U. S. Department of Labor
Mine Safety and Health Administration
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Engineering and Testing Division
Engineering Support Branch

Electrical Protection

of

Starting Circuits on Diesel Engines

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ABSTRACT

A procedure was developed to determine diesel engine starting circuit nominal inrush and cranking currents, in order to determine specifications for the overcurrent protective device(s) necessary to comply with the provisions of 30 CFR §§ 75.1910(a), 75.1910(b), 75.1910(e), and 75.1910(f). The procedure was successfully used to select readily available time delay fuses that provides short circuit and overload protection for three diesel engines used in underground coal mines. Note that for the purposes of this paper overcurrent protection is defined as overload protection plus short circuit protection.

The procedure was used and overcurrent protection selected from Gould Shamut time delay fuses as follows (Note that fuses manufactured by others could also be selected to provide the necessary protection):

1. American Isuzu Motors Incorporated, Engine Model C240 (QD60); use the TRS125RDC,

2. Chrysler Corporation's Dodge Ram, Engine by Cummins Engine Company Incorporated, Model 6.2L; with a single battery use the TRS150RDC and with two parallel batteries use the TRS100RDC, and

3. AM General Corporation's Hummer, Engine by General Motors Corporation, Model 6.2L; use the TRS80RDC.

INTRODUCTION

This investigation was conducted to assist mine operators in complying with the new safety regulations for nonpermissible diesel-powered equipment used in underground coal mines. The goal of the investigation was to:

1. develop a procedure mine operators can use to determine appropriate short circuit, overload, and conductor insulation protection for diesel engine starting circuits as required under §§ 75.1910(b), 75.1910(e), and 75.1910(f) that go into effect November 25, 1999, and

2. use the procedure to select overcurrent protective devices for three diesel engines used in underground coal mines.

The three engines selected were American Isuzu Motors Incorporated's, Model C240 (QD60), Chrysler Corporation's Dodge Ram, Model 6.2L Engine by Cummins Engine Company Incorporated, and AM General Corporation's Hummer, Model 6.2L Engine by General Motors Corporation.

BACKGROUND

On October 25, 1996, the Mine Safety and Health Administration (MSHA) published the final rule covering approval, exhaust gas monitoring, and safety requirements for the use of diesel-powered equipment in underground coal mines. Many requirements in the rule deal with the potential fire hazard of electrical components on diesel-powered equipment. A significant number of fire accidents have occurred in the electric start circuits of nonpermissible diesel equipment. To specifically address the fire hazard related to the starter circuit, § 75.1910(b) of this rule requires that each electric conductor from the battery to the starter motor be equipped with short circuit protection and that the short circuit protective device be placed as near as practical to the battery terminals. Section 75.1910(e) requires that each motor and charging generator be protected from overload by an automatic overcurrent device. Section 75.1910(f) requires electric conductors for starting motors be sufficient in size and have adequate current carrying capacity and be of such construction that a rise in temperature resulting from normal operation will not damage the insulating materials. These requirements go into effect November 25, 1999. The selection of adequate overcurrent protective devices will minimize the risk of fire accidents involving electric starting circuits.

DISCUSSION

The electrical parameters for an engine's "normal" starting conditions must be defined before any type of overcurrent protective device can be selected to react to "abnormal" conditions, i.e. short circuit and/or overload. To define these conditions, starter inrush and cranking currents were measured when the engine started and when the engine failed to start. Once "normal" conditions were defined, abnormal conditions were then identified as those values that exceeded the normal starter inrush and cranking current time frames, in seconds, necessary to successfully start an engine.

Test equipment was selected to effectively capture and record the expected current values and a collection of curves assembled that reflected a range of peak inrush starting currents and RMS cranking currents for each particular engine. The equipment consisted of:

1. a Tektronix Model 720 Digital Storage Oscilloscope,

2. a 500 ampere 100 millivolt shunt,

3. a laptop computer for data storage,

4. two 4 foot pieces of single conductor cable, and

5. an assortment of battery connectors for top and side post connecting batteries.

Although this equipment was selected and used by MSHA personnel, other equipment is available that does the job equally as well.

It was found that installing the recording equipment in the grounded battery lead prevented accidental arcs and sparks mishaps during the installation process. To eliminate accidental triggering of the oscilloscope, the ignition switch was turned until the very next position actuated the starting circuit. This permitted any accessories to be powered prior to the starting circuit activating. The oscilloscope was then initialized to capture the starter inrush and cranking currents.

Initially, 30 seconds was selected as the test frame for recording starter currents. It was later determined, however, that a period of approximately 5 to 10 seconds better represented typical time frames for engine starting. An engine that has not started within 5 to 10 seconds will typically not start until additional action, external to the starting circuit, is taken. A generalized test procedure used by the Approval and Certification Center (A&CC) personnel is attached as Appendix No. 1.

Manufacturer's cable markings were not visible on the battery cables in each of the field situations to determine the maximum temperature rise that could be sustained by the cable insulation without damage, as required by § 75.1910(f). Since the insulation materials could not be identified, it was decided that insulation damage calculations would be based on a No. 2 AWG copper cable with EPR insulation. Note that if a manufacturer uses a different size cable or cable with insulation other than EPR, the characteristics of that cable will have to be used in the calculations.

It was also not possible in field circumstances to test engines that had not been operated for several hours as some vehicles were driven directly to the test site from positions of use. It was anticipated that such engines would possibly yield higher inrush and cranking currents than engines that were well lubricated and/or "warmed up." This theory could not be substantiated, however, because of the short time frames since use, and a number of other factors, such as the stages of wear of the engines. A total of 72 recordings were made for the three manufacturer's engines tested. One recording has been labeled and is included as Appendix No. 2.

Fuse Selection

The data from the recordings were applied to time-current curves of various Gould Shawmut fuses. An equal degree of protection can be achieved by using time-current curves produced by Bussmann, Littelfuse, etc,. Based on the characteristics of the time-current curves, fuses were selected that permit a reasonable time frame for “normal” current flow in the starting circuit, while interrupting current flow before the starter motor or cable are damaged from overcurrent conditions. The selection of the fuse must ensure that the conductor's insulation is not damaged by the rise in temperature induced by both the inrush and cranking currents. Since information was not visible on the battery cables installed in the equipment tested, this investigator’s selection of fuses were based on a conductor having a known insulation. The conductor used is a No. 2 AWG (66,370 circular mils) copper conductor cable with 90°C EPR insulation. See Appendix No. 3 for the calculations of the conductor temperature rise and starter motor overload protection used in selecting the fuses.

The selection of fuses must be carefully determined by knowledgeable personnel and based on all the characteristics of the circuit such as electrical supply (in this case a battery), voltage, inrush current, highest steady state cranking current, lowest steady state cranking current, size of cables used, cable insulation, and motor overload protection. The catastrophic potential of a fire in an underground coal mine must be considered and the choice of fuse must be appropriately conservative in light of the potential consequences. Substantial emphasis must also be placed on a fuse’s maximum voltage and current interrupt ratings. These ratings must not be exceeded by the circuit in which they are placed. It is important to note that our circuit is a dc circuit.

A selection of current recordings for the Isuzu C240 and Cummins 6.2L were supplied to an Applications Engineer at Gould Shawmut for an opinion on selecting fuses that could afford reasonable protection for the starting circuit. The recommendations provided by Gould agree with the A&CC’s selection for the Isuzu C240 and Cummins 6.2L with a single battery. The selections differed, however, for the Cummins 6.2L with parallel batteries. Gould recommended the TRS125RDC for the Cummins 6.2L with parallel batteries while A&CC selected a TRS100RDC. A&CC’s fuse selection for the parallel battery arrangement at the 100A level provides additional safety, as the fuse selected sized to interrupt “normal” current flow if it persists for a longer period of time, not on an increase in current. Furthermore, this level of protection provides greater assurance that the starting battery can supply sufficient current to cause the fuse to interrupt current flow in the starting circuit under A&CC’s defined “abnormal” operating conditions.

Since there is no guarantee that the battery will supply the inrush and cranking currents for extended time periods, I recommend that fuses be selected such that the inrush current, highest cranking current, and lowest cranking current be interrupted as follows:

1. Interrupt the inrush current in one (1) second or less,

2. Interrupt the highest cranking current in 30 seconds or less, and

3. Interrupt the lowest cranking current in 100 seconds or less.

Based on the inrush and cranking currents recorded in the field tests, the calculated temperature rise of the chosen conductor, assumed cable size and insulation, motor overload protection for the starter motors and the above time constraints, the following fuses were selected:

1. American Isuzu Motors Incorporated, Engine Model C240 (QD60); use the TRS125RDC,

2. Chrysler Corporation's Dodge Ram, Engine by Cummins Engine Company Incorporated, Model 6.2L; with a single battery use the TRS150RDC and with two parallel batteries use the TRS100RDC, and

3. AM General Corporation's Hummer, Engine by General Motors Corporation, Model 6.2L; use the TRS80RDC.

CONCLUSION

This investigation successfully developed a procedure to determine appropriate overcurrent protection for diesel engine starting circuits, as required under 30 CFR §§ 75.1910(a), 75.1910(b), 75.1910(e), and 75.1910(f). The procedure can be used by mine operators to comply with the new regulations on diesel-powered equipment used in underground coal mines. Further, the field testing of the three diesel engines used in underground coal mines provides mine operators with examples of fuses which can be installed in efforts to provide the required protection.

Based on the inrush and cranking currents recorded in the field tests, the calculated temperature rise of the chosen conductor, cable size and insulation, motor overload protection for the starter motors, and the time constraints established for the inrush and cranking currents, the following fuses were selected:

1. American Isuzu Motors Incorporated, Engine Model C240 (QD60); use the TRS125RDC,

2. Chrysler Corporation's Dodge Ram, Engine by Cummins Engine Company Incorporated, Model 6.2L; with a single battery use the TRS150RDC and with two parallel batteries use the TRS100RDC, and

3. AM General Corporation's Hummer, Engine by General Motors Corporation, Model 6.2L; use the TRS80RDC.

Note that the size of conductor and insulation of the cable used in the insulation damage calculations will have an impact on the time necessary to produce insulation damage and could result in the selection of a different fuse.

Appendix No. 1 - Test Procedure.

WARNING: FAILURE TO PROTECT PERSONNEL FROM ACCIDENTAL VEHICLE MOVEMENT, VEHICLE MOTION, AND ELECTRICAL SHOCK COULD RESULT IN INJURY OR DEATH TO TEST PERSONNEL

The following is a generalized step - by - step procedure used by A&CC personnel to record the current flow from the battery to the starter motor during the test starting sequence. The procedure is not 100% inclusive and may need minor modifications from machine to machine. It is therefore necessary to caution that, "**Only qualified personnel should be installing the equipment and performing the current recording tests.**"

1. Place vehicle in "park" or "neutral" and block the vehicle against accidental movement or motion,

2. Inspect the equipment to determine the type of engine, battery cables, and battery connections on the equipment,

3 Install appropriate connectors on test cables to mate with the negative battery lead and terminal,

4. Remove the negative battery lead from the battery terminal and install the 500 ampere 100 millivolt shunt in series with the negative battery lead,

5. Connect the recording instrumentation to the shunt in accordance with the manufacturer's instructions such that all current flow from the battery to the starter motor is recorded during the test starting sequence,

6. Disable the fuel supply such that fuel will not flow during the starting sequence (**if the fuel line is disconnected, insure that fuel does not flow from the open line at any time**.)

7. Disable the backup alarm and any buzzers actuated by the ignition key circuit (these cause false triggering of the oscilloscope),

8. Rotate the ignition key until the very next position actuates the starter motor,

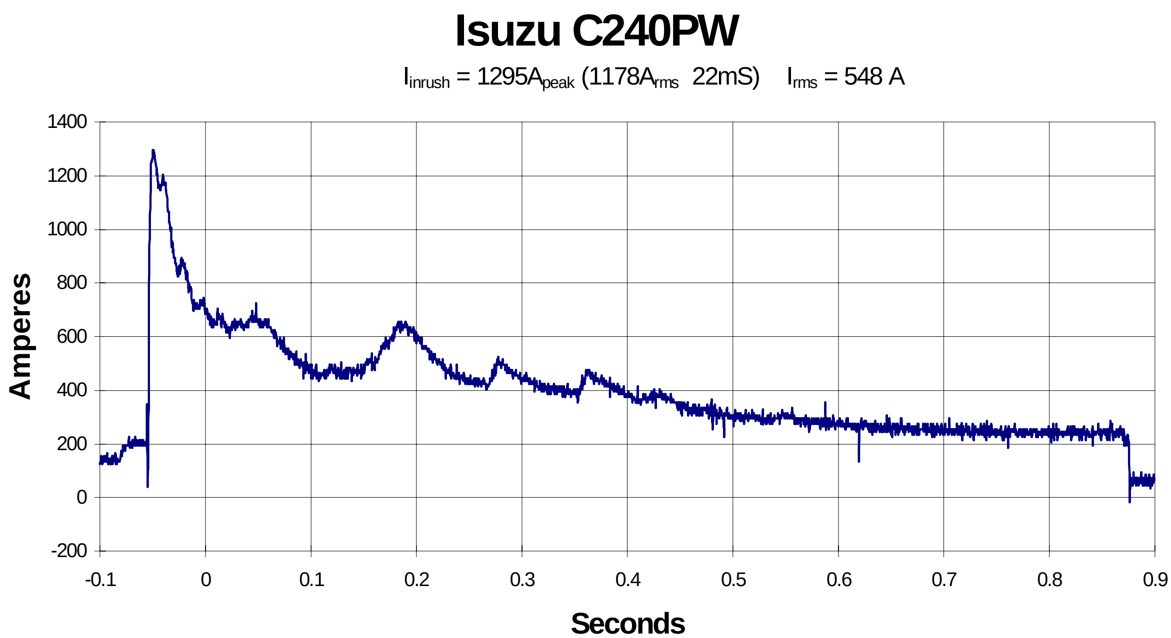
9. Initialize the oscilloscope to record the starter current and engage the starter for approximately 10 seconds,

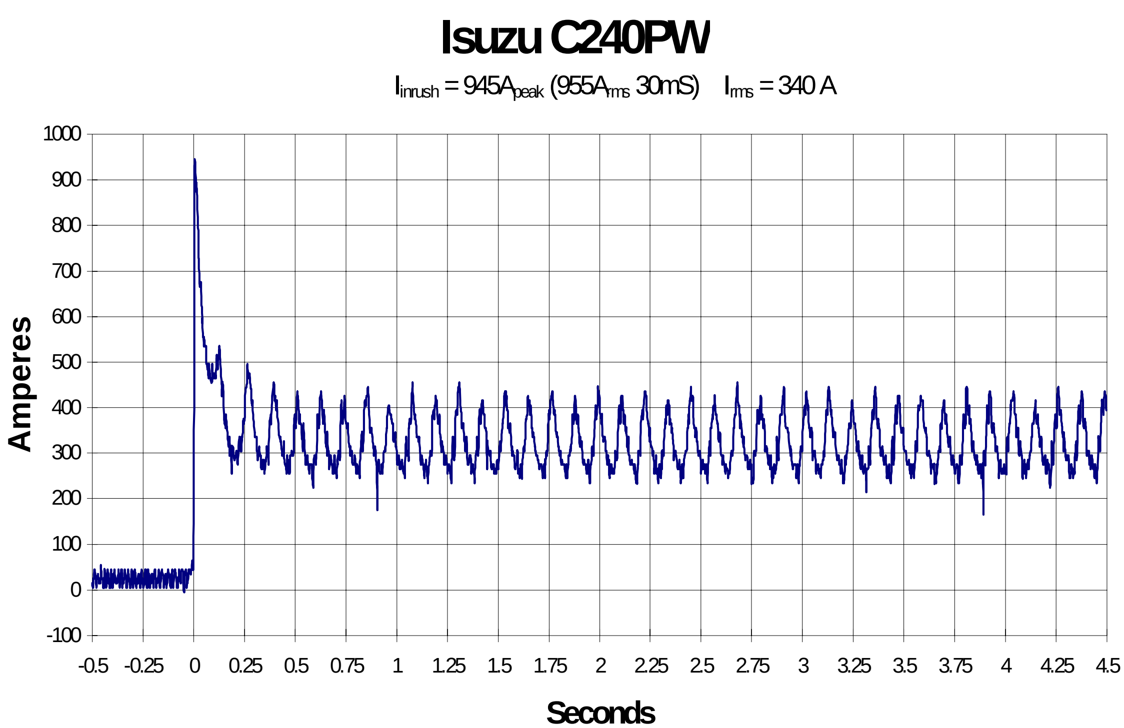
10. Store the waveform on the laptop computer and collect at least four more waveforms so that a total of at least five waveforms has been collected,

11. Disconnect the test equipment and restore the vehicle to operating condition (make a special note to reconnect the backup alarm).

12. Follow fuse selection procedure to select fuse.

Appendix No. 2 - Sample Inrush and Cranking Current Recordings.





Appendix No. 3 - Conductor Temperature Rise and Motor Overload Calculations.

Temperature rise of the starter cable (battery cable) conductor must be computed to determine if the fuse selected interrupts the current in sufficient time to maintain the conductor temperature at less than or equal to the maximum conductor temperature allowed. The largest size conductor encountered during the field investigation was a 2/0 AWG and the smallest was a No. 2 AWG. Identifying markings were rarely found on any of the cables. For this investigation a maximum conductor temperature of 250°C was chosen a No. 2 AWG (66,370 circular mils) copper conductor cable with 90°C EPR insulation.

The following formula from The Anaconda Company's Mining Cable Engineering Handbook, 1976, page 36, was used to calculate the time for the conductor to rise to 250°C at a given level of current flowing in the starting circuit.

$$t = \frac{0.0297(A)^2}{(I)^2} \log_{10}((T_2 + 234)/(T_1 + 234)) \text{ seconds,}$$

where A is the area of the conductor in circular mils, I the conductor current in amperes, T_1 the temperature rating of the cable in degrees Celsius, and T_2 the maximum allowed short circuit conductor temperature in degrees Celsius.

The time periods that must be considered are at the starter current inrush, at the highest cranking current recorded, and at the lowest cranking current recorded. The three time periods are represented by t_i for the inrush, t_h for the highest cranking, and t_l for the lowest cranking. The following values were recorded for the Isuzu Model C240 engine, 1295A inrush current, 548A high cranking current, and 340A low cranking current. Substituting these values into the above equation yields

$$t_i = \frac{0.0297(66{,}370)^2}{(1295)^2} \log_{10}((250 + 234)/(90 + 234)) \text{ seconds, then}$$

$$t_i = 13.59 \text{ seconds,}$$

$$t_h = 75.93 \text{ seconds, and}$$

$$t_l = 197.26 \text{ seconds.}$$

Examining these time frames indicates that the inrush current of 1295A would have to be present for 13.59 seconds to produce cable insulation damage and so forth for the highest and lowest cranking currents.

To insure that sufficient current is available to interrupt the fuse, it is recommended that the fuse be selected such that the inrush current, highest cranking current, and lowest cranking current be interrupted as follows:

1. Interrupt the inrush current in one (1) second or less,

2. Interrupt the highest cranking current in 30 seconds or less, and

3. Interrupt the lowest cranking current in 100 seconds or less.

The reason for these time limits is that there is no assurance that the battery will supply inrush and cranking currents for greater time periods.

Candidate fuses were selected from Gould Shawmut's TRS-RDC series of fuses. The 70 to 600 amp rated fuses in this series have a 20,000 amp current interrupt and 600 volt dc rating.

A candidate fuse is selected, in this case a TRS125RDC fuse, and the curve examined to determine when the fuse interrupts these current values. Examining the curve (See Appendix No. 2), 1295A is interrupted in approximately t_i = 0.5 seconds, 548A is interrupted in approximately t_h = 17 seconds, and 340A is interrupted in approximately t_l = 64 seconds. Note that these values of time meet the established limits for the inrush and cranking currents and they are much less than the time required to raise the conductor to 250°C.

We next examine the fuse for starter motor overload protection. The examination must made for both the highest (548A) and lowest cranking currents (340A). The Approval and Certification Center's policy for direct current motors is 150% of normal current flow. Multiplying both numbers by 1.50 yields 822A and 510A. Checking these values on the TRS125RDC curve shows that 822A is interrupted in approximately 6 seconds and 510A is interrupted in approximately 20 seconds. We therefore see that the TRS125RDC fuse provides short circuit protection, protection against cable insulation damage, overload protection for the starter motor, and meets the time constraints for the inrush and cranking currents. Therefore, the TRS125RDC is an appropriately selected fuse for the Isuzu C240 engine.

The same calculations are performed for the Dodge Ram's Cummins 6.2L engine and the Hummer's General Motors 6.2L engine. For the Cummins 6.2L engine with a single battery, the following was recorded, 1475A inrush current, 704A high cranking current, and 543A low cranking current. From these current values, the time to produce the 250°C conductor temperature is t_i = 10.48 seconds, t_h = 46.01 seconds, and t_l = 77.34 seconds. Examining the TRS150RDC fuse curve, 1475A is interrupted in approximately 0.70 seconds, 704A is interrupted in approximately 15 seconds, and 543A is interrupted in approximately 28 seconds. Again, these values of time meet the established limits for the inrush and cranking currents and they are much less than those values that raise the conductor to 250°C.

Examining the TRS150RDC fuse for starter motor overload protection, we find that the highest cranking current is 704A and the lowest cranking current is 543A. Multiplying both numbers by 1.50 yields 1056A and 814A. Checking these values on the TRS150RDC curve shows that 1056A is interrupted in approximately 3.70 seconds and 814A is interrupted in approximately 10 seconds. We therefore see that the TRS150RDC fuse provides short circuit protection, protection against cable insulation damage, overload protection for the starter motor, and meets the time constraints for the inrush and cranking currents. Therefore, the TRS150RDC is an appropriately selected fuse for the Cummins 6.2L engine with a single battery.

For the Cummins 6.2L engine with two parallel batteries, the inrush current was 925A, the high cranking current was 335A, and the low cranking current was 278A. From these current values, the time to produce the 250°C conductor temperature is t_i = 26.65 seconds, t_h = 203.19 seconds, and t_l = 295.06 seconds. Examining the fuse curves, the TRS100RDC interrupts 925A in approximately 0.9 seconds, 335A is interrupted in approximately 40 seconds, and 278A is interrupted in approximately 86 seconds. Again, these values of time meet the established limits for the inrush and cranking currents and they are much less than those values that raise the conductor to 250°C.

Examining the fuse for starter motor overload protection and multiplying the highest and lowest cranking currents by 1.50 yields 502A and 417A. Checking these values on the TRS100RDC curve shows that 502A is interrupted in approximately 14 seconds and 417A is interrupted in approximately 23 seconds. We therefore see that the TRS100RDC fuse provides short circuit protection, protection against insulation damage, overload protection for the starter motor, and meets the time constraints for the inrush and cranking currents. Therefore, the TRS100RDC is an appropriately selected fuse for the Cummins 6.2L engine with two parallel batteries.

For the Hummer's General Motors 6.2L engine, the inrush current was 715A, the high cranking current was 456A, and the low cranking current was 301A. From these current values, the time to produce the 250°C conductor temperature is t_i = 44 seconds, t_h = 109 seconds, and t_l = 251 seconds. Examining the fuse curves, the TRS80RDC interrupts 715A in approximately 1 second, 456A is interrupted in approximately 9 seconds, and 301A is interrupted in approximately 30 seconds. Again, these values of time meet the established limits for the inrush and cranking currents and they are much less than those values that raise the conductor to 250°C.

Examining the fuse for starter motor overload protection, multiplying the highest and lowest cranking currents by 1.50 yields 684A and 452A. Checking these values on the TRS80RDC curve shows that 684A is interrupted in approximately 1.2 seconds and 452A is interrupted in approximately 9 seconds. We therefore see that the TRS80RDC fuse provides short circuit protection, protection against insulation damage, overload protection for the starter motor, and meets the time constraints for the inrush and cranking currents. Therefore, the TRS80RDC is an appropriately selected fuse for the Hummer 6.2L engine.