It is known and accepted in fire investigation that a fire occurring in any parked vehicle with the engine shut off for longer than an hour or so is either of incendiary or electrical cause. A fire in the engine compartment makes the charging system a potential ignition source that must be addressed. The principal emphasis of this article is on automobiles produced since the mid-1960s. However, it also applies to any equipment with an internal combustion engine, a charging system, and a battery, be it stationary, marine, construction, or a bus, truck, ATV, garden tractor or motorcycle.

ALTERNATOR FIRES IN VEHICLES

BY PAUL W. HANSEN, P.E, EDINA, MINNESOTA—Vehicles built before the 1960s had generators — direct current (D.C.) machines — rather than alternators. Unless the charging system was modernized subsequently, this article does not apply to such vehicles. Generators, in addition to being heavy and expensive, were unreliable by today's standards and required replacing brushes frequently. In addition to this periodic maintenance, it was also necessary to have a relay between the generator and the battery to prevent the battery from discharging through the generator windings when the engine was off. The alternator was a huge step forward for electrical reliability in vehicles. The solid-state rectifier diode made the use of an alternator in a vehicle possible. This advance in alternator technology was pioneered by the Chrysler Corporation in the early 1960s. Other manufacturers quickly followed suit.[1]

THE ALTERNATOR

An alternator is a rotating machine. In its simplest form an alternator is made by rotating a magnet inside a field of *pick-up coils* which translate this moving magnetic field into a sinusoidal alternating current (A.C.) voltage. Figure 1 depicts this simple machine. The A.C. produced by the alternator is turned into a D.C. voltage to charge the battery and run the electrical system. Diodes, the critical element in changing A.C. into D.C., are solid state devices that block current in one direction but easily pass it in the opposite direction. In drawings, they are represented by an arrowhead with a bar at the point of the arrow. Current — from positive to negative — passes easily in the direction of the arrow, but is blocked in the opposite direction. Figure 2 shows typical rectifiers for single-phase and three-phase alternators. The output of an alternator with its diodes arranged in what is often called a *bridge* or *full-wave* rectifier is a voltage roughly similar to D.C. The difference between a D.C. voltage from a battery and the output of the rectifier bridge is that the output voltage of the rectifier bridge oscillates around a flat-line output where the battery voltage does not. These oscillations are referred to as *ripple*. Practical A.C. alternators are polyphase: that is, there is more than one winding set inside the alternator. These sets of windings each produce an A.C. output offset from the other similar outputs. The more of these windings (or *phases* as they are referred to) there are, the smaller the ripple and the smoother (more resembling the battery flat-line) the D.C. output. Such alternators have three or more phases. For simplicity, we shall discuss the three-phase machines, but the same principles apply regardless of the number of phases. Figure 3 shows the outputs of single- and three-phase alternators before and after rectification. The three-phase rectified output is obviously closer to D.C. and more desirable than is the single-phase output.

FIGURE 1
Simple Single-Phase Alternator

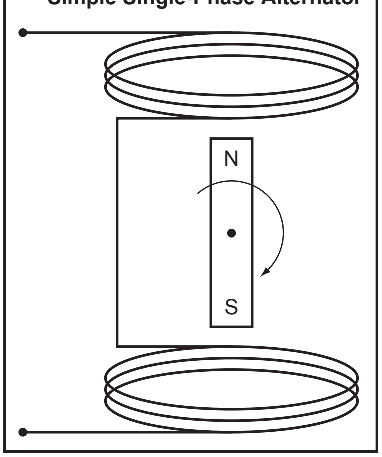


FIGURE 2
Rectifier Circuits

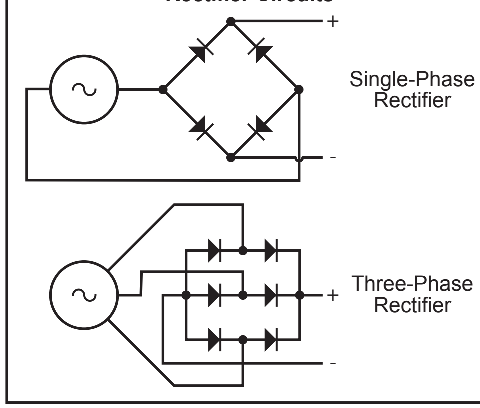
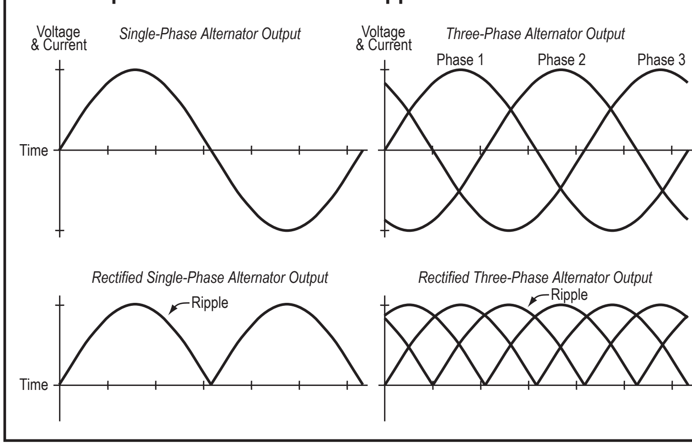
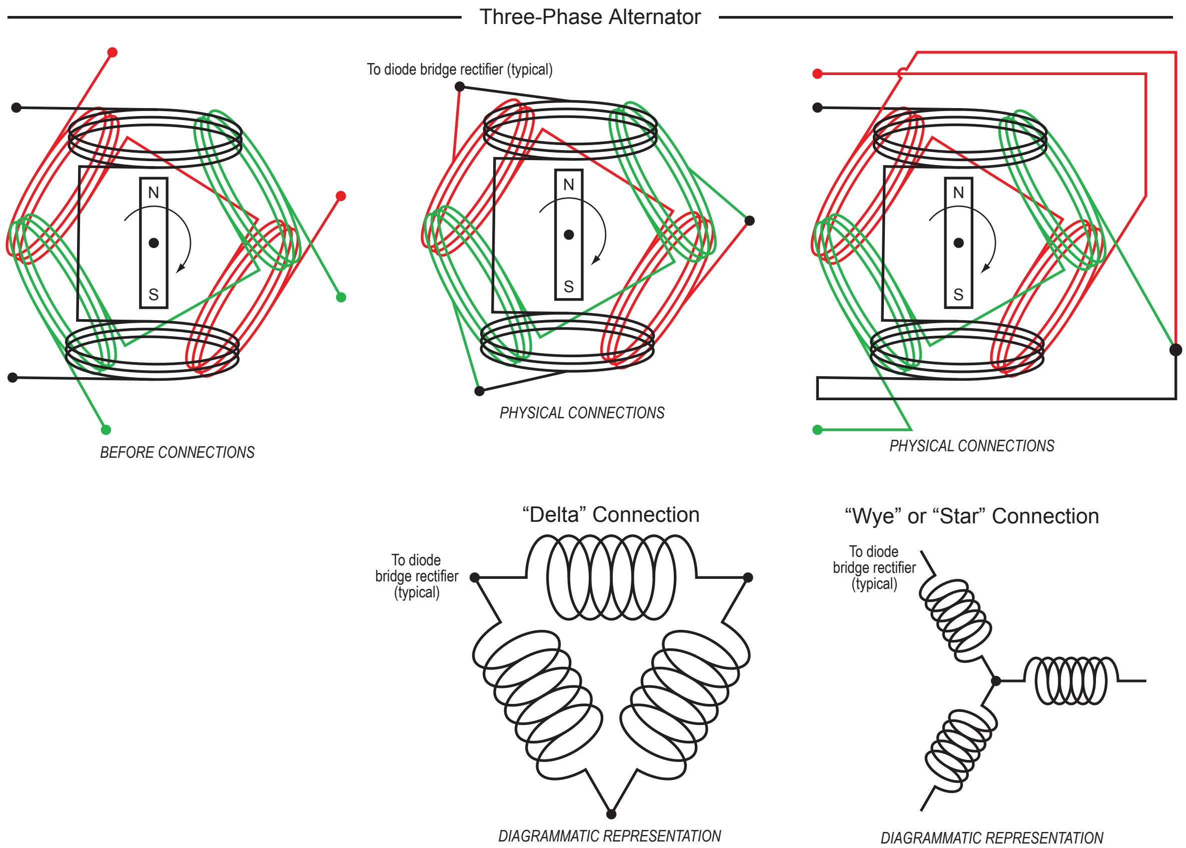


FIGURE 3
Multi-phase alternators reduce ripple and make "better DC"



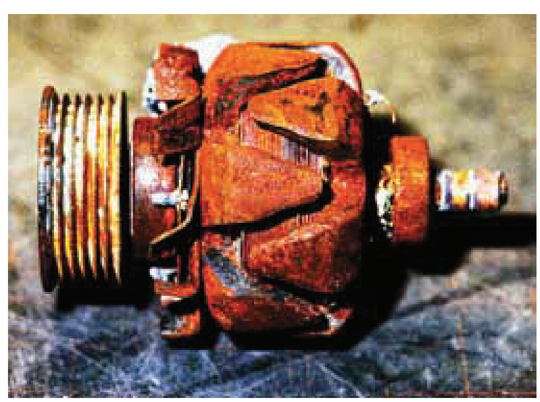
There are two ways to connect the windings of a polyphase (we shall assume 3-phase) alternator. In one scheme, one end of each of the windings is connected together in a common connection, and each of the other ends feeds the rectifier. This connection is referred to as a *star* or *wye* (*Y*) connection. Alternatively, the outputs can be *daisy-chained* in a circle, that is, the output of one feeds the input of the next and so on until the output of the last is connected to the input of the first. This method is called a *delta* connection. Figure 4 shows these two connection schemes. In the delta connection, each tied-together connection is an output of the alternator windings to the rectifier. Over the years, both connections have been used for automotive applications, but lately, the delta connection has been used far more frequently. Since this change about 25 years ago, it is interesting that most automotive manufacturers have not bothered to update the drawings in their manuals. Although the manuals invariably show a wye-connected alternator, the actual (newer-model) alternator is delta-connected. Delco, for one, changed designs from wye- to delta-connected around the mid-1980s. Delta-connected alternators have **two** wires coming from the windings to each of the three rectifier connections. Note that some alternator re-builders cut one wire short and connect to the rectifier bridge circuit with only one wire per connection. Electrically this is equivalent; mechanically this is easier for the re-builder.

FIGURE 4
Possible (Practical) Alternator Connections



ALTERNATOR CONSTRUCTION

The *Lundell Claw-Pole* alternator commonly seen in vehicles today was developed in the 1930s by the Chrysler Corporation. When originally developed, these alternators lacked a reliable rectifier circuit, which made them unusable. However, with the invention of the solid-state diode in the late 1950s, they became practical and were introduced by Chrysler in 1961. By 1965, Ford and General Motors had adopted the technology.[2] The Lundell Claw-pole alternator is typically a three-phase machine designed to produce adequate voltage over a fairly wide range of RPMs — because engine speed is not constant. The field or *magnet* of the alternator is the rotating piece (*rotor*) of the alternator; the stationary part (*stator*) is the windings or pick-up coils where the voltage/current is produced by the rotating magnetic field. There is a voltage regulation circuit to ensure that the output voltage remains close to the desired voltage level over the operating RPM range. This device regulates the current/voltage in the rotor. Since the voltage regulator is not a high-current device, it is not a practical candidate for fire ignition. The heart of the automotive three-phase alternator is a full-wave rectifier consisting of six power diodes which convert the three-phase alternating current (A.C.) output into near-D.C. as described earlier. Lundell was the engineer at Chrysler who



This rotor from a fire-damaged Lundell alternator shows the unique "claw-pole" configuration.

developed the design, and *claw-pole* refers to the unique configuration of the rotor. In recent-model alternators, both the voltage regulator (encapsulated) and the rectifier assembly (six diodes) are in the end cap of the alternator opposite the drive pulley.

Varying temperature requirements are a concern with *generic* motors and alternators. For non-automotive applications, generally there are nameplates with the various ratings — notably temperature — imprinted. With this information the end user can make an informed decision as to whether or not the motor or generator is suitable for the application. Such is not the case for an automotive alternator: these devices have no application beyond the vehicle/engine compartment for which they were designed, so the *nameplate* data consists of "for a 1993 Mustang V-8". One may have the option of *heavy-duty* or *standard*. Usually, heavy-duty means that the alternator puts out a few more amperes than the standard unit, which is useful if one has added after-market electrical equipment (stereo system, electric water pump, cooling fan, etc.) or will be towing a trailer with electrical requirements. Typically, the only nameplate data is a model number stamped or printed somewhere on the alternator housing.

The power diodes forming the full-wave rectifier in contemporary 12-volt systems are rated for 48-volts and, typically, will be rated for at least 1/3 of the nominal current rating of the alternator. For example, a 120 ampere alternator will have diodes rated for at least 40 amperes.

POWER DIODES

Diodes are designed for two different purposes: high-speed switching and power rectification. The latter are used in the rectifier circuits of alternators. To summarize briefly how a diode works, it is a device with one junction — a region in the volume of the device where a semiconductor doped with positive ion impurities (*p region*) abuts a semiconductor region doped with negative ion impurities (*n region*). Together, this forms what is called a *p-n junction*. In a diode, there is only one junction. At this junction is a *depletion region* overlapping the junction on both sides. Negatively-charged ions collect in the p region and positively-charged ions collect in the n region. The bottom line is that the device will conduct current very easily in one direction, but will block current in the opposite direction — up to a certain voltage. This maximum voltage is determined by the characteristics designed into the depletion region. Failure mechanisms of a diode junction invariably involve heat and the migration of the p impurities into the n region and vice-versa, destroying the junction. The process occurs — usually slowly — over time. It is accelerated both by heat and excessive voltage applied in the reverse direction (the direction normally blocking current flow). The process is also aggravated if the diode junction is not built properly (manufacturing defect). Failure of the junction itself initially results in a shorted diode.[3,4] As heat and temperature increase with current flow, the lead may *unsolder* or the junction may destroy itself. Either case results in an open-circuited diode. Naturally, a failure mechanism of the diode package can be a disconnected lead. The open circuit thus resulting will be of no interest to a fire investigator. In the tests I ran, I began by systematically causing diode failure with a combination of heat and high voltage. I found that new, properly-made, diodes are generally quite robust. The conclusion is that a failed diode in a one-year-old alternator almost certainly shows a manufacturing defect in the diode. Older diodes typically require less reverse voltage and less current through the junction (producing heat in the junction) to cause failure.

Diode junctions typically fail first as shorted: i.e. allowing current flow easily in both directions.[3,4] This is the failure mechanism of interest to a fire investigator. If this situation persists, the diode may eventually destroy itself with heat, resulting in an open circuit. This of course can occur only if sufficient current and heat is available for a long enough period to cause such a demise.

ALTERNATOR FAILURES — FAILURES ANYWHERE BUT IN THE RECTIFIER

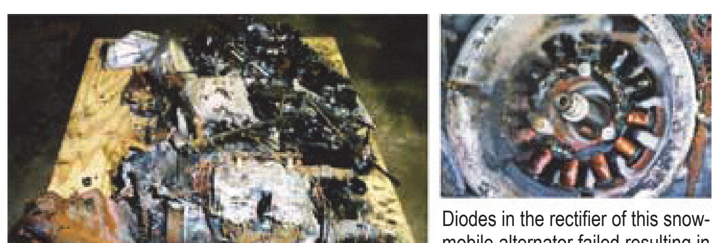
Winding-to-winding shorts reduce the number of effective turns in both motors and alternators. In the case of an alternator, which generates electricity, the net effect is a reduction of the voltage output for that winding, which results in a reduced overall output, but not in a heat problem within the alternator. Further, a winding-to-winding short-circuit by itself cannot and will not cause a fire in a vehicle that is not running. For this *short* to produce excessive heat, electricity must flow into the alternator, and this circumstance requires a failure in the rectifier. However, given an initial rectifier failure in which power flows through a winding, the likely outcome is that the winding will develop multiple short circuits due to overheating, thus drawing even more current from the battery as available.

Bearing failures can occur in the alternator, and the failure of a bearing has its own obvious symptoms. Either the bearing itself overheats and produces ignition, or the alternator (as with all belt-driven equipment) seizes and the belt ignites. A bearing failure as an ignition source is not possible for a fire occurring long after the vehicle has been shut off and parked.

ALTERNATOR FAILURES — FAILURES IN THE RECTIFIER

Regardless of whether the alternator is delta or wye-connected, the phases (we assume three) from the stator are each connected to the rectifier bridge. As noted earlier in this article, the standard manufacturer's drawing shows a wye connection, but the fact is that the delta connection is used almost exclusively today.

With properly-functioning diodes, power can flow only one way — from the alternator to the battery — never the reverse. The fact is, with windings that are not shorted to ground, two diodes must fail in a delta-connected rectifier in order to let battery current flow through the alternator. Referring to the three-phase rectifier in Figure 2, a failure (shorted diode) of one of the left three diodes and one of the right three will result in a path through the alternator (windings) in two of three cases and in a dead short through two diodes (not involving the



Diodes in the rectifier of this snowmobile alternator failed resulting in a fire causing selective damage to the windings embedded within the engine housing. This type of winding damage is proof of diode failure, but not all diode pair failures will result in this indication or "tell". Ignition occurred at the charging system cables.

windings) in one out of three cases. Note that two failed diodes on the same side of the rectifier cause no battery current flow, and there will be no resulting fire.

It is very possible that the failure of a single diode will go unnoticed and that, while the alternator output is degraded, the battery will probably still charge, particularly if most driving occurs at highway speeds and the trips are not short.

A HISTORICAL NOTE FOR FIRE INVESTIGATION:

Until about the mid-1980s, automobiles typically had a grounded capacitor at the generator or alternator positive output to filter out brush noise so it would not get into the radio. This capacitor was a throw-back to the days of the generator, where there was always electrical noise from the brushes and commutators which made annoying contributions to the sound from the radio. This capacitor, connected as it was between the battery positive terminal and ground (connected to the battery negative) is problematic if it short-circuits. This puts full battery current to ground through the capacitor resulting in the spectacular destruction of the capacitor. Generally around the mid-1980s, automobile manufacturers stopped putting these capacitors in charging systems. The failure of such a capacitor is indicated by an obvious hot spot on or in the alternator casing. For these older vehicles, the electrical manual published by the manufacturer is the best place to start to determine if this device is even in the circuit. It is always best to go to the manufacturer for specific information. The "one-book-fits-many" manuals spanning a few years often provide incorrect information. The location of the radio noise capacitor varied from manufacturer to manufacturer. For instance, Delco (General Motors) mounted them inside the alternator end cap, and Honda mounted them externally on the alternator housing.

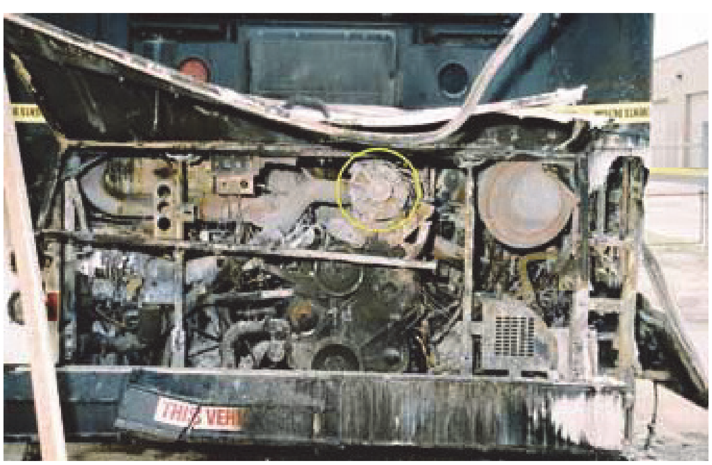
EXPERIMENTAL RESULTS

The accompanying photograph demonstrates the viability of shorted battery current through an alternator winding as an ignition source. The experiments were done with a cheesecloth wrap simulating a nearby fuel load, reminiscent of standard U.L. testing. The first test, done by physically hard-wiring a winding to the positive and negative terminals (the post and ground, respectively) resulted in the depicted fire in about 20 minutes.

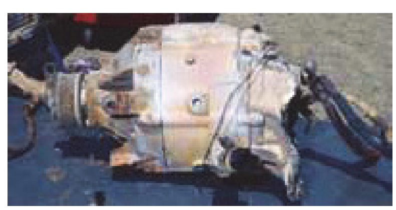
Diode junctions typically fail in two stages: first they short-circuit, then they destroy themselves and the connections open.[3,4] Causing a bad diode is successfully accomplished by applying a current-limited high-voltage reverse current to the selected diode. Once so-damaged, the diode will reliably conduct current in both directions. In my tests, battery current alone was never sufficient to cause a short-circuited diode to open. However, in a fire involving typical engine compartment fuels (which my testing did not), the heat and fire is much more severe than it was in these tests, where the fuel load was cheesecloth. Therefore, more destruction to the alternator and its components, including diodes, is expected. This is borne out by my field observations. The various photographs included with this article illustrate this point.

INDICATIONS OF A CHARGING SYSTEM FIRE

Obviously, the fire originates in the engine compartment, and an incendiary fire is contra-indicated. The origin of the fire will be centered around the alternator, which is a discrete component in many, but not all, applications. It is also possible that the fire will originate at the cable or cables between the battery and the alternator. In some applications, there is a single cable between the alternator and the battery; but in most applications, the positive terminal of the starter is the connection point between the alternator cable and the heavier cable from the battery. In applications where the alternator is in a massive, totally-enclosed steel housing, such as in buses and large vehicles, ignition typically occurs along the cable to the alternator. In the cases of those vehicles not having a discrete-component alternator (which I shall refer to as a *dispersed charging system*, ignition usually occurs along the cable because the alternator windings are buried in the engine itself. Garden tractors and ATVs typically have dispersed charging systems. In dispersed systems, the condition — principally the lack of recognizable remains — of the diode assembly will be one indication. Also, in a dispersed system, inspection of alternator windings will often (in 2/3 of the cases) show heat damage to what should have been protected windings — one of the three windings will show overheating. Since some (1/3) of the combinations of diode failures capable of starting a fire will result in no current passing through the windings, the lack of damage to the alternator windings does not absolutely preclude a fire caused by the charging system. However, assuming the windings were protected during the fire, "inexplicable" damage to them is conclusive in demonstrating diode failures in the distributed alternator system.

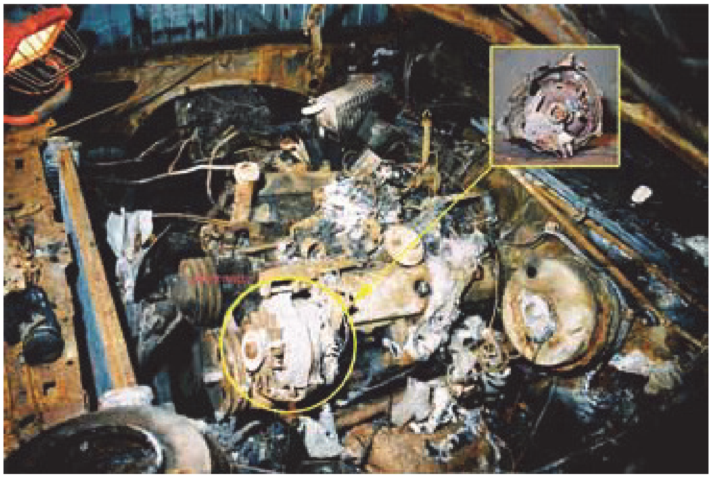


The engine compartment of a bus after an alternator (circled) fire.

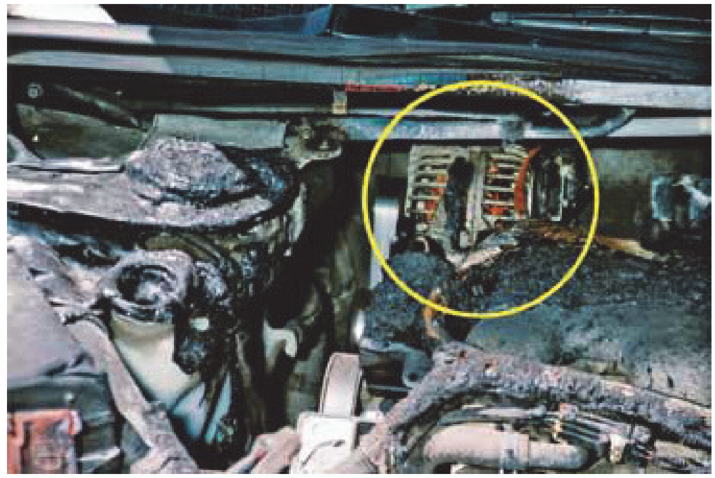


The damaged alternator after it was removed from the bus engine.

Two views of the cable between the battery and the alternator which was the source of ignition.



Typical fire caused by an alternator failure on an automobile engine. The inset shows rear view (electronics end) of the failed alternator.



An engine compartment fire **NOT** caused by alternator failure. Note the lack of damage to the alternator.

An alternator caused fire in a parked logging machine burned itself out over the night and was discovered the next day.

The alternator burned through its mounts and was discovered on the floor pan of the logging machine's engine compartment.

The remains of the burned alternator after it was removed.

The above alternator, the cause of the engine fire pictured on the right, had actually fallen from its original mounted position on the front of the engine. It was recovered by the fire department.

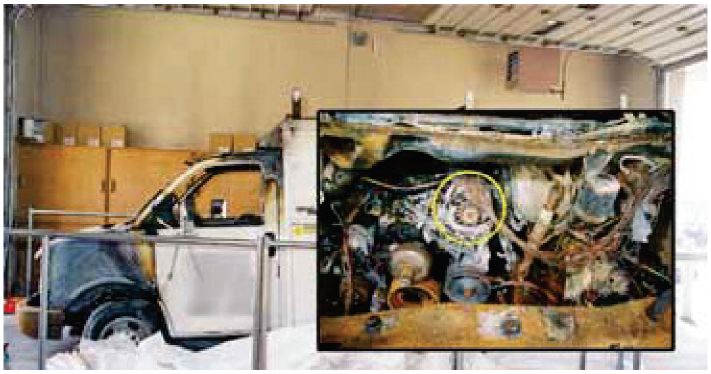
SYMPTOMS

These scenarios are the result of consecutive failures of two diodes (delta-connected alternators). Until the second diode fails, often the only *symptom* will be the loss of charging capacity of the alternator. It is possible that the driver may have noticed hesitation during hard acceleration (reduced voltage at the ignition or "spark" coil is the culprit). In a vehicle where the alternator is generously-sized compared with the electrical requirements, it is likely that the loss of the first diode will never be noticed. If it is noticed, the problem may be attributed to a "bad battery", and the vehicle may be jump started occasionally and never taken in for a diagnosis. When interviewing insureds, "Has your vehicle needed a jump start or new battery recently?" is an appropriate question to ask.

"LOOSE ENDS" - A DIODE FAILURE AND A WINDING SHORTED TO THE FRAME

Theoretically, a shorted diode and a winding short-circuited to ground will also result in full battery current through alternator windings. Technically, this scenario can also produce a fire. However, windings typically short out to adjacent windings, not to the frame. In the case of wye-connected alternators, if the first failure is a short-circuited common connection (of the windings), alternator output is not affected at all.

(In fact, in most non-automotive applications, this connection is intentionally grounded.) In automotive alternators, this common winding connection often "hangs" in the space near the grounded frame of the alternator. While it is easy to visualize this connection touching the housing and short-circuiting, the testing I did revealed that this shorted connection is often not solid enough to endure through ignition of nearby combustibles.



The fire in the engine compartment of this delivery van was caused by a failure of the diodes in the alternator. The fire was not related to a recent service to the van's starter motor.

An alternator failure resulted in the engine fire of this truck. The insets show the destroyed engine compartment and alternator.

WHAT THE FUTURE HOLDS

The internal combustion engine is going to be around for a while before it finally goes the way of the Viking ship — or the Studebaker. The trend is to incorporate more and more electrical equipment in the engine, and, for that matter, in the chassis. In years gone by, a 6-volt system was sufficient for a vehicle's electrical system. Twelve volts is common now, but industry experts predict 48-volt systems for internal-combustion-powered vehicles in the near future. In 2004, a test engine using electrically-actuated valves was built and run.[5] The possibilities of this technology are exciting (Imagine a 190-degree factory cam becoming a 232-degree full-race cam with the turn of a switch!), but the increased demand for auxiliary electrical power is apparent. It is clear that as long as there are internal combustion engines powering vehicles, there will be charging systems and their attendant problems that must be addressed by fire investigators. ●

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Mr. Hansen graduated from Purdue University in 1970 with a Bachelor of Science in Physics and a minor in Electrical Engineering. After serving in the United States Air Force during the Vietnam War, he worked as a plant electrical engineer for a power company for several years and as a design-for-construction electrical engineer for several more years. Mr. Hansen has been working in the forensic engineering field since 1984 and has been employed for the past seventeen of those years by EFI Global and its predecessor companies. In addition to his degree in Physics, Mr. Hansen has a Masters of Management from Northwestern University (1981) and has recently completed several graduate-level courses in Electrical Engineering at the University of Wisconsin - Milwaukee. Mr. Hansen currently works out of his office in a western suburb of Milwaukee, Wisconsin.