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REPORT ON FORCE 10 BURNER CONTROL BOARD
VERSION 2.2

For International Thermal Research Ltd.
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Richmond, B.C. V6V 1Y3

FET FAILURE IN THE IGNITION CIRCUIT

The failure of this device, Q7 in the schematic, a type IRF740 disables the entire circuit as the burner can no longer be ignited. Since this device is well protected in its enclosure, failure has to come from an electrical source. There are two ways to destroy a device of this nature electrically, both of which result in a short circuited device. These are through excessive current and excessive voltage.

Failure through excessive current can ocure in two ways. The first is when there is a sudden current spike which causes localized heating in MOSFET devices like this one. This type of device is not actually 1 transistor. An individual MOSFET type transistor is incapable of sufficiently low turn on resistance or high enough current carrying capacity. Therefore, the actual device is actually an intergated circuit with possibly several hundred transistors wired in parallel. This both reduces the turn-on resistance as well as increases the current carrying capacity.

However, when a current pulse occurs, in excess of the device rating, such as in an ignition circuit, this can cause localized heating in one spot of the integrated circuit, possibly causing only 1 or a few of the transistors to fail. This, then renders the entire device useless. In testing, this 10 amp device, while being subjected to an average current of only 2 amps, the peak current readily visible on the oscilloscope was 7 amps. In addition, as in most inductive circuits, there is a shorted, virtually invisible spike as well of somewhat higher current. However, a 10 amp device such as this should be able to handle this. Still, the peak current visible was 7 amps, 70% of the device rating. To have reliable circuitry, it is common practice not to exceed 50% of a device's ratings.

However, because the average current is 2 amps and because the first production batch worked well, I am non convinced that this is the root of our problem.

The other way failure could be occuring through over current is with general over heating of the device. Since the device is turned on fully, the voltage applied does not affect this. The heating is 100% a function of the average current applied. This is set by the ignition duty cycle control and is set to 2 amps to assure an adequate spark.

Since this device has an R_{DS} rating of 0.55 ohms and the average current is 2 amps, the heat generated in the device will be 2.2 watts.[1] The peak current of 7 does cause heating of 27 watts through part of the cycle. However, it is the average that causes part failure. However, the tiny heatsink used, which appears to be a Wakefield type 289 (I cannot be sure as it is not indicated in the parts list) is quite inadequate for the job. While I do not have specs, the virtually identical IERC brand type PA1-1CB allows a heatsink temperature rise of 50 C when the device is dissapating 2.2 watts. This is with unimpeded natural convection. Inside an enclosure, the temperature rise could be quite a bit higher.

When the ambient temperature is 25 C, this heatsink allows the temperature of the heatsink will rise at least 50 C to at least 75 C. If the heater has been running or the sun has ben shining on the heater case and the ambient temperature in the case is higher than 25 C, the final temperature reached will be higher by a like amount. There is the thermal resistance of the insulating washer and the device itself to consider but these are minor, totalling only about 2 C per watt, contributing to an internal device temperature rise of about 55 C above the starting temperature.

Therefore, under some operating conditions, the junction (internal) temperature can reach 80 C or higher. Another effect, I have not taken into consideration is that according to International Rectifier, the device's R_{DS} rating, which directly determines device heating increases from a nominal 0.8 ohms at 25 C to 1.5 ohms at 80 C, effectively doubling heat dissapation which may raise the temperature of the device another 50 C.

The maximum junction temperature allowed for this device [2] is 150 C and as you can see, we are really pushing the limit. With heating a device, the greater the temperature rise, the fewer thermal cycles can be endured by such a device. With a temperature rise of 60 C, the plastic TO-220 case used by this device will lose its hermetic seal in about 3000 thermal cycles. The device will fail some random time after this, possibly from 1 to 1000 days later due to environmental contamination. Its operation may also become intermittent in this time.

Of course, when the ambient temperature is lower than 25 C, the final temperature reached by the device will be lower by the same amount which will increase the life of the device somewhat. However, the thermal cycle available to the device are determined by the amount of rise and not the actual temperatures involved to a great extent.

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[1] The formula for calculating heat generation is current squared times the device on resistance or I^2 X R_{DS}. I is the symbol for current and R_{DS} is the symbol for the DC resistance of the transistor when it is turned on.

[2] According to the International Rectifier HEXFET Power MOSFET Designer's Manual 1987 Version.

My personal experience is that if a plastic cased semiconductor device is allowed to operate at a temperature that is uncomfortable when holding a finger to it for several minutes, it will fail in an unacceptably short period of time.

Therefore, on the existing boards, I recommend a larger heat sink be added to the existing heat sink. In addition the use of a thermally conducting grease must be used between these two heatsinks to facilitate the transfer of the heat. Please contact me at the time this work will be done and I will suggest a lower cost alternative to the industry norm heat sink compound ($5.00 for 400 grams versus $20.00 for 25 grams). For future production, I will show you at that time how to heatsink the devices so that their temperature will rise less than 10 C while costing no more than you spend now.

While this may be the fault in some cases, it usuallys shows up only a year or more down the road. Therefore, while the inadequate heatsinking is a problem that must be corrected, the rash of early failures is probably caused by other reasons.

Note that this is a design fault and the fault be that of the designer and not the assembly contractor.

The other failure mode possible is excessive voltage. While the IRF740 device used is rated to handle 400 volts[3] and is operating on a 12 volt circuit, oscilloscope analysis shows a that the transistor is subjected to a voltage spike of over 500 volts on one part of the waveform. The spike was flattened at the top as well. This is not normal and indicates to me that the device was going into what we call the "avalanche" mode for that parts of the cycle. This means that the device is "breaking down". While International Rectifier, the original designer of this device claim the device can handle some avalanche effect, the amount it can handle goes down dramatically with increased temperature, going to zero at about 125 C. As indicated in the previous section, this device is being operated hotter than advisable. When a device is being constantly run in avalanche mode, failure is considered inevitable.

In addition, International Rectifier claim that the breakdown voltage rating of the device declines 5% at -40 C. Therefore, operation in very cold conditions may affect the device's behaviour in avalanche conditions.

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[3] This is a manufacturer's absolute maximum rating. This means that they guarantee that 100% of the devices can handle this voltage and possibly somewhat more voltage. However, the amount of higher voltage the device can handle is unspecified. This can vary widely between device manufacturers as well as between production batches from the same manufacturer or even within the same production batch. In addition, what the device does when subjected to voltages in excess of its breakdown voltage is unspecified and not guaranteed by the manufacturer. The policy of most designers is to normally operate transistors at 50% or less of their maximum rating for best reliability.

The avalanche effect occured at a voltage from 450 volts to 500 volts on the three sample devices tested.However, for any reliability, operating any device in the avalanche mode is considered to be strictly forbidden. In TV sets where transistors are used in similiar circuits as well as on older automotive ignition systems using points, a capacitor is placed in parallel with the switching device to minimize the maximum voltage amplitude of the voltage spike that occurs when switching an inductive device such as a high voltage ignition coil.

With a capacitor value of 0.22 µFd. the voltage spike was reduced to 200 volts. A 0.47 µFd. capacitor reduced the voltage spike to 150 volts. The size of capacitor used in automotive ignition circuits ia approximately 0.5 µFd. There appeared to be no apparant degradaion of the spark. In addition, the current consumed satyed the same and the burner seemer to light off equally well.

Therefore, I recommend that a 0.22 µFd. 400 Volt rating capacitor be placed in parallel with the transistor. This capacitor may be connected between the "BAT -" and the "IGNI" terminals on the connector CN1. This technique is an industry standard technique used in all manner of high voltage circuits.

This will completely eliminate the switching transistor from going into avalanche mode. I realize that the first production run of boards seemed to be much more reliable and the best explanation I can come up with is that the production run of IRF740 devices used then were better able to tolerate being driven past their absolute maximum voltage rating somewhat better than the next production run.

Concerning the device used for Q7, type IFR740.

	Brand	Date Code
Boards 1, 2, 3, 5, 7	ST	99136 - 1991 Week 36
Board 4	ST	99118 - 1991 Week 18
Board 6	ST	98948 - 1989 Week 48
Board 8	ST	90012 - 1990 Week 12
Board 9	IR	9051 - 1990 Week 51

I am not sure which boards were from which production batch therefore, others will have to determine which devices from which production run are where.

Note that the circuit designer's spec does not specify the brand name of the device to be used. However, it is common industry practice to not specify a brand. It is considered that devices from different manufacturers with the same part number will be 100% equivalent when operated within the maximum ratings. Regardless, all devices of a given type will meet the minimum spec but it is completely undefined how a device will act when driven past that spec.

BALLAST RESISTOR

In addition to the above, we also tested the circuit with ballast resistors of 0.5 ohms, 1.0 ohms and 2.0 ohms in series with the positive lead of the ignition coil. These were very successful in reducing stress on the ignition FET. However, it was felt by the burner designer that the degradation to the quality of the spark made this a non-viable alternative.

To use a ballast resistor the value of either R76 or R58 will have to be changed on the board in order to increase the duty cycle of the transistor in order to have an acceptable spark at all. To make the spark fully as strong as before would require switching from a coil designed for transistor ignition to one designd for operation from points.

POWER TRANSISTOR MOUNTING

The mounting of the four power transistors, the FETs is not adequate from the standpoint of long term vibration resistance. The system will be used in mobile applications where the circuit boards may be subject to vibration over a long period of time. The FETs are simply soldered into the circuit board by their leads. The weight of the device is raised by the addition of a heatsink and attachment hardware. This combination will vibrate and will someday cause the leads of the FET to fracture resulting in intermittent operation.

While fine in the lab, the mounting of the FETs will someday cause trouble in many units though the time frame will generally be beyond the period of the warranty. There are heatsinks that may be purchased for these devices with mounting ears that allow them to be solidly attached to the circuit boards to prevent this sort of trouble. These heatsinks have been widely available for over 10 years and there is no more difficulty to get them compared to other types.

To fail to use a better mounting technique is a failure of design and I would also have expected the assembly contractor to have pointed this out.

I recommend that existing boards have the heatsinks secured to the printed circuit boards by applying a dab of silicone adhesive between the heatsink and the circuit board. In addition, capacitor C4 should also be siliconed to the board. It is industry standard practice to use clear silicone adhesive for this purpose. Weather sealer silicone, available in caulking gun sized tubes is fine. Do not use silicone described "Bathtub Sealer". This product has a fungicide in it that may make it somewhat conductive to electricity.

The new heatsink design I will recommend in future production will totally eliminate this problem at no more cost than at present.

TRANSISTOR INSULATION

The designer's specification calls for the FET devices to be mounted to their heatsinks with a "TO220 Nylon Insul Bushing MOT B51547F019" and a "Thermal Conductor TO220Pad 173-7-240P IR/Wakefield". The Nylon bushing is missing on every unit I examined.

Since this was specified in the parts list, failing to put this in has to be a problem caused by the assembler. The only other explanation is that the designer changed the specification verbally to the assembler but failed to update the parts list.

The problem with this is that is they designer decided to not insulate the transistors from the heatsink, they would have eliminated the relatively costly thermal conductor pad in favour of much more economical thermal grease to ensure good heat transfer to the heatsink.

The board was designed with individual heatsinks for each transistor, therefore, it is not really necessary to insulate them from the transistors anyway. However, in the field, the FETs are only a fraction on a centimeter from the side of the case and if the FET is bent over, either due to mis-handling or vibration, trouble may occur. This is especially a concern as the heatsinks were not properly secured to the circuit board.

The effects that would occur for each device if it touched the side of the case are:

Q7 - Ignition FET - The coil would start to conduct heavy current which would blow fuse F4. No damage would occur to the FET.

Q8 - Air Fan FET - The fan would run until a person shut off the power to the system. No damage would occur to the FET.

Q9 - Air Pump or Compressor FET - The airpump/compressor would start to run, not stopping until a person switched off the power. If the fuel system had any pressure in it, fuel may be drawn into the burner. No damage would occur to the FET.

Q11 -Fuel Pump FET - Q11 would be destroyed when the system is turned on as the short circuit would bypass the fuse F1. Because the fuse is bypassed, the fuse protecting the entire system would eventually blow. The fuel pump would not run.

I recommend on existing units that a piece of insulating material be placed between the circuit board and the side of the case where the FETs are located. This may be a material called "fish paper" or it may be a piece of plastic that can handle the temperatures to which it may be subjected.

The heatsink design I will propose for future production will eliminate this problem from occuring.

DEVICE TOLERANCE

This circuit uses some analog circuitry where the circuit accuracy is determined by the value of resistors. In most places, the standard 5% resistors are quite adequate but there are some places where 1% tolerance parts[4] must be used. The designers correctly used 1% parts to determine the operation of U1A and U1C, the thermocouple pre-amps.

However, in some other places the higher temperature stability of 1% devices should have been considered. These include R6, 8, 9 & 10 which determine the shut off point for the ignition as controlled by the thermocouple. Elsewhere, the 5% parts specified are alright.

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[4] 1% tolerance parts are more accurate and they drift less when the circuit is subjected to extremes of temperature.

This operation circuit depends quite heavily on the stability of the DC power supply voltage determined by zener diode D21 (9.1 volts) and on the stability of the 5 volt reference determined by D20 (5.1 volts). These are not the most stable temperature devices available and their accuracy may be seriously compromised at sub zero temperatures.

If they were affected equally, there would be little problem. The catch here is that all zener diodes do not have the same temperature co-efficient. Zeners of the 1N5221 to 1N5272 family below approximately 5 volts have a negative temperature co-efficient (their voltage drops with rising temperature) while above 5 volts, they have a positive temperature co-efficient, (the voltage rises with increasing temperature).

As the temperature to which the system is subjected changes, the two reference voltages drift with relation to each other. The 9.1 volt zener which determines the main operating voltage and which is used as a reference through much of the circuitry will drift at about +5 mV/ C of temperature change. This means from the lowest to highest operating temperature of the system, from -40 C to +40 C, the supply voltage will vary about 0.4 volts. On the other hand, the 5 Volt reference which is used by about 1/2 of the circuitry, has a temperature co-efficient of about +0.7 mV/ C causing a vairation of about 0.06 volts. The effect of this could be anything from no visible change of operation to total inability of the circuit to function through its entire temperature range.

Therefore most designers planning for operation at very low temperatures design their circuits to operate depending on ratios (if possible), where the absolute value of voltages are not important. Where this is not possible, they try to use zener diodes of about 5 volts as the only reference. To make this easier, semiconductor makers provide integrated circuits that have a high stability reference and use this through various methods to provide various voltages.

An example is the device type 78L05. This device provides a temperature stable voltage (down to -55 C is some versions) of 5.0 volts at a current of up to 100mA. This device sells, in 100 quantities for about $0.39. This costs slightly more than D20 and R13 required in the circuit to do this same function but since one less part need be installed and that the area of circuit board that need be given to the device is smaller, the final cost is no greater.

My own experience is that even the consumer grade version of this device is stable down to lower than -50 C. While changing the references is too dificult on current boards, for future production, I recommend that the voltage reference part of the circuitry be revised.

COST ITEMS

There are a number of places that extra cost has been incurred that may be unnecessary. The use of Quad Op-amps for inverters is an example. U16D, U5C, U9D, U17D, U5B and U2D are all sections of LM2902 quad op amps. To buy these in -40 C rated automotive versions costs about $1.00 per device with 4 op amps in it or $0.25

per op amp. They could have been replaced by a 4584 Hex Schmidt Trigger/Inverter for $0.69 with 6 devices in the one package or about $0.13 per inverter. Also because of device selection criteria, they wasted two op amps, U18B and U18C. These are not used and have been left unconnected. The problem here is that unconnected devices have to have their outouts tied to their inverting inputs and then have the non-inverting inputs tied to a reference voltage. Otherwise, if they are left in the open loop mode like they have been, they may break into oscillation and cause interference with other circuitry.

U18A and U12C are serving as buffers where the load being driven is within the capacity of the previous device and could have been eliminated altogether.

The timers consisting of U15A, U11B, U11A and U15B, representing 2 relatively expensive ($1.00 ea. or more) IC's may have been able to be replaced by a single 4584 device for $0.69.

U16, another quad op-amp could have been replaced by a single 7 segment line driver IC for the same cost. The difference is that this IC would have given us three additional inverters to use else where in the circuit, further reducing the parts count.

The MC33284 op amp used by the thermocouple amplifier is a split power supply device that needs a negative supply voltage. This is supplied by a DC-DC converter circuit that costs about $1.50 to include. This converter could have been eliminated by using the MC3303 of LM224 quad op amp which costs about the same amount. This device, used in a competing design of thermocouple preamp does not require a negative supply voltage.

These are primarily nit picky thinks and it is easy to criticize the designer after the fact. Circuit design always involves compromises but I feel that some more attention could have been placed on reduction of IC count. The main saving is in board area and assembly cost as well as saving on the parts themselves.

RECOMMENDATIONS SUMMARIZED

1. Additional heatsinking must be provided for Q7.
2. A 0.22 µFd. 400 Volt capacitor must be added between the "BAT-" and "IGNI" terminals of the connector CN1.
3. Secure the heatsinks and C4 to the board with dabs of clear silicone adhesive.
4. Place a piece of insulating material between the FETs and the case.

In future production, the heatsinking, FET mounting and voltage reference circuits be revised as per the guidelines previously mentioned.