| SURFACE VEHICLE RECOMMENDED PRACTICE | J1614™ | JUL2024 |
|---|---|---|
| | Issued 1998-03<br>Revised 2012-09<br>Reaffirmed 2024-07<br><br>Superseding J1614 NOV2018 | |

# Wiring Distribution Systems for Off-Road, Self-Propelled Work Machines

RATIONALE

Electrical wiring systems are becoming large and complex. There is a desire to reduce cable size to address large wiring system bundle sizes and also to address wiring to components that have small integral electrical connectors.

OEM's with machine or tractor designs produced in multiple global locations may desire the use of ISO 6722-1 cable sizes to facilitate local wiring system manufacture outside of North America.

This standard is being revised to address the potential use of smaller cable sizes and ISO 6722-1 cable types required by current and future off-road, self-propelled earthmoving machines and agricultural tractors.

Additional changes include correction to cable resistances and 1 volt drop run lengths, addition of data for smaller cable sizes and ISO 6722-1 cable types, added references to SAE AWG size, and added a section on Battery Disconnect Switch.

SAE J1614 has been reaffirmed to comply with the SAE Five-Year Review policy.

## 1. SCOPE

This SAE Standard specifies requirements and design guidelines for electrical wiring systems of less than 50 V and cable diameters from 0.35 to 19 $mm^2$ used on off-road, self-propelled earthmoving machines as defined in SAE J1116 and agricultural tractors as defined in ASAE S390.

## 2. REFERENCES

### 2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J163 Low Tension Wiring and Cable Terminals and Splice Clips

SAE J378 Marine Propulsion System Wiring

SAE J553 Circuit Breakers

SAE J1116 Categories of Off-Road Self-Propelled Work Machines

SAE J1127 Low Voltage Battery Cable

SAE J1128 Low Voltage Primary Cable

SAE J1493 Guarding of Starter System Energization

SAE J1908 Electrical Grounding Practice

2.1.2 IEC Publication

Available from International Electrotechnical Commission, 3, rue de Verambe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +41-22-919-02-11, www.iec.ch.

IEC 617 Graphical Symbols for Diagrams

2.1.3 ASABE Publication

Available from ASABE, 2950 Niles Road, St. Joseph, MI 49085-9659.

ANSI/ASAE S390 Definitions and Classifications of Agricultural Equipment

2.1.4 DIN Publication

Available from Deutsches Institut fur Normung, Postfach 1107, D-1000 Berlin 30, Germany

DIN 76 722 Road Vehicles, Low tension cables, Composition of type codes

2.1.5 ISO Publication

Available from International Organization for Standardization, 1, rue de Varembe, Case postale 56, CH-1211 Geneva 20, Switzerland, Tel: +41-22-749-01-11, www.iso.org.

ISO 6722-1 Road vehicles – 60 V and 600 V single-core cables – Dimensions, test methods and requirements

ISO 9247 Earth-moving machinery – Electrical wires and cables – Principles of identification and marking

2.1.6 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Boc C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM B 1 Standard Specification for Hard-Drawn Copper Wire

### 2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

#### 2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J562 Nonmetallic Loom

SAE J821 Electrical Wiring Systems for Construction, Agricultural, and Off-Road Machines

## 3. DEFINITIONS

### 3.1 ELECTRICAL CIRCUITS

An electrical circuit includes all the components and connecting cables, starting from the electrical energy source, going to the functional component(s) and the return route to the energy source.

### 3.2 ELECTRICAL COMPONENT

An electrical component is normally a combination of parts, sub-assemblies, or assemblies and is a self-contained element intended to store, generate, distribute, alter, or consume electrical energy.

### 3.3 CONDUCTOR(S)

The current carrying element(s) in a cable.

### 3.4 ELECTRICAL CABLE

Insulated stranded electrical conductor used to establish a single current path.

### 3.5 HARNESS

A group of two or more cables bundled together.

### 3.6 TERMINAL

An electrically conductive device attached to a cable to facilitate connection to an electrical component, cable, or termination.

### 3.7 CONNECTOR

A coupling device which provides an electrical and/or mechanical junction between two cables or between a cable(s) and an electrical component.

### 3.8 WIRING

Collectively, the cables, harnesses, connectors, terminations, and supporting components used in the electrical wiring distribution system.

# 4. WIRING DESIGN

## 4.1 Cable Selection

The preferred cable shall meet the requirements of SAE J1127 type SGX and SAE J1128 type SXL. Other cable types may be required for specific applications.

When changing cable sizes from SAE J1128 to ISO 6722-1, the cross-sectional area of the conductor will change. SAE J1128 specifies minimum cross-sectional area which is different than the SAE “cable size”. ISO 6722-1 specifies minimum electrical resistance and references nominal conductor cross-sectional area. When changing from one specification to the other, it is necessary when the copper cross-sectional area is reduced to repeat the cable size selection process as specified in Section 4 of this specification to ensure adequate current carrying capability and meet maximum allowable voltage drop.

When changing cables sizes from SAE J1128 to ISO 6722-1, the wiring system designer will also need to verify that the selected terminal’s conductor crimp range will accept the alternative conductor diameter. The cable insulation thickness is also different so that the cable seal diameter range for the connector must also be reviewed to ensure sealing to the new cable diameter and that the terminal’s insulation crimp range is within tolerance.

The insulation naming convention for ISO 6722-1 cables can be found in DIN 76 722. The near equivalent to SAE type XLPO cable insulation is DIN 76 722 type FL2X.

## 4.2 Cable Size Determination

Cable size is determined by consideration of the following factors:

a. Cable mechanical strength

b. Maximum temperature rise

c. System voltage drops

d. Selected connectors

4.2.1 Apply the procedure in Figure 1, Cable Sizing Flowchart, for determining cable sizes.

These factors vary in importance depending upon the application. Details specific to each are found in the following paragraphs.

4.2.1.1 Configure the electrical circuit including grounds and connectors.

4.2.1.2 Determine current requirements and cable lengths.

4.2.1.3 Determine fuse, circuit breaker, or other requirements applying appropriate de-rating factors.

4.2.1.4 A minimum size cable, or larger, shall be selected which meets all the previous requirements.

4.2.2 For mechanical strength, the minimum cable size recommended shall be 0.8 $mm^2$ in harnesses and/or protected areas in exterior or unprotected interior applications. A cable size of 1 $mm^2$ shall be the minimum cable size in areas susceptible to physical damage, or where one or two cables are extended from the harness. For protected areas within an enclosed compartment such as a cab or operator accessible electronic enclosure, the minimum cable size shall be 0.35 $mm^2$.

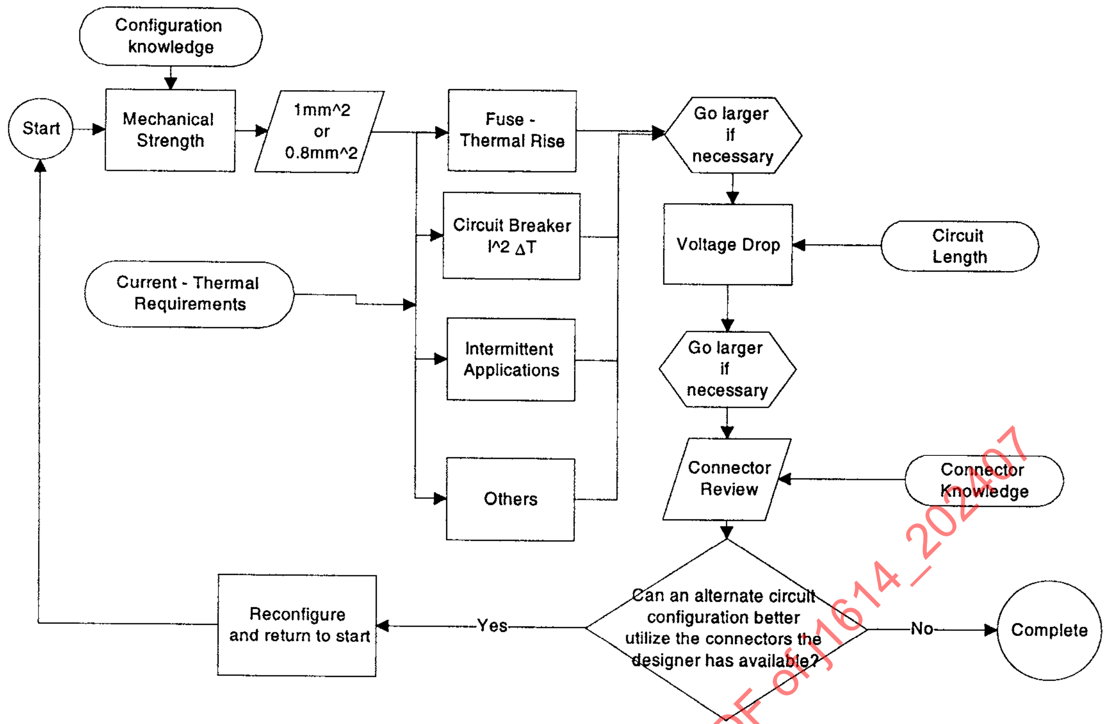


FIGURE 1 - CABLE SIZING FLOWCHART



4.2.3 The maximum temperature of the cable with steady-state currents shall not exceed the continuous duty temperature rating of the cable insulation, connector molding material, or other materials which the cable may come in contact with.

4.2.4 Fault Condition Maximum Temperature Rise

4.2.4.1 To control maximum temperature rise in a fault condition the cable must be sized for the circuit protection installed in the circuit. When a circuit breaker is used, it is important that the cable and the breaker be sized in such a way that the thermal circuit breaker "heats" at a rate higher than the cable to protect the cable from damage. Table 1 lists the minimum cable sized for given thermal circuit breakers. Table 1 is intended for manual reset breakers but can also be used for fuses. Auto-reset breakers require additional consideration to prevent overheating. See SAE J553 for additional guidance. In ambient temperatures up to 65 °C, the circuit breaker must be de-rated typically to 70% of its rating to prevent possible opening under steady-state conditions. In a fault condition, it is typical for the temperature of the cable to be raised by the fault current in the cable.

TABLE 1 - CABLE SIZED FOR THERMAL CIRCUIT BREAKERS

| 70% Load Operating Current (A) | Circuit Breaker Rating (Thermal type) (A) | Smallest SAE Cable Size Acceptable ($mm^2$/AWG) Calculations for this column are found in Appendix A. |
|---|---|---|
| 2.8 | 4.0 | 0.35 / 22 |
| 3.5 | 5.0 | 0.5 / 20 |
| 5.2 | 7.5 | 0.8 / 18 |
| 7.0 | 10 | 1 / 16 |
| 10.5 | 15 | 2 / 14 |
| 14 | 20 | 3 / 12 |
| 21 | 30 | 5 / 10 |
| 28 | 40 | 8 / 8 |
| 42 | 60 | 13 / 6 |
| 56 | 80 | 19 / 4 |

4.2.5 For Steady-State Thermal Capacity, the selected cable size should be verified by load testing. Table 2 gives the values of currents permissible based on the assumptions of 30 °C rise for cables bundled in a harness and 10 °C rise of a single cable in free air due to steady-state current heating. Circuit protection should be sized for the smaller size cable within the circuit.

TABLE 2 - STEADY-STATE THERMAL CAPACITY(1)

| SAE Cable Size ($mm^2$/AWG) | SAE Ratings (A) |
|---|---|
| 0.35 / 22 | 4.0 |
| 0.5 / 20 | 5.5 |
| 0.8 / 18 | 7.5 |
| 1 / 16 | 10 |
| 2 / 14 | 14 |
| 3 / 12 | 20 |
| 5 / 10 | 29 |
| 8 / 8 | 41 |
| 13 / 6 | 60 |
| 19 / 4 | 82 |

1. Dimensions used in calculating this table are typical industry values. Values found in this table are based on the calculations found in Appendix A.

4.2.6 Intermittent Load Cycles

For circuits where the electrical load is of a short duration, a 90-s rating can be used. As an example, a cable which is at a 40 °C ambient and is allowed to thermally rise to 150 °C. A short-term rating can be calculated based on its thermal mass. Based on the formula $\frac{\text{Current}}{\text{Area}} = 13.82$, the following ratings and sizings would be established. Please see Appendix A for the derivation of the constant.

8 $mm^2$ is rated90 A
13 $mm^2$ is rated160 A
19 $mm^2$ is rated250 A

4.2.7 The procedure used to determine voltage drop with respect to cable size begins with establishing maximum allowable voltage drop VD (volts), length of cable l (mm), and maximum operating current in circuit i (A).

4.2.7.1 Calculate cable resistance in micro-ohms/mm (r) as shown in Equation 1:

$$r = \frac{VD}{li} \times 10^6 \quad \text{(Eq. 1)}$$

4.2.7.2 After finding the calculated resistance, select the cable size from Table 3 or referring to ISO 6722-1 for additional ISO 6722-1 conductor sizes.

TABLE 3 - VOLTAGE DROP RESISTANCE

| SAE Cable Size ($mm^2$/AWG) | SAE Maximum Resistance (μΩ/mm) | ISO Cable Size ($mm^2$) | ISO Maximum Resistance (μΩ/mm) |
|---|---|---|---|
| 19 / 4 | 0.94 | | |
| | | 16 | 1.16 |
| 13 / 6 | 1.43 | | |
| | | 10 | 1.82 |
| 8 / 8 | 2.39 | | |
| 5 / 10 | 3.71 | 5 | 3.94 |
| 3 / 12 | 5.93 | 3 | 6.15 |
| 2 / 14 | 9.32 | 2 | 9.42 |
| 1 / 16 | 15.4 | 1 | 18.5 |
| 0.8 / 18 | 22.7 | 0.75 | 24.7 |
| 0.5 / 20 | 33.9 | 0.50 | 37.1 |
| 0.35 / 22 | 53.2 | 0.35 | 54.4 |

NOTE: ISO 6722-1 specified maximum cable resistance is about 8% higher than if calculated from the nominal diameter. SAE J1128 specifies the minimum cable cross-sectional diameter so the theoretical maximum resistances were calculated per ASTM B 1.

Examples of typically acceptable run lengths with a 1 V drop in a 12 V system are given on Tables 4a and 4b. Please note certain systems require voltage drops as small as 0.1 V. Calculation of the full system voltage drop is always recommended. (Note: run length is ½ of loop length.)

Maximum voltage drop shall be established to provide optimum performance and reliability of the components, e.g., voltage sensitive devices.

TABLE 4A - TYPICAL 1 V DROP RUN LENGTHS FOR SAE J1128 CABLE SIZES

| | 0.35 / 22 | 0.5 / 20 | 0.8 / 18 | 1 / 16 | 2 / 14 | 3 / 12 | 5 / 10 | 8 / 8 | 13 / 6 | 19 / 4 | SAE Size (mm$^2$/AWG) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Amperage (amps) | | | | | | | | | | | |
| 2.5 | 3.8 | 5.9 | 8.8 | 13 | 22 | 34 | 54 | 84 | 140 | 212 | |
| 5 | | 2.9 | 4.4 | 6.5 | 11 | 17 | 27 | 42 | 70 | 106 | |
| 7.5 | | | 2.9 | 4.3 | 7.2 | 11 | 18 | 28 | 47 | 71 | |
| 10 | | | 2.2 | 3.2 | 5.4 | 8.4 | 14 | 21 | 35 | 53 | |
| 12.5 | | | | 2.6 | 4.3 | 6.8 | 11 | 17 | 28 | 43 | |
| 15 | | | | | 3.6 | 5.6 | 9.0 | 14 | 23 | 35 | |
| 20 | | | | | 2.7 | 4.2 | 6.7 | 11 | 18 | 27 | |
| 25 | | | | | | 3.4 | 5.4 | 8.4 | 14 | 21 | |
| 30 | | | | | | 2.8 | 4.5 | 7.0 | 12 | 18 | |

Marginal Acceptable

TABLE 4B - TYPICAL 1 V DROP RUN LENGTHS FOR ISO 6722-1 CONDUCTOR SIZES

| | 0.35 | 0.5 | 0.75 | 1 | 2 | 3 | 5 | 10 | 16 | ISO Size (mm$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Amperage (amps) | | | | | | | | | | |
| 2.5 | 3.7 | 5.3 | 8.0 | 11 | 21 | 32 | 54 | 107 | 172 | |
| 5 | | 2.7 | 4.0 | 5.3 | 11 | 16 | 27 | 54 | 86 | |
| 7.5 | | | 2.7 | 3.6 | 7.1 | 11 | 18 | 36 | 57 | |
| 10 | | | 2.0 | 2.7 | 5.3 | 8.0 | 13 | 27 | 43 | |
| 12.5 | | | | 2.1 | 4.3 | 6.4 | 11 | 21 | 34 | |
| 15 | | | | | 3.6 | 5.3 | 8.9 | 18 | 29 | |
| 20 | | | | | 2.7 | 4.0 | 6.7 | 13 | 21 | |
| 25 | | | | | | 3.2 | 5.4 | 11 | 17 | |
| 30 | | | | | | 2.7 | 4.5 | 8.9 | 14 | |

Marginal Acceptable



4.2.8 Procedure for Resistance Budget

a. Determine entire voltage drop that is acceptable from the positive terminal of the battery to the negative terminal of the battery.

b. Divide the voltage drop by the anticipated current draw of the load to calculate the entire resistance that is tolerable ("Resistance Budget").

c. Subtract known resistance values from the budget amount. Suppliers of components should be able to provide component specifications. If not, they can be measured or estimated by considering electrical contact junctions equal to 1 mΩ per contact and internal switch contacts equal to 8 mΩ each.

d. Divide the remaining resistance by the distance to and from the load. This is the "Maximum Allowable Resistance".

e. Use Table 3 to determine the cable size needed based on resistance.

f. If an iron casting or steel frame is used for ground return, that resistance will have to be calculated and subtracted from the resistance budget before calculating the power source cable size.

4.2.9 Consideration must be given to the connectors that have been chosen when determining cable size. In the case where the cable is too large for the connector, there is an acceptable alternative. Here, a smaller diameter cable can be used and the electrical load split between two cables with two separate connections. Circuit protection for the smaller cable diameters of such split loads must be reconsidered.

4.3 Terminals

4.3.1 A corrosion-resistant conductive plating is recommended.

4.3.2 Terminal materials and platings shall be chosen to reduce galvanic corrosion when mated. Low-energy circuits may require terminal materials which prevent degradation due to vibration, fretting, corrosion, and oxidation.

4.3.3 All terminations shall conform to the physical and electrical performance requirements of SAE J163, except that the voltage drop test is to be modified as follows:

a. 200 off/on cycles at 125 °C ± 3 °C, 60 min off at 21 °C ± 2 °C.

b. Transition between temperature states to occur at 3 °C $^{+3\,°C}_{-0\,°C}$ per min with the power off during the transition. Terminals shall meet the contact resistance test after cycling.

4.3.4 Contact resistance measurement of connection resistance as illustrated in Figure 2. The resistance of the cables shall be subtracted from measured values.

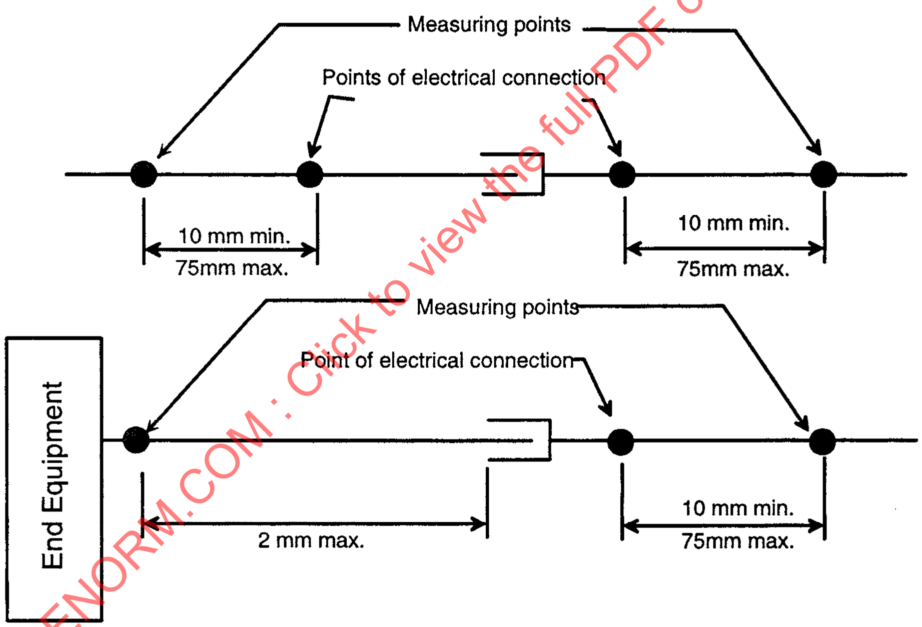


FIGURE 2 - CONTACT RESISTANCE TEST POINTS

4.3.5 Measurements at specified test current shall be taken after thermal equilibrium at current levels shown in Table 5.

TABLE 5 - CONTACT RESISTANCE TEST CURRENTS

| SAE Cable Size (Ref. J163) ($mm^2$/AWG) | Test Current (A) |
|---|---|
| 0.35 / 22 | 5 |
| 0.5 / 20 | 7.5 |
| 0.8 / 18 | 10 |
| 1 / 16 | 15 |
| 2 / 14 | 20 |
| 3 / 12 | 30 |
| 5 / 10 | 40 |
| 8 / 8 | 50 |
| 13 / 6 | 60 |
| 19 / 4 | 70 |

4.3.6 Acceptance criteria of connection resistance is:

10 mΩ maximum initially.
20 mΩ maximum after endurance testing.

4.3.7 Maximum allowable voltage drop across a terminal as depicted in Figure 2 shall be 100 mV.

4.3.8 Terminals shall be used and applied according to manufacturers' specifications. Special consideration shall be given to terminals carrying low-voltage signals.

4.3.9 Terminals shall have cable insulation support or the connector body/device shall provide support for the cable.

4.4 Connector Selection

4.4.1 Single connections shall be used in close proximity to each other only where there is no possibility of mis-connection in assembly or service.

4.4.2 Connector bodies shall be used at all points where two or more cables terminate, and where there is a possibility of mis-connection in fabrication, assembly or service.

4.4.3 Cable-to-cable connectors shall have positive locking devices. The locking device shall withstand a pulling force defined by 111 N times the number of contacts or a maximum of 444 N. The load shall be applied for 30 s.

4.4.4 Connectors shall be polarized.

4.4.5 Minimum terminal retention, within the connector, shall be 111 N for terminals with cable size 0.8 $mm^2$ and larger. The minimum terminal retention within the connector shall be 89 N for terminals with cable sizes of 0.35 and 0.5 $mm^2$.

4.4.6 Secondary locks for the terminal and/or connector are highly recommended.

4.4.7 Connectors exposed to the outside environment require adequate protection from hazards (brush snags, rock impact, splash proof, etc.) associated with that environment.

4.5 Splicing

4.5.1 When splices are required, they shall be located dimensionally on drawings to preclude being located:

a. In areas of harness flexing

b. Within 50 mm of a clamp

c. Within 50 mm of a branch of the harness

d. Within 25 mm of any other adjacent splice

e. Within 100 mm of any connector or termination

f. Within 150 mm between connected/consecutive splices

4.5.2 Configure splice so that

a. Cables are not doubled back within the harness bundle.

b. Splices are within the covered or bundled section of the harness.

c. The cross sectional area of the cables on either side of the splice are approximately equal.

4.5.3 Splice Construction

The cable conductors shall be reliably terminated. All splices shall conform with the electrical specifications for splices per SAE J163. Additionally, the splices must meet or exceed the minimum pull test as shown in Table 6 (Extracted from SAE J378). Value to be based upon smallest cable in splice.



TABLE 6 - SPLICE PULL OUT REQUIREMENTS

| SAE Cable Size ($mm^2$/AWG) | 1-s Pull Value (Newtons) |
|---|---|
| 0.35 / 22 | 40 |
| 0.5 / 20 | 60 |
| 0.8 / 18 | 80 |
| 1 / 16 | 124 |
| 2 / 14 | 155 |
| 3 / 12 | 177 |
| 5 / 10 | 200 |
| 8 / 8 | 222 |
| 13 / 6 | 355 |
| 19 / 4 | 440 |

4.6 Harness Assembly Construction

4.6.1 Cables shall be grouped, where practical, into harnesses.

4.6.2 Harness covering shall be selected in accordance with the application. Examples of typical harness coverings are as follows: polyvinyl chloride tape, extruded plastic (PVC) tubing, flexible thermoplastic conduit (typically slit lengthwise), metal conduit, braid (vinyl/nylon or vinyl/polypropylene).

4.6.3 The wiring harness covering shall be adequate to protect the harness in the expected environment and shall furnish protection during machine assembly and operation.

4.7 Cable Circuit Identification

4.7.1 Circuits shall be identified with either color, numbers, letters, symbols, or a combination thereof per ISO 9247.

Identification shall change when passing through an electrical component, but not when passing through a terminal block, connector, splice, or common junction.

4.7.2 Identification Durability Requirements

4.7.2.1 Abrasion Resistance Test

Place the cable on a firm surface with the circuit identification markings face up. Secure the cable in place. With a force of 30 N, wipe a "Pink Pearl" or equivalent eraser across the cable and markings parallel to the centerline ten times.

4.7.2.2 Fluid Resistance Test

Immerse a 200 mm length of cable in 25 °C ± 5 °C fluid for 10 min. Remove and wipe the insulation two times with slight pressure using a paper towel. The fluids required for this test are: diesel fuel, gear and engine oil, antifreeze fluid, hydraulic fluid, and gasoline. Other fluids may be added to this test at the manufacturer's discretion.

4.7.2.3 Acceptance Criteria

The characters on the cable insulation shall be legible in low lighting after each test.

4.8 Assembly Routing and Protection

4.8.1 Harness design should prevent misconnection during assembly or service.

4.8.2 Harness routing shall be such that maximum protection is provided by the machine covering and structure.

4.8.3 Devices such as grommets and/or insulated clamps, are required to provide adequate protection from sharp edges and vibration.

4.8.4 Wiring shall be located to afford protection from exposure to the following: moving mechanisms, stones, abrasives, grease, oil, water, and fuel.

4.8.5 Wiring shall be routed to avoid excessive heat areas.

4.8.6 Strain relief may be necessary for some connector applications and can be addressed by connector design or by clamping, routing, and harness support.

4.8.7 Protection (i.e., boots or shields) against accidental shorting shall be provided for terminals which always have voltage present. This protection shall conform to SAE J1493. Some examples of continually live electrical terminals include:

- Battery terminals
- Alternator output terminals
- Accessory relay terminals

4.8.8 Fluid conduits/lines shall not be used as support for wiring harnesses.

4.9 Electrical Grounding Practice

4.9.1 Grounding connections shall conform to SAE J1908.

4.10 Battery Disconnect Switch

4.10.1 The Battery Disconnect Switch, when used, may be installed on the ground or the positive side of the battery system.

## 5. NOTES

5.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE COMMON TESTS TECHNICAL COMMITTEE C2—
ELECTRICAL COMPONENTS AND SYSTEMS

APPENDIX A

A.1 This appendix is provided for informational purposes and is not to be considered as part of the document.

A.2 CABLE THERMAL RISE

From thermodynamics a first order equation that is often used is:

$$\text{Heat(H)} = \text{Constant(C)} \text{ x Surface Area(A) x Temperature Rise } (\Delta\theta) \quad \text{(Eq. A1)}$$

This can be written:

$$H = CA\ \Delta\theta \quad \text{(Eq. A2)}$$

For a cable with current (I) and resistance (R) in steady-state:

$$I^2 R = CA\Delta\theta \quad \text{(Eq. A3)}$$

The resistance can be written as Equation A4. Also see Figure A1.

$$R = \rho \frac{\Delta 1}{\pi / 4D^2} \quad \text{(Eq. A4)}$$

where:

D = diameter
$\Delta 1$ = length
$\rho$ = resistivity

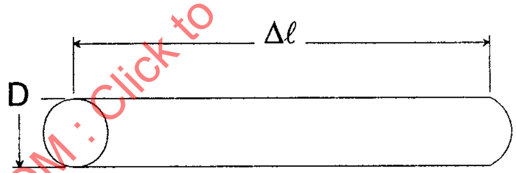


FIGURE A1 - CABLE DIMENSIONS

The area of the surface is:

$$A = \pi D \text{ x } \Delta 1 \quad \text{(Eq. A5)}$$

At the fusing condition copper melts, and

$$\begin{aligned} F.C. = I,\ \ \Delta\theta &= \theta_M - \theta_A \\ \theta_M &= 1083\,^\circ C \\ \theta_A &= 20\,^\circ C \end{aligned} \quad \text{(Eq. A6)}$$

where:

F.C. = Fusing Current
$\theta_m$ = Melting Point Temperature
$\theta_A$ = Ambient Temperature

then

$$\sqrt{\frac{C}{4\rho}\pi^2(\theta_M - \theta_A)D^{\frac{3}{2}}} \quad \text{(Eq. A7)}$$

The W. H. Preece Equation at fusing is F.C. = 10 244 $D^{3/2}$ (where D is in inches).

For a thermal rise of 10 °C at 20 °C ambient, we can write a similar equation.

$$I = \sqrt{\frac{C}{4\rho}\pi^2(\theta_{M1} - \theta_A)D^{\frac{3}{2}}} \quad \text{(Eq. A8)}$$

Dividing one equation by the other we obtain

$$\frac{I}{F.C._{\theta_A}} = \sqrt{\frac{\theta_{M1} - \theta_A}{\theta_M - \theta_A}} = \sqrt{\frac{\Delta\theta_1}{\Delta\theta_{F.C.}}} \quad \text{(Eq. A9)}$$

at $\theta_M$=1083 °C, $\theta_A$=20 °C, $\theta_{M1}$=30 °C

$$\frac{I}{F.C.20\,°C} = \sqrt{\frac{10\,°C}{1063\,°C}} \quad \text{(Eq. A10)}$$

NOTE: These equations are approximations. They neglect other heating effects such as resistivity, radiation, conduction, and convection. Adding insulation to the cable may cause a higher temperature rise.

Table A1 represents the preceding equations applied to typical industry values.

TABLE A1 - THERMAL RISE IN STEADY-STATE CONDITIONS

| Cable Size ($mm^2$/AWG) | SAE Area | Fusing Current (F.C.) | Ratings (A) |
|---|---|---|---|
| 0.35 / 22 | 0.324 | 41.2 | 4.0 |
| 0.5 / 20 | 0.508 | 57.7 | 5.5 |
| 0.8 / 18 | 0.760 | 78.1 | 7.5 |
| 1 / 16 | 1.13 | 105.1 | 10 |
| 2 / 14 | 1.85 | 152.1 | 14 |
| 3 / 12 | 2.91 | 213.7 | 20 |
| 5 / 10 | 4.65 | 303.7 | 29 |
| 8 / 8 | 7.23 | 422.9 | 41 |
| 13 / 6 | 12.1 | 622.3 | 60 |
| 19 / 4 | 18.3 | 848.7 | 82 |

## A.3 FAULT CONDITIONS

In a fault condition, the cable must be sized for the circuit protection provided. It is important that the cable and breaker are sized in such a way that the thermal circuit breaker "heats" at a rate higher than the cable if we are to protect the cable from any damage. Table 1 in SAE J1614 lists the minimum cable sizes for a given thermal circuit breaker.

In a fault condition, it is typical that all the heat generated ($I^2R$ loss) is put into increasing the temperature of the cable. This is usually a good assumption since the fault occurs very fast.

$$\text{power x delta time} = \text{mass x specific heat x delta temperature} \quad \text{(Eq. A11)}$$

where:

- I = Current in Amperes
- R = Resistance in ohms
- A = Cross sectional area of cable in $mm^2$
- F.C. =Fusing current in Amperes
- L = Length of cable in mm
- K = Specific heat in Watt seconds per gram Centigrade
- $P\theta$ = resistivity in ohm millimeters
- $t, \Delta T$ = time in seconds
- $\theta$ = temperature in °C
- $\theta_M$ = maximum temperature in °C
- $\theta_A$ = Ambient temperature
- $\alpha(\theta_0)$ = Coefficient of electrical resistance per °C
- $\rho_M$ = density in grams per $mm^3$
- d = differential operator

$$I^2 dR dt = K\rho_M A dL d\theta \quad \text{(Eq. A12)}$$

$$dR = \frac{\rho\theta}{A} dL \quad \text{(Eq. A13)}$$

$$\rho\theta = \rho(\theta_0)(1 + (\theta - \theta_0)\alpha(\theta_0)) \quad \text{(Eq. A14)}$$

$$I^2 \frac{\rho(\theta_0)}{A}(1 + (\theta - \theta_0)\alpha(\theta_0))dt = K\rho_M A d\theta \quad \text{(Eq. A15)}$$

Assuming a point solution, the dLs cancel, (i.e., cable temperature is assumed constant along the cable length.) we find:

$$\int_0^{\Delta T} \frac{I^2\rho(\theta_0)}{K\rho_M A^2} dt = \int_{\theta_A}^{\theta_M} \frac{d\theta}{1 + (\theta - \theta_0)\alpha(\theta_0)} \quad \text{(Eq. A16)}$$

$$\text{Let } \theta_t = \frac{1}{\alpha(\theta_0)} - \theta_0 \text{ where } \alpha \neq 0 \quad \text{(Eq. A17)}$$

$$\frac{I^2\rho(\theta_0)}{K\rho_M A^2}\Delta T = \frac{1}{\alpha(\theta_0)}\int_{\theta_A}^{\theta_M}\frac{d\theta}{\theta_t + \theta} = \frac{1}{\alpha(\theta_0)} \ln \frac{\theta_t + \theta_M}{\theta_t + \theta_A} \quad \text{(Eq. A18)}$$