effects of heating observed in various materials in a motor and the minimum temperature at which these effects are possible [14, 15]. Motors found in some fires are so damaged from an extensive fire, it is difficult to observe all of these patterns. Figure 6 shows several cases of failure when a motor started smoking or when a fire was quickly extinguished. It can be seen which parts of the fan and motor reached certain temperatures and which did not. With an advancing fire, one would expect
the heat to be uniform, but in many cases there is non-uniform heating traced to the motor windings. We have also encountered motors with melted copper, indicating it reached 1085°C, while the bobbin is undamaged—indicating a maximum temperature of approximately 215°C. The measured distance between the two was 0.7 cm, which is a temperature gradient of 1240°C/cm. This gradient corresponds to a heat flux of 22 W/cm², which is much higher than the 2 W/cm² produced by an advancing fire at flashover [16]. From these cases it is clear that internal localized heating that could lead to a fire is possible.

## 4. Proposed Failure Mechanism

We propose a failure mechanism that is consistent with all of the evidence we have gathered. The failure mechanism can best be described by comparing an electric motor to a transformer. A transformer and a motor both transfer energy through a magnetic field. A motor converts the energy into mechanical energy causing something to rotate. A transformer converts the magnetic energy back into electrical energy for use in an electrical circuit [17]. The top of Fig. 7 shows the diagram of a transformer with a primary coil on the left and a secondary coil on the right. Assuming that energy is conserved, the power in each coil should be the same, but the current will depend on the number of turns in the coil. The ratio of current in each coil is inversely proportional to the voltage and number of turns according to the following equation:

\[
\frac{V_P}{V_S} = \frac{N_P}{N_S}
\]

where \( V \) is voltage, \( I \) is current and \( N \) is the number of turns. The subscript \( P \) indicates the primary coil and the subscript \( S \) indicates the secondary coil. Transformers are a useful tool in electronics for changing voltage or current while preserving power [18].

### Table 1

**Heat Effects on Fan Components [14, 15]**

| Material                  | Observed change                  | °C  | °F   |
|---------------------------|----------------------------------|-----|------|
| Cu wires                  | Melting                          | 1085| 1984 |
| Al wires                  | Melting                          | 660 | 1221 |
| Wire insulation           | Charring                         | 425 | 797  |
|                           | Clean burn                       | 550 | 1022 |
| Nylon bobbin              | Brown/black discoloration        | 250–300 | 482–572 |
|                           | Charred black                    | 300 | 572  |
| Zinc bearings             | Melting                          | 400 | 752  |
| Electrical leads (PVC insulation) | Melting                  | 200 | 392  |
| Al housing                | Melting                          | 660 | 1221 |
A typical transformer consists of two separate coils that are not electrically connected. Power is transferred between the coils through magnetic flux. An auto-transformer is a particular implementation of a transformer that appears to use only a single coil for both input and output voltages [19, 20]. An electrical node in the middle of the coil effectively splits it in two. The first winding is the entire coil and the second winding is the common winding. The bottom of Fig. 7 is the dia-

**Figure 6. Incipient failures showing heating of motor.**

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gram of an autotransformer showing the different current in the two coils. We note that input and output current are equal, but where the short takes place the current could be dramatically different. Autotransformers are used in some cases because they can be considerably smaller in size and weight as well as have decreased losses [18].

Any coil, such as the primary coil in the fractional horse power exhaust fans, could potentially become an autotransformer if there is a short between turns in the coil. For a short to occur between two points of the wire, there would need to be a high enough voltage to break down the electrical insulation around the wires or the insulation would need to degrade. The electrical breakdown voltage of the insulation is thousands of volts, which would be unlikely given household voltage in the United States is 110 V. The insulation does degrade over time though, especially when heated. During normal operation the coil is heated to approximately 110°C, with local hot spots having a higher temperature. The TCO should prevent

Figure 7. Above—transformer diagram. Below—autotransformer diagram.
the windings from getting hotter, but it has been shown that the TCO does not necessarily work as described. Others have demonstrated that some of the TCOs still operated up to 260°C when it was rated at 136°C. In most electrical circuits, a short would result in enough current to activate the fuse or the TCO. In a transformer, the short-circuit current between a few turns can be very high while the terminal current can be small [21].

The failure mechanism described explains why the coil will heat enough to degrade the insulation to the point that a short will happen and why a short will not activate the TCO. With enough heat, materials in the motor will ignite and cause a fire. Our proposed mechanism is consistent with electromagnetic theory and results observed in the field. Additionally, it is known that transformers fail similar to motors resulting in fires. NFPA 921 includes a section on examining transformers as a potential source of fire. It states that with long-term use and elevated temperatures, the windings may deteriorate. Windings may then begin to short to each other, resulting in an impedance drop and more current flows leading to greater heating. It is known that a very high percentage of all transformer failures arise from faults between turns [21]. NFPA 921 says, “Overheating of the windings can be determined when there is a clear pattern of internal heating, arcing turn to turn, and a pattern of fire travel out from that source [13]”. This description applies to the cases we have shown previously where we have identified shorting turn to turn. Such shorting has also been reported by others [7].

Another proposed failure mode is a substantial build-up of lint igniting when an arc forms at the crimp connection between the aluminum windings and the copper lead that goes to the AC plug. The crimped splice can create an issue of different coefficients of thermal expansion and different electrical resistances. A failure may occur which would initiate a momentary arc. In a larger electrical system with more power, such an arc is a well-known cause of fires. The power of such an arc in a fractional horsepower fan is small and could only ignite a liquid, vapor or perhaps lint. The autotransformer mechanism we have explained in this paper results in melting of the bobbin, which creates vapors that can ignite. We have observed many field examples where the crimp was intact and the bobbin melted, consistent with our autotransformer explanation and not consistent with an arc at the crimp. Additionally, we have seen field examples of fans in use for a short time where lint could not have built up. All of the dozens of field examples we have seen are consistent with the autotransformer explanation, while only some examples are consistent with an arc at the crimp connector or the possibility of lint igniting. There are cases we have observed that are consistent with both explanations. It may be that the excessive current in the autotransformer heats the bobbin and creates a vapor while the extra draw in current leads to the crimp failing and an arc ignites the vapor and creates a sustained fire.
5. Experiments and Field Results

In this section we demonstrate experimentally three parts to our proposed mechanism: (1) how the electrical insulation can break down, (2) how a short between wires results in significantly more current in the coil than the winding near the TCO and (3) how heat does not transfer efficiently from within the coil to the TCO. Together these experiments show how the assumptions necessary for the TCO to prevent a fire can both be incorrect. Lastly, we also demonstrate that an electrical short in the motor wiring causes ignition and sustained burning of an exhaust fan.

5.1. Insulation Breakdown

The insulation around the wires is often a varnish applied in liquid form, which then dries to provide an insulating layer around the metal. As pointed out elsewhere, the thickness of the insulation may be non-uniform due to the manufacturing process which results in regions that have much less insulation between wires [7]. Insulation is given a rating based on the maximum operating temperature allowed. The insulation used in these motors has been found to be NEMA class B or F with a maximum allowable operating temperature of 130°C or 155°C, as seen in Table 2. So even if the TCO rated at 136°C worked perfectly and the heat transfer between the coil and TCO were perfect, the temperature could exceed the operating point of the insulation leading to degradation [22].

We used FTIR spectroscopy to determine that the insulation material is made from thermoplastic polyurethane (TPUR), which loses most of its strength above 100°C [23]. We were also informed that the insulation is polyurethane covered by polyamide, but we did not independently confirm the polyamide covering.

We also heated the wiring to a given temperature for 10 min and observed the effects on the insulation as shown in Fig. 16 in the Appendix. Note that after just 10 min at 260°C the degradation of the insulation is visible, but starting at lower temperatures. Degradation is not just a function of maximum temperature reached, but also is cumulative over time. Substantial damage may occur below 260°C if it takes place over a long time.

The literature reports that for approximately every 10°C Celsius above the rated insulation temperature, the time-to-endpoint or lifetime of the motor decreases by 50% [24]. Figure 8 shows this relationship for 4 different NEMA class materials.

| Temperature tolerance class | Max operating temperature (°C) | Max operating temperature °F |
|-----------------------------|--------------------------------|------------------------------|
| A                           | 105                            | 221                          |
| B                           | 130                            | 266                          |
| F                           | 155                            | 311                          |
| H                           | 180                            | 356                          |
It can be seen that once the temperature of the motor rises above the rated temperature, the lifetime is rapidly reduced. A 30°C temperature rise over the threshold leads to a 90% decrease in motor lifetime. For a class B material that temperature would be 160°C. For reference, if the insulation had been class F the decrease in motor lifetime would only have been 25%, or a 7.5 times longer life at that temperature.

The maximum or hot spot temperature can also be related to the percent load on the motor [24]. As the load increases, there is more loss in the motor turned into heat, which in turn decreases the lifetime of the motor. Table 3 shows the relationship between the increase in load and lifetime of the motor for class B insulation [24]. The far right column shows the expected life assuming the motor is originally rated for 20,000 h. The hot spot temperature is calculated using the equation $T_{HS} = F \times AT + T_A$ where $T_{HS}$ is the hot-spot temperature, $F$ is the rated loss factor, $AT$ is the allowable temperature rise for that class of material and $T_A$

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**Figure 8. The relationship between maximum temperature and lifetime of the motor for different NEMA class insulations.**

**Table 3**

| % Load | % Loss factor | Hot spot temp °C | Expected life (%) | Hours |
|--------|---------------|------------------|------------------|-------|
| 100    | 100           | 130              | 100              | 20,000|
| 110    | 119           | 147              | 29               | 5800  |
| 115    | 130           | 157              | 14               | 2800  |
| 125    | 146           | 171              | 5.4              | 1080  |
| 150    | 212           | 231              | 0.09             | 18    |

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is the ambient temperature set to 40°C. It can be seen that a relatively small increase in the load, which could be due to the fan bearings wearing, can lead to a dramatic decrease in expected life of the motor.

The increase in operating temperatures that would lead to the degradation may be traced to the increased mechanical load on the rotor. As described previously, it is well known that a locked rotor will result in a dramatic increase in temperature in the primary coil wire. Heating will also be observed to lesser degrees when the rotor is not working efficiently. We measured the force at the edge of the fan blade necessary to stop it from moving to be 20 g resulting in a stall torque of 117 g-cm. Such a small torque could be the result of the rotor bearing wearing over time. This explanation is consistent with the fact that many of the earliest fires reported from these fans were in commercial settings where the fans would have been operating nearly continuously, resulting in the bearings wearing out more quickly.

Samples taken from fire investigations show a pattern of degraded, charred or completely burned insulation. Figure 17 in the Appendix shows wires that are charred brown or black or even where the insulation is cleanly burned off.

5.2. Autotransformer Heating

To demonstrate heating due to the autotransformer effect, we performed several tests. Figure 9 shows the setup and result of the first experiment. Figure 20 in the Appendix shows a diagram of the setup for more detail. We disassembled the motor and created a short by exposing one of the wires in the coil and connected it electrically to one of the motor leads as seen on the left. The coil resistance was approximately 25 Ω and the electrical connection shorted the final 25% of the coil. We did not remove the TCO in this experiment. We then reassembled the motor and turned it on for several minutes as seen in the center. The test was stopped when the motor started sparking. We then disassembled the fan and examined the wiring shown on the bottom right of Fig. 9. The heating was sufficient to cleanly burn off much of the wire insulation, indicating a temperature in excess of 550°C. Such dramatic heating could not be the result of increased current due to a reduction in the impedance by 25%, but is the result of the autotransformer effect that can heat the wiring significantly.

In the second experiment weshorted the coil wiring in the same manner with a 20% tap of the autotransformer. In this experiment we left the TCO in place. We installed two thermocouples to measure temperature, one near the core of the coil and one near the TCO. The motor was placed back in the fan housing and ran for several minutes. Figure 10 shows the steady state operating temperature near the TCO is approximately 110°C. When the short was applied the temperature rose to 200°C before the TCO activated. Once the TCO shut off the current the temperature dropped down.

The third test was to measure the current in the shorted coil compared to the main coil to verify that current was different in the two coils because of the autotransformer effect. We shorted a 4.5 Ω section of a 33 Ω coil motor running with an impellar. The line current before shorting was 0.79 A and after shorting it was
Figure 9. Testing autotransformer heating by exposing a wire in the middle of the coil, shorting it with the electrical ground and observing heat damage after operating.

Figure 10. Temperature at two points on a motor with a shorted coil.
1.24 A. The external shorting wire had a current of 4.2 A, so the current in the second coil was approximately 3 A. When we account for current converted to mechanical motion of the impellar, the motor losses and the variance of coil turn length our results approximately match the transformer equation. We note that the increase in current in the small coil is 375% compared to 30–40% in the locked rotor case.

A fourth experiment was conducted to verify that the current in the smaller coil is produced by the autotransformer effect. With a typical shaded-pole motor we wound an additional 100 turn coil around the outside of the existing coil, while ensuring it was electrically independent of the existing motor coil. When the motor was plugged in and the two ends of the additional coil were left unconnected in an open circuit, the running current of the motor was 0.22 A and there was no current in the additional coil. When the two ends of the additional coil were shorted, the current in the main coil increased to 0.38 A and the current in the additional coil was 3.9 A. Given that the two coils are electrically isolated, the only way for power to be coupled from the motor coil to the additional coil is through magnetic induction.

The resistance of the additional coil was measured to be 1.5 Ohms and with 3.9 A of circulating current it would produce 22.8 W of thermal power. We ran this for approximately 1 min and using a type K thermocouple measured a surface temperature in excess of 120°C. This experimental setup is unlike the previous tests because the two coils are electrically isolated. So we connected the additional coil to the 120Vac circuit and the behavior of the additional coil did not change. This final circuit setup is equivalent to creating a short in the middle of the windings as done in the previous experiments.

From these experiments it is clear that the autotransformer effect results in two currents and heats the coil in a non-uniform manner. It is also clear from the second experiment that the TCO did not operate according to specifications, which is supported by other literature [7].

Examples collected from fire investigations have shorted wires as seen in Fig. 11. On the left is the motor coil under an optical microscope while the fig-

![Figure 11. Shorted wires magnified.](image-url)
ure on the right is an SEM image of such a short at high magnification. Isolated beads like these are indicative of an electrical failure and not damage from an advancing fire [25].

We so far have demonstrated that the insulation can break down, leading to a short and we have demonstrated that a short can lead to localized heating. The next section examines why the TCO does not activate if the coil is hot enough to ignite.

5.3. Heat Transfer

If heat was transferred efficiently in the motor, then a heated coil quickly results in a heated TCO and cuts off the current. How efficiently heat is transferred depends on the thermal conductivity of the material and its geometry according to Fourier’s law discussed earlier. The thermal conductivity of Cu is 385 W/(m °C) and of Al is 204 W/(m °C). The length of the coiled wire is approximately 100 m with a diameter of 0.3606 mm or a cross-sectional area of $9.8 \times 10^{-8}$ m$^2$. The thermal conductance or an equivalent heat along the length of the wire is calculated to be approximately $3.77 \times 10^{-7}$ W/°C.

The other path for the heat to transfer would be straight from the source to the TCO. In this path there is the electrical insulator and air spaces between the wires. The effective thermal conductivity in this path will be much smaller than if the space was completely filled with metal. The geometry is complicated, so an analytical model is difficult and we instead measured it experimentally. To measure conductivity, we applied heat uniformly to the primary coil of the motor and measured the temperature at different points in the coil. Heat was applied using two 2000 Watt (W) infrared heaters. A heat flux sensor was used to adjust the heaters to obtain an average flux of 2 W/cm$^2$. Temperatures were measured in the coil using the $\Delta R$ method at three different locations (inner, middle and outer wraps of the coil wiring) and a type K thermocouple was placed under the insulating wrap next to the outer windings of the coil. Figure 18 in the Appendix shows a diagram of the setup.

Figure 12 shows the temperature data collected at the four different locations over time. Two temperature differences are plotted. In the bottom plot “TC_Outer-Coil_Outer” represents the temperature difference between a thermocouple close to where the TCO is located and the temperature of the outermost wire. “Coil_Outer-Coil_Inner” represents the temperature difference between the outermost and innermost coil wires. From this data we calculated the thermal conductivity in the coil to be approximately $0.0162$ W/(cm °C).

We performed another test to verify our conductance measurements. In this experiment we heated the coil from the inside by connecting a DC power supply to the inner most coils of the wire. We measured the temperatures in the same manner as described in the previous experiment. Figure 13 shows the temperature data collected at the same four locations over time. We performed the test at several different power levels. We then calculated the conductivity to be approximately $0.018$ W/(cm °C), which is within 10% of the previous experiment.
If the distance is approximately 1 cm, the conductance is approximately 0.016–0.018 W/°C. This result shows that the heat transfers more quickly along the direct path to the TCO than along the length of the wire, but the thermal conductance along the direct path is still small—less than 0.5% of that of pure copper. This result implies that the temperature difference between the locations in the coil and the TCO may be large. If the temperature difference can be large, the coil can overheat and cause ignition before the TCO gets hot enough to activate.

**Figure 12.** Temperature at different locations in the motor when external heat of 2 W/cm² applied.
5.4. Ignition

The final experiments tested our proposed failure mechanism in a working motor to see if a shorted coil would ignite a fire. We used a typical bathroom exhaust fan and a two speed motor (ACME model 4673) with approximately the same resistance as the original motor (36.7 Ω compared to 25 Ω). We chose this motor because it already had a tap to create the autotransformer and the TCO removed. The tap for the higher speed was at 26.7 Ω, so we shorted the final 10 Ω for the ignition test.

Figure 13. Temperature at different locations in the motor when internally heated with DC current.
The first test was with a motor and fan removed from the exhaust fan assembly. Figure 14 shows the test setup and progression, including when the fan starts, when the coil is shorted, and several seconds later when the motor starts smoking.

**Figure 14. Ignition of fan motor with coil shorted.**
followed by a flash when the motor ignites. The motor can be seen with flames coming out of it which ignites the impeller that eventually burns completely.

To confirm these results in a complete fan assembly we repeated the experiment with a shorted motor in a completely assembled fan. Figure 15 shows a sequence of frames from the video of this experiment from top left to bottom right. The fan housing is in the position it would be when installed and a mirror is placed at a 45° angle underneath the assembly to show the underside of the fan housing. The first frame shows the setup right before turning on the fan. After several minutes of operating, the fan begins smoking and then a flash is observed followed by the flames in the area of the motor. The first frame on the next row shows the plastic covering catching fire followed by flaming melted plastic dropping. The entire plastic covering then drops and continues burning vigorously for several minutes before it was put out with a fire extinguisher for safety. The entire sequence takes place over approximately 12 min.

These experiments show that shorting the coil wires does in fact lead to ignition of the motor, the fan impeller and the fan housing. The extent of the flames was large and could easily have ignited other materials if it was installed in a building.

6. Discussion

In this work we provide an explanation of the mechanism that results in ignition of fractional horsepower motors consistent with the early failures of the motors in practice. Ignition is possible because the resistive heating in the coil is high enough to ignite materials in the fan. The current is large because of the autotransformer effect that results in effectively two coils with different currents. The autotransformer effect occurs when a short occurs between turns of the motor wires. A short is possible because the insulation covering the wires degrades over time, especially when heated. Heating can occur because the bearings on the fan wear down, causing more friction in the rotor. The increased friction results in more energy in the coils causing the heating. The thermal cutoff does not prevent such heating because it is on the outside of the coil and there is a small thermal conductivity between the coil and the TCO. It has been shown that the TCO often does not work as specified, further compounding the problem.

Our experimental results confirm each step explained above. Finally, we tested the complete system to see if ignition would take place. To the best of our knowledge, this is the first example of an experimental demonstration of ignition of such a fan. We also show throughout the paper that the explanations are consistent with results found in practice from fire investigations. Our results are consistent with recent results published by the Consumer Product Safety Commission, which tested on 100 fans and TCO devices. The report supports making changes to the relevant standards [26].

One question that arises is why there was a sudden rise in the number of fires attributed to these fans. Several changes to motor designs may contribute to the sudden increase in fires. In 1994, UL tests required that fans not exceed 200°C (392°F) in a 14-day locked rotor tests. Thermal cutoffs (TCO) were incorporated
Figure 15. Ignition of an assembled fan motor with coil shorted. A mirror was placed at a 45° angle underneath the fan assembly to view the bottom of the fan assembly.
into motors to prevent this situation. In the year 2000, some motors started using a new type of TCO that has been demonstrated experimentally to perform significantly less than its specifications [7]. The type of wire used changed from copper to aluminum, lowering the melting point. Also the wire insulation changed to have a lower degradation temperature. Each of these changes likely contributed to the problem.

Many of these motors were produced from 2000 to 2003. The first fires were reported within a few years. It may have taken some time for the bearings of the fans to wear out. Interestingly, many of the first fires reported were in commercial buildings where the fans would have been used much more frequently or even continuously. In residential buildings it would be expected that such fans are used much less frequently. As more of these fans have reached the point of degradation over time we have seen more fires reported in residential locations.

7. Conclusions

Though some have claimed that fractional horsepower motors cannot ignite fires, our results demonstrate this is not the case. As fans get older, the bearings will wear, resulting in degradation of the wire insulation, leading to shorting between the coil wires, resulting in high currents due to the autotransformer effect and subsequently causing more fires. These results have important consequences given that tens of millions of such fans are installed in businesses and homes throughout the country.

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Appendix

See Figs. 16, 17, 18, 19, 20 and 21.
Figure 16. Thermal degradation of outer coil insulation at different temperatures for 10 min.
Figure 17. Thermal degradation of wire insulation in practice.

Figure 18. Diagram of experimental setup to measure temperature gradient. This is a cross-sectional view, so each colored layer is a coil. The voltage and current of each of the three coils was measured.
Figure 19. Photograph of experimental setup with IR heaters and motor in the center. Diagram of setup with dimensions and heat flux.
Figure 20. Diagram of motor with shorting wire to create autotransformer. The red line is an additional wire which is electrically equivalent to the adjacent wires shorting.

Figure 21. Temperature gradient induced by locked rotor test on new fan.
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