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(Revision of
IEEE Std 1018-1991)

1018™

IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Ethylene-Propylene Rubber Insulation

IEEE Industry Applications Society

Sponsored by the
Petroleum and Chemical Industry Committee

IEEE

3 Park Avenue, New York, NY 10016-5997, USA

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IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Ethylene-Propylene Rubber Insulation

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Petroleum and Chemical Industry Committee
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IEEE Industry Applications Society

Approved 1 February 2005

American National Standards Institute

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IEEE-SA Standards Board

Abstract: Minimum requirements for the construction, manufacturing, purchasing, and application of electric submersible pump cable are presented. The cable is round or flat, with ethylene–propylene rubber insulation, nitrile jacket, ethylene–propylene diene monomer (EPDM) jacket or lead sheath, and armor. These cables are for voltages not exceeding 3 kV or 5 kV (phase to phase) and conductor temperatures not exceeding 140 ºC (284 ºF) for nitrile or a maximum of 204 ºC (400 ºF) for EPDM jacket or lead sheath cable. Conductors, insulation, barrier (optional), assembly and jacket, armor, requirements for testing by the manufacturer, and cable ampacity are covered.
Keywords: ampacity ratings, assembly, cable construction, cable testing, field testing, submersible pump cable

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Introduction

This introduction is not part of IEEE Std 1018-2004, IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Ethylene-Propylene Rubber Insulation.

This recommended practice, under the jurisdiction of the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society, presents the minimum requirements for the construction, manufacturing, purchasing, and application of electric submersible pump cable. The configuration of the cable is either round or flat, with ethylene-propylene rubber insulation, with a nitrile jacket, EPDM jacket, or lead sheath and armor.

Anyone desiring to use this recommended practice may do so. It is presented as minimum criteria for construction of this class of submersible cable. It is not intended to restrict innovation or to limit development of improvements in cable design. Every effort has been made to assure the accuracy and reliability of the data contained herein; however, the committee makes no representation, warranty, or guarantee in connection with the publication of this specification and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use; for any violation of any federal, state, or municipal regulation with which it may conflict; or for the infringement of any patent resulting from the use of this document.

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IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Ethylene-Propylene Rubber Insulation

1. Scope

This recommended practice establishes requirements for three-conductor new round-and-flat-type oil-well cables used in supplying three-phase ac electric power to submersible pump motors. The three major cables by components are (1) cables with copper conductors, ethylene-propylene diene monomer (EPDM) insulation, nitrile jacket, and galvanized armor; (2) cables with copper conductors, EPDM insulation, EPDM jacket, and galvanized armor; and (3) cables with copper conductors, EPDM insulation, lead sheath, and galvanized armor. Cables meeting the requirements of the recommended practice should be rated for voltages not exceeding 3 kV or 5 kV (phase to phase).

Conductor temperatures for cables with nitrile jacket should not exceed 140 °C (284 ºF). Use of nitrile jacketed cable above the rated temperature can cause premature hardening of the jacket, which therefore reduces the jacket life. Conductor temperatures for cables with EPDM jacket or lead sheath may be rated up to 204 °C (400 ºF); for temperatures rated over 204 °C (400 ºF), please consult cable suppliers. Voltage ratings are nominal phase-to-phase ratings.

Cable purchased under the recommendation of this recommended practice, unless otherwise specified herein, should meet the requirements of ASTM B3, ASTM B8, ASTM B33, ASTM B189, ASTM B496, and ICEA S-68-516/NEMA WC 8, where applicable.[1]

This recommended practice recognizes the common practice of continuing to operate the pump's electrical system after a phase has faulted to ground and that some power distribution systems are even designed with one corner of the delta system grounded. The purpose of this recommended practice is not to condone or disapprove of such practice, but the user should be aware that such operation produces a higher than normal phase-to-ground voltage across the insulation jacket dielectric of the two ungrounded conductors. Due to the disruption of the normally balanced three-phase field, such operation produces stresses through the insulation/jacket dielectric, which shortens cable life. ICEA S-68-516/NEMA WC 8 recommends a 173% insulation level for grounded-phase operation, but this is often impractical for downhole oil-well cable; therefore, this specifying standard recommends insulation thickness based on a normal three-phase energized delta or wye system, with no phase grounded.

[1]Information on references can be found in Clause 2.

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2. Normative references

The following referenced documents are indispensable for the application of this recommended practice. For dated references, only the edition cited applies. For undated references, the latest edition of the reference document (including any amendments or corrigenda) applies.

API RP 11S3, Recommended Practice for Electric Submersible Pump Installations, 2nd ed.[2]

API RP 11S4, Recommended Practice for Sizing and Selection of Electric Submersible Pump Installation, 3rd ed.

API RP 11S5, Recommended Practice for Application of Electric Submersible Pump Cable Systems, 1st ed.

API RP 11S6, Recommended Practice for Testing of Electric Submersible Pump Cable Systems, 1st ed.

ASTM A90, Standard Test Method for Weight [Mass] of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings.[3]

ASTM B3, Standard Specification for Soft or Annealed Copper Wire.

ASTM B8, Standard Specification for Concentric-Lay—Stranded Copper Conductors, Hard, Medium-Hard, or Soft.

ASTM B33, Standard Specification for Tinned Soft or Annealed Copper Wire for Electrical Purpose.

ASTM B189, Standard Specification for Lead-Coated and Lead-Alloy-Coated Soft Copper Wire for Electrical Purposes.

ASTM B496, Standard Specification for Compact Round Concentric-Lay—Stranded Copper Conductors.

ICEA S-68-516/NEMA WC 8, Ethylene-Propylene-Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy.[4]

IEEE Std 1017™, IEEE Recommended Practice for Field Testing Electric Submersible Pump Cable.[5]

3. Conductors

3.1 Material

Conductors should be annealed, coated or uncoated, copper in accordance with ASTM B3 for uncoated conductors, in accordance with ASTM B33 for tin-coated conductors, or in accordance with ASTM B189 for lead or lead-alloy coated conductors.

[2]API publications are available from the Publications Section, American Petroleum Institute, 1200 L Street NW, Washington, DC 20005, USA (http://www.api.org/).

[3]ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

[4]ICEA publications are available from ICEA, P.O. Box 20048, Minneapolis, MN 55420, USA (http://www.icea.org/).

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3.2 Construction

Conductors should be solid or concentric-stranded as shown in Table 1 and Table 2. Concentric-stranded conductors should conform to ASTM B8, or when compact round conductors are used, they should conform to ASTM B496, with diameters nominally 92% of corresponding noncompact conductors. When stranded products are used, the interstices should be filled for gas blockage.

Table 1—Conductor characteristics (metric units)

Conductor	Conductor area	Nominal weight	Nominal diameter of conductor (mm)			Conductor resistance (Ω/km @ 25 °C)	
Trade size	(mm^2)	(kg/km)	Solid	Stranded 7 wire	Compact 7 wire	Plain copper	Tinned copper
10 mm^2	10.0	88.5	3.57	—	—	1.87	1.88
6 Awg	13.3	118.0	4.11	—	—	1.32	1.36
16 mm^2	16.0	140.0	4.48	—	—	1.17	1.18
4 Awg	21.1	188.0	5.19	—	—	0.830	0.856
4 Awg	21.1	188.0	—	5.89	5.41	0.846	0.882
25 mm^2	25.0	222.0	5.64	—	—	0.742	0.749
2 Awg	33.6	306.0	6.54	—	—	0.522	0.538
2 Awg	33.6	306.0	—	7.42	6.81	0.531	0.554
1 Awg	42.4	386.0	7.35	—	—	0.413	0.426
1 Awg	42.4	386.0	—	8.33	7.57	0.423	0.440
1/0 Awg	53.5	475.0	—	9.35	8.56	0.335	0.348
2/0 Awg	67.4	599.0	—	10.80	—	0.266	0.276

3.3 Conductivity

Conductors should have a direct current resistance at 25 °C (77 ºF), not to exceed the values listed in Table 1 or Table 2.

4. Insulation

4.1 Material

Insulation should be constructed of ethylene-propylene rubber that meets the properties shown in Table 3 when tested in accordance with ICEA S-68-516/NEMA WC 8.

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Table 2—Conductor characteristics (inch-pound units)

Conductor	Conductor area	Nominal weight	Nominal diameter of conductor (inches)			Conductor resistance (Ω/kft @ 77 °F)	
Trade size	(cmil)	(lb/kft)	Solid	Stranded 7 wire	Compact 7 wire	Plain copper	Tinned copper
10 mm^2	19 644	59.7	0.140	—	—	0.569	0.572
6 Awg	26 240	79.4	0.162	—	—	0.403	0.414
16 mm^2	31 109	95.6	0.178	—	—	0.357	0.360
4 Awg	41 740	126.0	0.204	—	—	0.253	0.261
4 Awg	41 740	126.0	—	0.232	0.213	0.258	0.263
25 mm^2	49 305	149.2	0.222	—	—	0.226	0.228
2 Awg	66 360	206.0	0.258	—	—	0.159	0.169
2 Awg	66 360	206.0	—	0.292	0.268	0.162	0.174
1 Awg	83 690	260.0	0.289	—	—	0.126	0.130
1 Awg	83 690	260.0	—	0.328	0.298	0.129	0.134
1/0 Awg	105 600	319.2	—	0.368	0.337	0.102	0.106
2/0 Awg	133 100	402.7	—	0.414	—	0.081	0.084

Table 3—Ethylene-propylene properties

Physical requirements—unaged	
Tensile strength, minimum, MPa	6.2 (900 psi)
Elongation at rupture, minimum, percent	100
Physical requirements—aged in air	
Oven at 121 °C (250 °F) for 1 week	
Tensile strength, minimum, percent of unaged value	70
Elongation at rupture, minimum, percent retention	70

4.2 Gas blockage

A 30 cm (12 in) specimen of insulated conductor removed from finished cable should be subjected to a 0.035 MPa (5 psi) differential air pressure for a period of 1 hour at 25 °C (77 ºF). The sample ends should be cut off flush with a fine-toothed saw blade, and one end of the sample should have a short section of clear flexible plastic tubing slid over the insulation to enable the specimen to be pressurized. The tubing should be attached in place with a small hose clamp [minimum width of binding collar = 6.4 mm (0.250 in)]. The clamp should be tightened with minimum torque to prevent leakage. The opposite end of the sample should be left submerged in water. No air bubbles should be detected at the submerged end of the cable during the test period.

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4.3 Construction

The insulation should be extruded on the conductor.

4.3.1 Nonlead sheath product

For 3 kV rated cable, average insulation wall thickness should be 1.9 mm (0.75 in) or more. The insulation minimum wall thickness should not be less than 1.7 mm (0.068 in) at any point. For 5 kV rated cable, the insulation average wall thickness should be 2.3 mm (0.090 in) or more. The insulation minimum wall thickness should not be less than 2.1 mm (0.081 in) at any point.

4.3.2 Lead sheath product

For 5 kV rated cable, the insulation average wall thickness should be 1.9 mm (0.075 in) or more. The insulation minimum wall thickness should not be less than 1.7 mm (0.068 in) at any point. Considerations other than voltage stress impact the thickness of insulation.

5. Barrier (optional)

5.1 Material

At the option of the purchaser, each insulated conductor could have additional constraining coverings used for fluid protection and hoop strength. These additional coverings may be extruded fluoropolymers, wrapped tapes, or tape and woven braid.

5.2 Flat cable with lead sheath

Each insulated conductor shall have a lead sheath extruded over the insulation. The average wall thickness should be 1.0 mm (0.040 in), with a minimum thickness of 0.8 mm (0.032 in).

6. Assembly and jacket

6.1 Material

Two basic types of jacket material are used for the cable jacket. The first type is a oil-resistant thermosetting nitrile rubber. The nitrile rubber should meet the properties shown in Table 4 and typically is rated at temperatures to 140 °C (284 ºF). The second type of rubber is an oil-resistant thermosetting EPDM. EPDM rubber for jacket purposes should meet the properties shown in Table 5. EPDM rubber is used in higher temperature wells and may be rated up to temperatures of 204 °C (400 ºF).

Both compounds must be tested in accordance with ICEA S-68-516/NEMA WC 8, Section 6.

6.2 Construction

6.2.1 Round cable

The three insulated conductors should be cabled around a centrally located filler that provides blockage. The conductors should be cabled with a left-hand lay having a maximum length of lay 35 times the individual conductor diameter.

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Table 4—Nitrile properties

Physical requirements—unaged	
Tensile strength, minimum, MPa	12.4 (1800 psi)
Elongation at rupture, minimum, percent	300
Physical requirements—aged in air	
Oven at 100 °C (212 °F) for 1 week	
Tensile strength, minimum, percent of unaged value	50
Elongation at rupture, minimum, percent retention	50
Physical requirements—aged in ASTM	
IRM 9002 oil at 121 °C (250 °F) for 18 hours	
Tensile strength, minimum, percent of unaged value	60
Elongation at rupture, minimum, percent retention	60

Table 5—EPDM jacket properties

Physical requirements—unaged	
Tensile strength, minimum, MPa	6.9 (1000 psi)
Elongation at rupture, minimum, percent	125
Physical requirements—aged in air	
Oven at 121 °C (250 °F) for 1 week	
Tensile strength, minimum, percent of unaged value	75
Elongation at rupture, minimum, percent retention	75
Physical requirements—aged in ASTM	
IRM 9002 oil at 121 °C (250 °F) for 18 hours	
Tensile strength, minimum, percent of unaged value	60
Elongation at rupture, minimum, percent retention	60

A jacket should be extruded over a cable core consisting of three insulating conductors and central filler. The jacket should be extruded to fill all interstices. The average wall thickness should be 1.5 mm (0.060 in), and the minimum thickness at any point should be no less than 1.2 mm (0.048 in).

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The outer surface of the jacket should have splines. These splines are not considered part of the specified wall; splines are provided for the grip of the overlying armor. The jacket should separate cleanly from the underlying components.

6.2.2 Flat cable nonleaded

Each insulated conductor should be individually jacketed. Splines are not required on the jacket. An alternative design may have the three conductors laid parallel within a common encapsulated jacket. All interstices are filled with the jacketing material. The jacket of either design should separate cleanly from the underlying surface.

Additional constraining coverings may be applied over the insulation or jacket. They may be extruded, wrapped, and/or woven type materials. Flat cable with a common encapsulated jacket or without individual constraining coverings may become oval during decompression from a gaseous environment.

For flat cable with additional constraining coverings, the average wall jacket thickness should be 1.3 mm (0.050 in). The minimum jacket thickness at any point should be no less than 1.0 mm (0.040 in).

For flat cable without additional constraining covering, the average jacket wall thickness should be 1.5 mm (0.060 in). The minimum jacket thickness at any point should be no less than 1.2 mm (0.048 in).

6.2.3 Flat cable with lead sheath

Each insulated conductor should have a lead sheath extruded over the insulation. The average wall thickness should be 1.0 mm (0.040 in). The minimum wall thickness at any point should be no less than 0.8 mm (0.032 in).

7. Armor

7.1 Material

The standard armor should be made from a galvanized steel strip.

7.1.1 Size

The thickness of the steel strip for round cable constructions, before galvanizing, should have a nominal thickness of 0.64 mm (0.025 in). The minimum wall thickness at any point should be no less than 0.56 mm (0.022 in). The thickness of the steel strip for flat cable constructions, before galvanizing, should have a nominal thickness of 0.51 mm (0.020 in). The minimum wall thickness at any point should be no less than 0.43 mm (0.017 in). The typical width of the steel strip is 12.7 mm (0.500 in) and should be no more than 19.1 (0.750 in) mm before forming.

7.1.2 Coating

The steel strip should be zinc-coated after slitting. The coating should be applied to all surfaces by the hot-dip galvanizing process.

7.1.3 Tensile strength and elongation

The zinc-coated strip should have a tensile strength of not less than 275 MPa (40 000 psi) elongation of not less than 10% in 25 cm (10 in). All tests should be performed in accordance with ICEA S-68-516/ NEMA WC 8 before application of the strip to the cable.

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7.1.4 Weight of zinc coating

The weight of zinc coating should be determined before application of the strip to the cable. The strip should have a minimum coating weight of 110 g/m^2 (0.35 oz/ft^2) of exposed surface. The weight of the coating should be determined in accordance with the method described in ASTM A90. The zinc-coated strip should not exceed the bare-metal strip thickness by more than 20% at any point.

7.1.5 Adherence of coating

The zinc coating should remain adherent without flaking or spalling when tested in accordance with ICEA S-68-516/NEMA WC 8.

7.1.6 Armor for harsh environments

Thicker steel strip can be provided. Heavier Type II galvanizing may be used as per ASTM A90. For extremely corrosive environments, stainless steel (316L) or other metal alloys are available.

7.2 Construction

7.2.1 Round cable

The armor strip should be applied over the cable core with sufficient tightness to compress the jacket splines. The strip should be helically applied and formed in such a manner as to be interlocked. The armor should withstand a seven times overall diameter bend radius without separation of adjacent turns.

7.2.2 Flat cable

The construction should consist of the three-phase conductors laid in parallel. The armor strip should be applied over the insulated conductors with sufficient tightness to fit snugly. The armor strip should be helically wrapped and formed in an overlapped manner. The assembly should withstand a bend that is seven times the major axis of the cable. The armor overlap should not open up between adjacent turns. The direction of bend should be in the normal direction of cable spooling.

8. Manufacturers' electrical test requirements

8.1 Conductor testing

Before application of any covering, conductors should be tested to meet the physical requirements of Clause 3.

8.2 Electrical testing

All submersible pump cables should be electrically tested by the manufacturer in accordance with this clause to determine compliance with these standards. Tests should be conducted on single-insulated conductors and on finished cable.

8.2.1 Electrical test methods

Unless otherwise noted, electrical tests should be performed per ICEA S-68-516/NEMA WC 8, Section 6.

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8.2.2 Single-insulated conductors before cabling

The insulated conductor should be immersed in water for a minimum of 6 hours, followed by a dc and/or an ac withstand test according to the values shown in Table 6. The duration of both tests should be 5 minutes.

Table 6—Test voltages for ESP cable[a]

Cable dating (kV rms) (phase-to-phase)	Factory test voltage (kV)	Acceptance test voltage[b] (kV)	Maintenance test voltage[c] (kV)
3	27	22	11
5	35	28	14

[a]All tests are dc, conductor to ground for 5 minutes.
[b]Acceptance test is 80% of factory test.
[c]Maintenance test is 40% of factory test.

8.2.3 Resistance

On completed cable, the conductor resistance test should be performed and should comply with Table 1 or Table 2.

8.2.4 DC withstand test

Finished armored cable should be tested in air by a dc withstand test according to the values shown in Table 6. Each phase conductor should be tested individually. The armor, and the phase conductors not being tested at the time, should be grounded during the test. The negative polarity should be applied to the conductor under test. The test duration should be 5 minutes.

8.2.5 Conductance leakage readings

All power cables should be tested and meet the minimum test requirements for factory testing of conductance leakage readings per Table 7 and Table 8 at the prescribed voltage level in Table 6. The leakage values are based on bulk resistivity factor of 6100 MΩ · km (20 000 MΩ · kft). Refer to API RP 11S6 for the calculation method.

8.2.6 Safety

After each test is completed, all conductors and armor must be shorted together and to ground. Maintain the ground for duration of at least twice the length of the previous test to ensure that there is no residual charge.

8.2.7 Field testing

See IEEE Std 1017 for related information on testing submersible cable. Some interpretation guidelines are also included in that recommended practice.

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Table 7—Conductance leakage readings (metric units)

Values for 1.91 mm (75 mil) insulation thickness 3 kV EPDM					
Conductor	**Conductor diameter**	**Insulation minimum point**	**Calculated insulation diameter**	**IR value 1 km**	**DC leakage 1 km**
Trade size	**mm (in)**	**mm**	**mm**	**MΩ**	**μA/kV**
10 mm^2	3.56 (0.140)	1.73	7.01	1797	0.56
6 Awg	4.11 (0.162)	1.73	7.57	1614	0.62
16 mm^2	4.52 (0.178)	1.73	8.01	1503	0.67
4 Awg	5.18 (0.204)	1.73	8.66	1347	0.74
25 mm^2	6.55 (0.258)	1.73	10.01	1121	0.89
2 Awg	7.42 (0.292)	1.73	10.87	1012	0.99
1 Awg	8.43 (0.332)	1.73	11.89	909	1.10
1/0 Awg	9.35 (0.368)	1.73	12.80	833	1.20
2/0 Awg	10.52 (0.414)	1.73	14.00	752	1.33
Values for 2.29 mm (90 mil) insulation thickness 5 kV EPDM					
Conductor	**Conductor diameter**	**Insulation minimum point**	**Calculated insulation diameter**	**IR value 1 km**	**DC leakage 1 km**
Trade size	**mm (in)**	**mm**	**mm**	**MΩ**	**μA/kV**
10 mm^2	3.56 (0.140)	2.06	7.01	2035	0.49
6 Awg	4.11 (0.162)	2.06	7.57	1835	0.54
16 mm^2	4.52 (0.178)	2.06	8.01	1713	0.58
4 Awg	5.18 (0.204)	2.06	8.66	1542	0.65
25 mm^2	6.55 (0.258)	2.06	10.01	1290	0.78
2 Awg	7.42 (0.292)	2.06	10.87	1168	0.86
1 Awg	8.43 (0.332)	2.06	11.89	1052	0.95
1/0 Awg	9.35 (0.368)	2.06	12.80	966	1.04
2/0 Awg	10.52 (0.414)	2.06	14.00	874	1.14

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Table 8—Conductance leakage readings (inch-pound units)

Values for 1.91 mm (75 mil) insulation thickness 3 kV EPDM					
Conductor	**Conductor diameter**	**Insulation minimum point**	**Calculated insulation diameter**	**IR value 1 kft**	**DC leakage 1 kft**
Trade size	**mm (in)**	**in**	**in**	**MΩ**	**μA/kV**
10 mm^2	3.56 (0.140)	0.068	0.276	5896	0.17
6 Awg	4.11 (0.162)	0.068	0.298	5294	0.19
16 mm^2	4.52 (0.178)	0.068	0.314	4930	0.20
4 Awg	5.18 (0.204)	0.068	0.341	4420	0.23
25 mm^2	6.55 (0.258)	0.068	0.398	3678	0.27
2 Awg	7.42 (0.292)	0.068	0.428	3321	0.30
1 Awg	8.43 (0.332)	0.068	0.468	2982	0.34
1/0 Awg	9.35 (0.368)	0.068	0.504	2732	0.37
2/0 Awg	10.52 (0.414)	0.068	0.550	2467	0.41
Values for 2.29 mm (90 mil) insulation thickness 5 kV EPDM					
Conductor	**Conductor diameter**	**Insulation minimum point**	**Calculated insulation diameter**	**IR value 1 km**	**DC leakage 1 km**
Trade size	**mm (in)**	**in**	**in**	**MΩ**	**μA/kV**
10 mm^2	3.56 (0.140)	0.081	0.302	6678	0.15
6 Awg	4.11 (0.162)	0.081	0.324	6021	0.17
16 mm^2	4.52 (0.178)	0.081	0.340	5621	0.18
4 Awg	5.18 (0.204)	0.081	0.367	5058	0.20
25 mm^2	6.55 (0.258)	0.081	0.420	4233	0.24
2 Awg	7.42 (0.292)	0.081	0.454	3833	0.26
1 Awg	8.43 (0.332)	0.081	0.494	3452	0.29
1/0 Awg	9.35 (0.368)	0.081	0.530	3169	0.32
2/0 Awg	10.52 (0.414)	0.081	0.576	2868	0.35

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9. Cable ampacity

9.1 Ampacity

Cable ampacity ratings are limited by the following factors:

a) Ambient temperature
b) Liquid/gas environment
c) Heat rise due to resistance heating
d) Heat distortion properties of insulation
e) Ability to dissipate heat

9.2 Temperature

Conductor operating temperature as a function of well temperature and current flow is shown in Figure 1 to Figure 16.[6] These figures are based on Neher-McGrath calculations in an air environment. It is recommended that 140 °C (284 ºF) be used as the maximum conductor operating temperature for EPDM insulation with a nitrile jacket. Conductor temperatures for cables with EPDM jacket or lead sheath may be rated up to 204 °C (400 ºF). For temperatures rated over 204 °C (400 ºF), please consult cable suppliers.

9.3 Safety factor

The Neher-McGrath calculations are based on the limit of performance for the material under ideal conditions. Because of real constraints in operating environments and the experience of the industry, it is necessary to restrict the temperature or current limits. The ampacity of the cable contains a safety factor that is 0.9 of the Neher-McGrath calculated value based on cable in air-filled buried pipe.

9.4 Conductor size

The conductor size depends on the length of the cable (D) in meters (feet), the current (I), the conductor resistivity (ρ), the ambient well temperature (T) in degrees Celsius (Fahrenheit), and the voltage drop (ΔV). The voltage drop is generally restricted to 5%.

The conductor resistivity is corrected for ac resistance and for temperature. The unit for resistivity is ohm square millimeter per meter (ohm circular-mil per foot). The basic value for bare copper resistivity is 0.017241 (10.371), and it is 0.017965 (10.810) for tinned copper.

$$\rho = \frac{0.017241 \times 1.02 \times (234.5 + T)}{254.5} \quad \text{METRIC UNITS}$$

$$\rho = \frac{10.371 \times 1.02 \times (234.5 + T)}{254.5} \quad \text{INCH-POUND UNITS}$$

The conductor area (A) is calculated from the following formula. The wire size is read from Table 1 or Table 2:

$$A = \frac{(\rho \times 1.732 \times D \times I)}{\Delta V}$$

[6]All figures cited in text can be found in Annex B.

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Example

Ambient temperature = 80 °C (1768 °F)

Distance = 1524 m (5000 ft)

Current = 60 A

Voltage = 2400 V phase to phase

Voltage drop = 5% = 120 V

$$p = \frac{0.017241 \times 1.02 \times (234.5 + 80)}{254.5} = 0.0217 \quad \text{METRIC UNITS}$$

$$A = \frac{(0.0217 \times 1.732 \times 1524 \times 60)}{120} = 28.64 \text{ mm}^2 \quad \text{METRIC UNITS}$$

$$p = \frac{10.371 \times 1.02 \times (234.5 + 80)}{254.5} = 13.07 \quad \text{INCH-POUND UNITS}$$

$$A = \frac{(13.07 \times 1.732 \times 5000 \times 60)}{120} = 56\ 593 \text{ cmils} \quad \text{INCH-POUND UNITS}$$

From Table 1 or Table 2, this calculation would equate to a conductor trade size of #2 Awg (33.6 mm^2) or larger.

Use this wire size to check the cable temperature with the conductor temperature charts in Figure 1 through Figure 16. Plot the intersection of the conductor current and the maximum well temperature. The conductor temperature must be less than the rated temperature of the insulation and jacket. If it is greater, select a larger wire size.

9.5 Economics

Conductor ampacity ratings are not the only criteria for selecting a conductor size. For example, the economics of having greater power losses with a smaller conductor must be weighed against the cost of a larger size conductor. See 10.2.5.

10. Tutorial information

10.1 Special terms

cable tensile strength: The strength of the cable is basically the strength of the conductors. The other components of the cable can be eliminated as strength members. The cables are not designed to be used as a pulling device for components such as packers, seals, pumps, and motors.

The following example is provided for information about maximum breaking strength of the cable. This consideration is important when the cable must be used as a tension device. The cable will be destroyed.

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Example: 3/C #4 Awg solid copper

Copper tensile breaking strength = 344.7 MPa (50 000 psi)

Conductor diameter = 5.182 mm (0.204 in)

Conductor area = 21.1 mm^2 (0.0327 in^2)

Cable weight = 1.265 kg/m (0.85 lbs/ft)

Calculate the maximum force a single conductor can support in metric units (US):

Maximum force = 344.7 MPa × 21.1 mm^2 = 7273 N/conductor

METRIC UNITS

(Maximum force = 50 000 psi × 0.327 = 1635 lbs/conductor)

INCH-POUND UNITS

Assume the tension is equal on all three legs of the cable. The maximum pulling force that can be applied on the cable would be three times that of the single conductor:

Maximum force = 7273 N/conductor × 3 conductors = 21 820 N/cable

METRIC UNITS

(Maximum force = 1635 lbs/conductor × 3 conductors = 4905 lbs/cable)

INCH-POUND UNITS

Determine the length of cable whose weight alone exceeds this force:

Maximum length = 2182.5/1.265 = 1725 m METRIC UNITS

(Maximum length = 4905/0.85 = 5770 ft) INCH-POUND UNITS

compounds modulus: A relative measure of the force achieved at a given elongation of the material. It is normally recorded as a stress (megapascal or pound-force per square inch) at the given percent elongation. A lower modulus material has more of a tendency to give before breaking, that is, less resistance to expansion.

elongation: The percent change in length for a given length.

EPDM: Terpolymer of ethylene, propylene, and a diene with the residual unsaturated portion of the diene in the side chain.

Ethylene-propylene monomer (EPM): Comprises copolymers of ethylene and propylene.

Ethylene-propylene rubber (EPR): Used as a generic term to define EPM or EPDM insulation.

hoop strength: It is a measure of the tangential resistance to elongation. As internal gas pressure pushes in a radial direction, it creates a tendency for the surface of the insulation and jacket to elongate and rupture in a tangential direction. The hoop strength resists this tendency and can be aided by additional wraps applied over the round components.

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tensile strength: The stress (megapascal or pound-force per square inch) required to break the item.

tensile stress: The force exerted per unit area.

toughness factor: It is a measure of material performance under stress. It measures the ability of a material to withstand energy input over a unit of time. The toughness of a material equals one half the product of the material's tensile strength and elongation ratings. For the same toughness factor, a more brittle material will have greater tensile strength and less elongation, whereas a more gummy material will have less tensile strength and more elongation.

ultimate elongation: The percent change in length at rupture.

shunt admittance: The reciprocal of impedance, with the units "mho." As used in this recommended practice, shunt admittance is a measure of leakage conductance to ground through the cable insulation.

voltage stress: It may be thought of as the electrical pressure being applied to the insulation in an effort to burst through the material and short to ground. It could be thought of as analogous to water pressure in a pipe, where the higher the pressure, the harder it tries to burst through. For an electrical insulation material, the resistance to bursting through is known as the dielectric breakdown strength. It is usually expressed in terms of volts/millimeter (or volts/mil) required to puncture a sample of known thickness. For conventional cables, the voltage stress is normally maintained at less than 2165 V/mm (55 V/mil).

With electrical stress, the further away (outward) from the conductor one moves, the lower the stress becomes. Formulas used to calculate the electrical stress levels. They assume that the cable insulation is surrounded by a shield (i.e., lead sheath) or other adequate source of ground potential. The electrical stress level (S) may be calculated by the following formula:

$$S = \frac{E}{\left[2.303 \times r \times \ln\left(\frac{D_i}{d_c}\right)\right]} \quad \text{(V/mm) METRIC UNITS}$$

where

S is the stress in the insulation at radius r, volts/millimeter (volts/mil) (1 mil = 0.001 in = 0.0254 mm)

E is the phase-to-ground voltage, volts; for three phase systems, (phase-to-phase voltage)/1.732

D_i is the diameter over the insulation, millimeters (inches)

d_c is the diameter over the conductor, millimeters (inches)

r is the radial distance from the center of the conductor at which it is desired to calculate the electrical stress, millimeters (inches)

The maximum stress (S_{max}) on the insulation is at the conductor surface. In this case, r would be equal to $1/2 \times d_c$.

$$S_{max} = \frac{E}{\left[2.303 \times \frac{d_c}{2} \times \ln\left(\frac{D_i}{d_c}\right)\right]} \quad \text{(V/mm) METRIC UNITS}$$

$$S_{max} = \frac{E}{\left[0.0584 \times \frac{d_c}{2} \times \ln\left(\frac{D_i}{d_c}\right)\right]} \quad \text{(V/in) INCH-POUND UNITS}$$

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The minimum stress (S_{min}) on the insulation is at the surface of the insulation. In this case, r would be equal to $1/2 \times D_i$.

$$S_{min} = \frac{E}{\left[2.303 \times \frac{D_i}{2} \times \ln\left(\frac{D_i}{d_c}\right)\right]} \quad \text{(V/mm) METRIC UNITS}$$

$$S_{min} = \frac{E}{\left[0.0584 \times \frac{D_i}{2} \times \ln\left(\frac{D_i}{d_c}\right)\right]} \quad \text{(V/in) INCH-POUND UNITS}$$

10.2 Application considerations

10.2.1 Installation

Cable installation requires running the cable over a sheave. The diameter of the sheave should be as large as possible, with a 137 cm (54 in) unit being the generally recommended size (see API RP 11S3). For round cable, the sheave surface should be concave to conform to the cable shape. Where flat cable is being predominantly run, the sheave should have a flat surface.

10.2.2 Pull rates

Gas will permeate the materials and try to expand and contract according to temperature and pressure changes. Pressure will increase when the well is shut in. It will decrease when the well is producing. Therefore, gas in the jacket is alternately compressed and expanded. Moreover, during a pulling operation, the absorbed gas tries to rapidly expand, which potentially causes ruptures in the cable insulation and jacket.

Some manufacturers provide cable that is designed to rapidly expel gas as the pressure is decreased. Others attempt to minimize ruptures due to gas expansion by providing additional hoop strength. Methods such as lead sheaths or a tape and braid are used. The cable armor also helps control “blow outs” from rapid depressurization.

Although these approaches are beneficial, none can be fully effective under all conditions. If gas is found to be causing the cable to swell or rupture, the operator should consider reducing cable pulling rates. Typical rates vary from 305 m to 1200 m (1000 ft to 4000 ft) per hour. However, the “proper rate” is whatever works for a particular well. Keep in mind that significant cable damage from factors other than gas expansion can also occur from excessively high pull rates.

10.2.3 Chemical treatments

Most corrosion inhibitors have adverse effects on the nitrile jackets protecting the cable insulation. They include such things as softening or hardening of the nitrile jacket, which is reflected in changes in the jacket compound’s modulus. Also, acid wash will cause the nitrile jacket to become brittle quickly. Inhibitors and well-treatment chemicals will also affect the cable armor. It is suggested that data from chemical tests on cable samples be reviewed before using a well treatment.

10.2.4 Balancing flat cable phase currents

Flat electric-motor cable has unbalanced series impedance, which causes current unbalance in electric submersible pump (ESP) motors. When flat cable is required, current unbalance can be minimized by rotating the cable connections to find the combination that produces the least unbalance.

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However, it should be noted that currents entering the cable at the surface are not necessarily the same as the currents entering the submerged motor. High and unequal shunt admittance can produce a zero-sequence current, which causes a downhole current unbalance that is not reflected at the surface. Grounded-neutral, wye-connected power transformers will create that condition.

Common practice tries to maximize run life by using an ungrounded power source. Two faults must then occur before operation ceases. The ungrounded power source prevents flow of zero-sequence current, which thereby minimizes unbalance problems.

Even if the transformer neutral is not grounded, having one phase grounded downhole will also allow some zero-sequence current. Therefore, before rotating phases to balance currents, it is necessary to ensure that no phase conductor is grounded.

As the motor is connected to the end of the cable, it is not possible to measure individual phase insulation resistance directly. The motor effectively shorts the three phase conductors together. All three phases will have essentially the same resistance to ground readings.

On ungrounded secondary systems, the quality of each phase insulation system can be determined by measuring individual phase-to-ground voltages. If each voltage reading is within 10% of the overall average, then rotating the phases to achieve minimum current unbalance can be beneficial.

The three possible cable-to-motor-starter connections can be compared for minimum current unbalance. All three conductors must be rotated in sequence to avoid reversing the direction of motor rotation. The unbalanced series impedance of the cable can then be optimally connected to offset unbalances in input voltage and produce minimum unbalance in motor currents.

10.2.5 Economic ampacity

The economics of decreasing losses in the cable will provide incentive to increase the size of conductors. The economic ampacity of a cable is influenced as much by the cost of energy as by the cable material. The economic ampacity is the current at which the energy cost for the losses in the wire are equal to the incremental cost of the next larger wire size.

The equation for calculating the economic ampacity is shown here. The following equation calculates ampacity that will provide break-even economics for the specific conditions. If the operating current is higher than the current calculated by the equation, then a larger size conductor can be installed with a payout that is less than the time entered into the equation:

$$I = \left[\frac{\text{\$ per km change in wire cost} \times 1000\ \text{W/kWh}}{\text{resistance difference} \times \text{\$/kWh} \times \#\text{ph} \times \text{PO years} \times 24 \times 365}\right]$$

where

I	is the economic current
\$ per km change in wire cost	is the cost difference between two cables using different conductor sizes
resistance difference	is the difference in resistance between two conductor sizes at the well's bottom-hole temperature
\$/kWh	is the electrical power cost
#ph	is the number of phases (normally there are three)
PO years	is the number of years to see payout using the larger conductor

According to API RP 11S4, a maximum of 5% voltage drop over the entire length of the cable will provide a reasonable operating efficiency. In addition, using larger conductors will improve cable life by reducing internal heating caused by current flowing in the cable.

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Annex A

(informative)

Cable designs and components

A.1 Round cable normally used in wells with operating temperatures less than 80 ºC (176 ºF)—Figure 17[7]

1) Copper conductor
2) Insulation—polypropylene
3) Jacket—polyethylene—excellent abrasion resistance

A.2 Round cable normally used in wells with operating temperatures less than 96 ºC (205 ºF)—Figure 18

1) Copper conductor
2) Insulation—polypropylene
3) Jacket—oil-resistant nitrile rubber
4) Armor—standard 0.64 mm (0.025 in) galvanized steel

A.3 Flat cable normally used in wells with operating temperatures less than 96 ºC (205 ºF)—Figure 19

1) Copper conductor
2) Insulation—polypropylene
3) Jacket—oil-resistant nitrile rubber
4) Armor—standard 0.51 mm (0.020 in) galvanized steel

A.4 Flat cable normally used in wells with operating temperatures less than 96 ºC (205 ºF)—Figure 20

1) Copper conductor
2) Insulation—polypropylene
3) Jacket—oil-resistant nitrile rubber
4) Barrier layer, normally tape and braid
5) Armor—standard 0.51 mm (0.020 in) galvanized steel

[7]All figures cited in Annex A can be found in Annex B.

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A.5 Round cable normally used in wells with operating temperatures less than 140 ºC (284 ºF)—Figure 21

1) Copper conductor
2) Insulation—EPDM
3) Jacket—oil-resistant nitrile rubber
4) Armor—standard 0.64 mm (0.025 in) galvanized steel

A.6 Round cable normally used in wells with operating temperatures less than 140 ºC (284 ºF)—Figure 22

1) Copper conductor
2) Insulation—EPDM
3) Optional, tape, braid, tape and braid, or extruded barrier
4) Jacket—oil-resistant nitrile rubber
5) Armor—standard 0.64 mm (0.025 in) galvanized steel

A.7 Flat cable normally used in wells with operating temperatures less than 140 ºC (284 ºF)—Figure 23

1) Copper conductor
2) Insulation—EPDM
3) Jacket—oil-resistant nitrile rubber
4) Barrier layer, normally tape and braid
5) Armor—standard 0.51 mm (0.020 in) galvanized steel

A.8 Round Cable normally used in wells with operating temperatures less than 204 ºC (400 ºF)—Figure 21 and Figure 22

1) Copper conductor
2) Insulation—EPDM
3) Jacket—EPDM rubber
4) Armor—standard 0.64 mm (0.025 in) galvanized steel

A.9 Round cable normally used in wells with operating temperatures less than 204 ºC (400 ºF)—Figure 21 and Figure 22

1) Copper conductor
2) Insulation—EPDM
3) Optional, tape, braid, tape and braid, or extruded barrier
4) Jacket—EPDM rubber
5) Armor—standard 0.64 mm (0.025 in) galvanized steel

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A.10 Flat cable normally used in wells with operating temperatures less than 204 ºC (400 ºF)—Figure 23

1) Copper conductor
2) Insulation—EPDM
3) Jacket—EPDM rubber
4) Barrier layer, normally tape and braid
5) Armor—standard 0.51 mm (0.020 in) galvanized steel

A.11 Flat cable lead sheath, for harsh environments and temperatures less than 204 ºC (400 ºF); for temperatures over 204 ºC (400 ºF), contact the manufacturer—Figure 24

1) Copper conductor
2) Insulation—EPDM
3) Jacket—Lead sheath
4) Bedding layer, can be braid or bedding tape
5) Armor—standard 0.51 mm (0.020 in) galvanized steel

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Annex B

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Figures

B.1 Conductor temperature charts

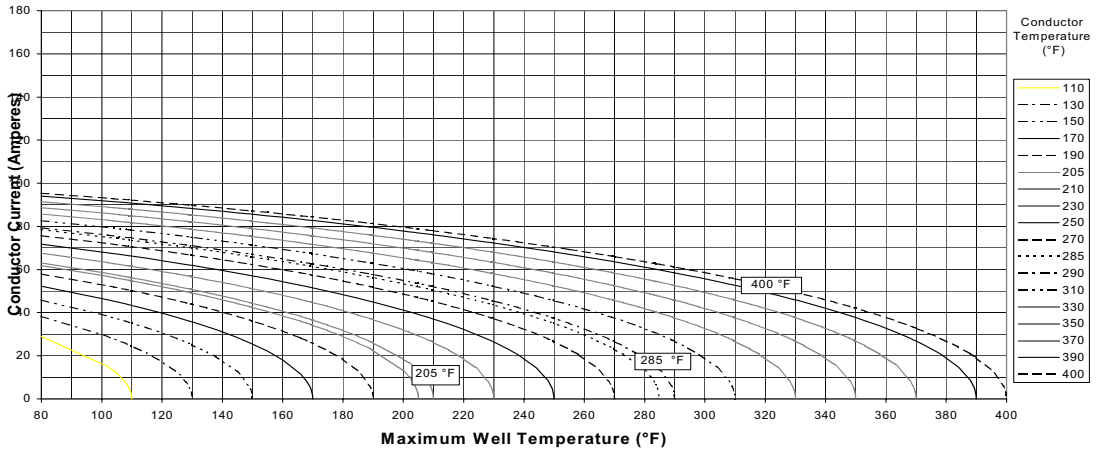


Figure 1—10 mm^2 solid flat pump cable conductor temperature chart

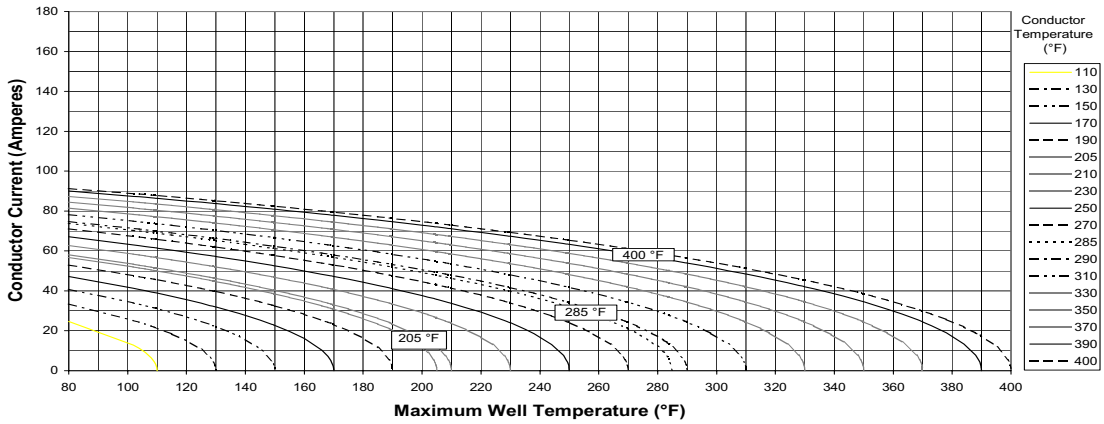


Figure 2—10 mm^2 solid round pump cable conductor temperature chart

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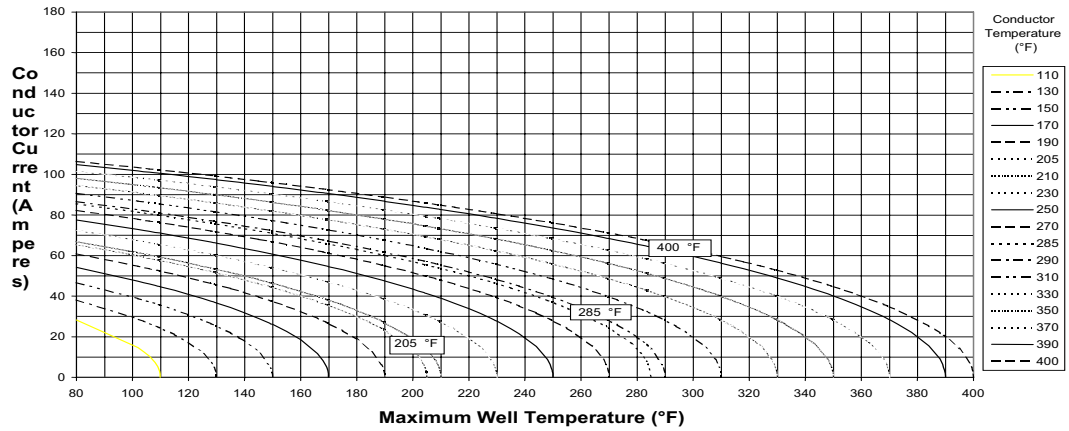


Figure 3—#6 Awg solid round pump cable conductor temperature chart

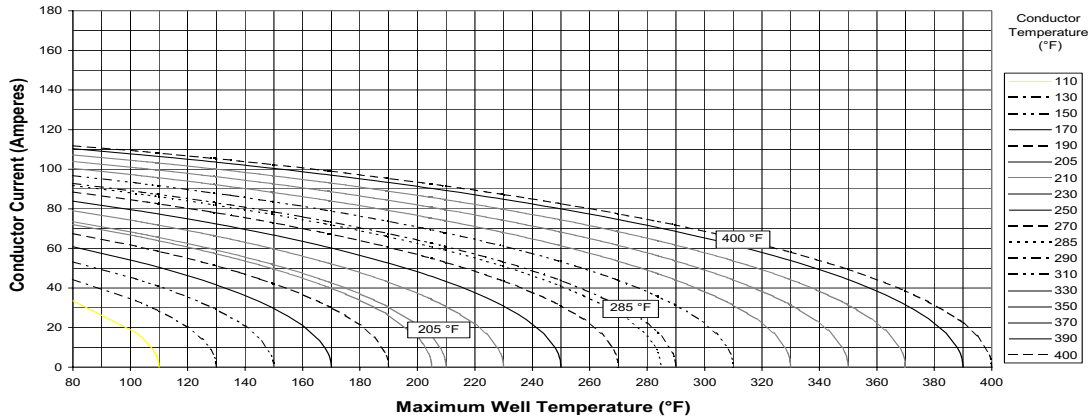


Figure 4—#6 Awg solid flat pump cable conductor temperature chart

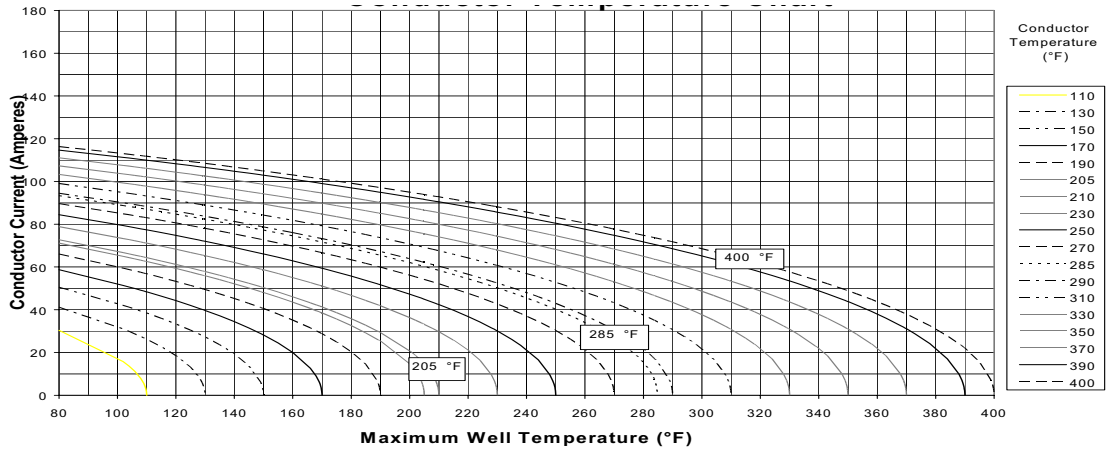


Figure 5—16 mm^2 solid round pump cable conductor temperature chart

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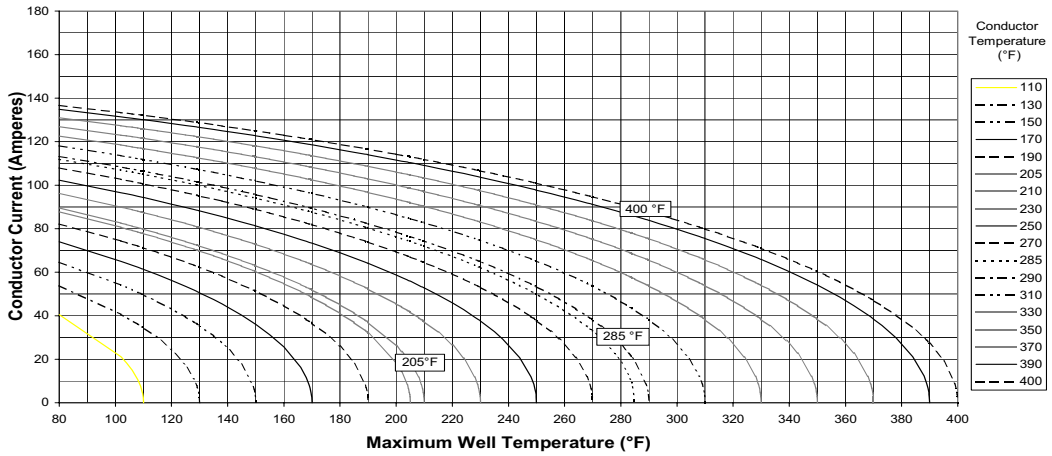


Figure 6—16 mm^2 solid flat pump cable conductor temperature chart

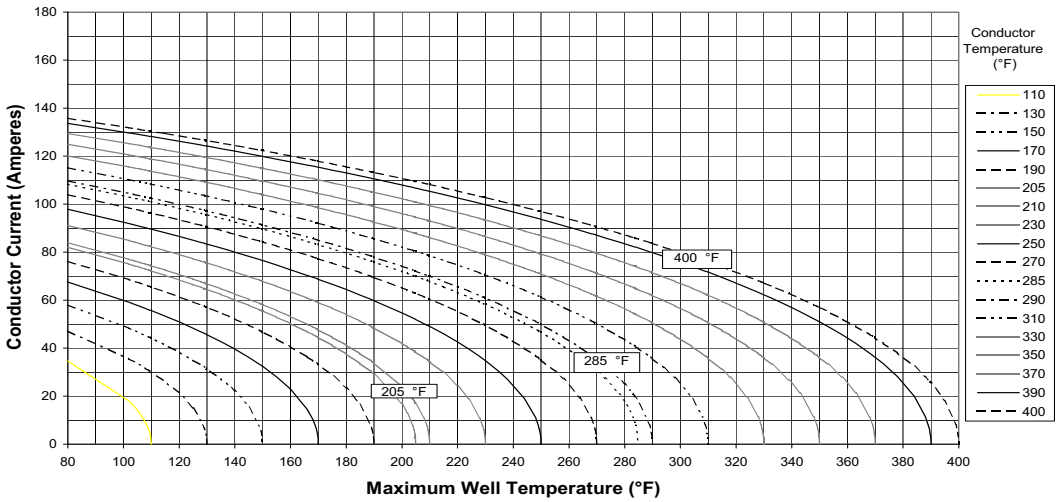


Figure 7—#4 Awg solid round pump cable conductor temperature chart

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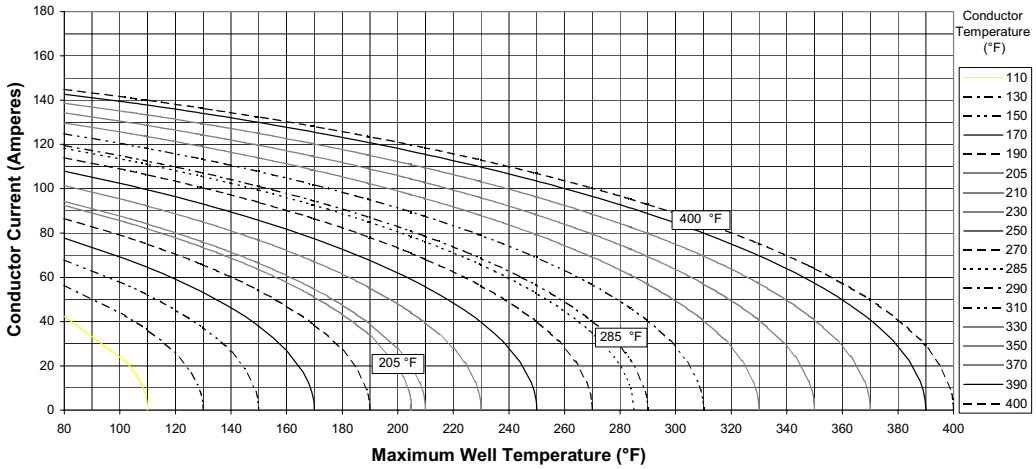


Figure 8—#4 Awg solid flat pump cable conductor temperature chart

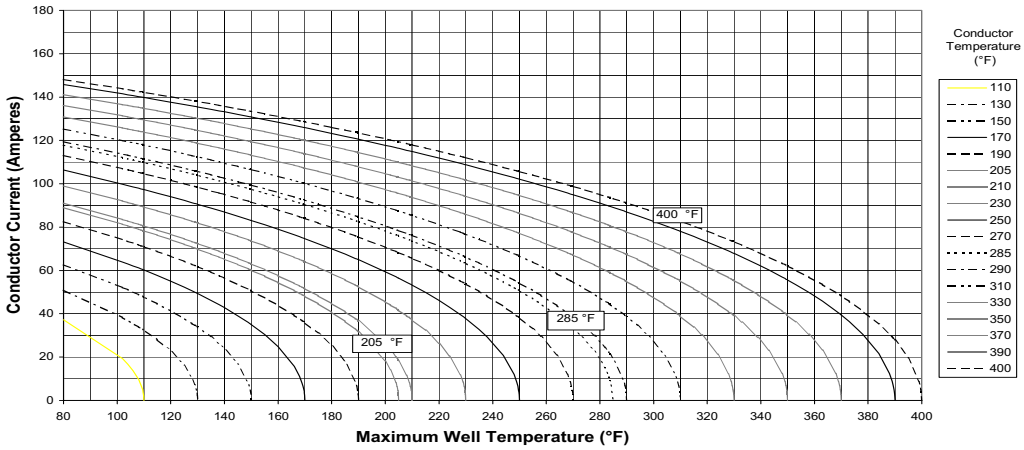


Figure 9—25 mm^2 solid round pump cable conductor temperature chart

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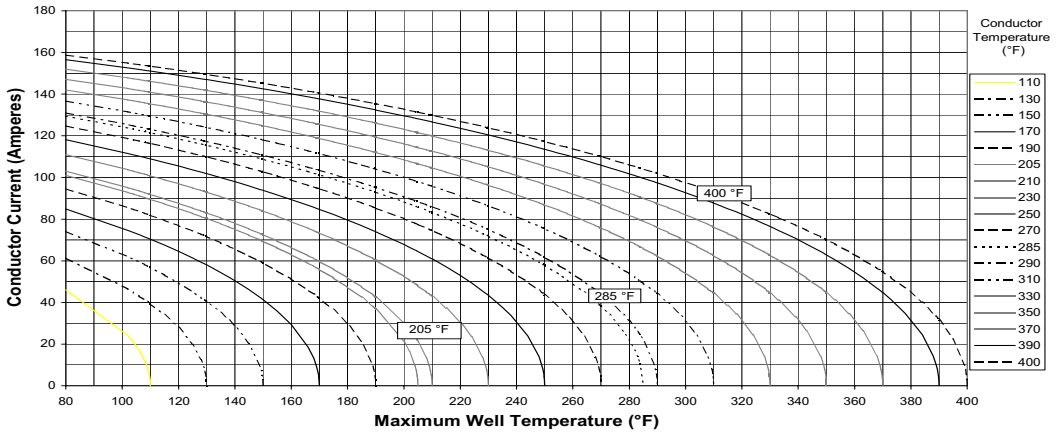


Figure 10—25 mm^2 solid round pump cable conductor temperature chart

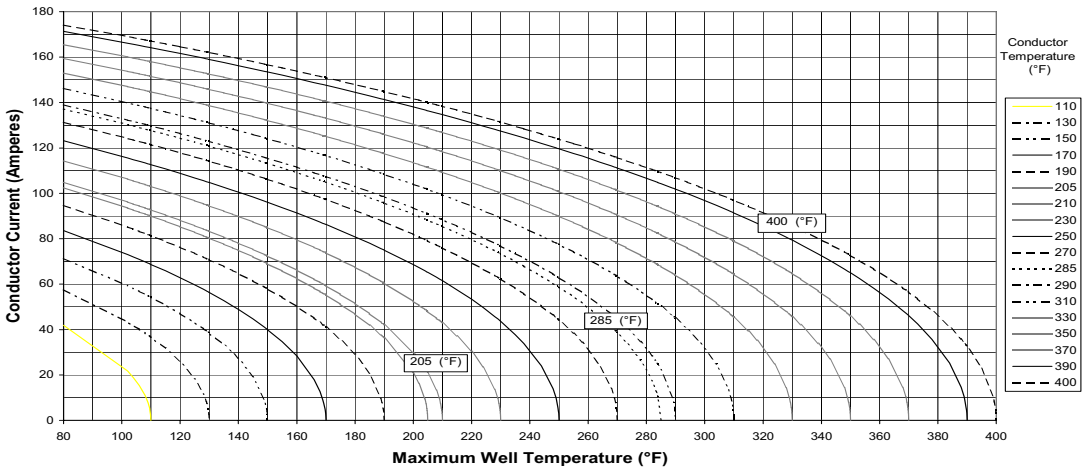


Figure 11—#2 Awg stranded round pump cable conductor temperature chart

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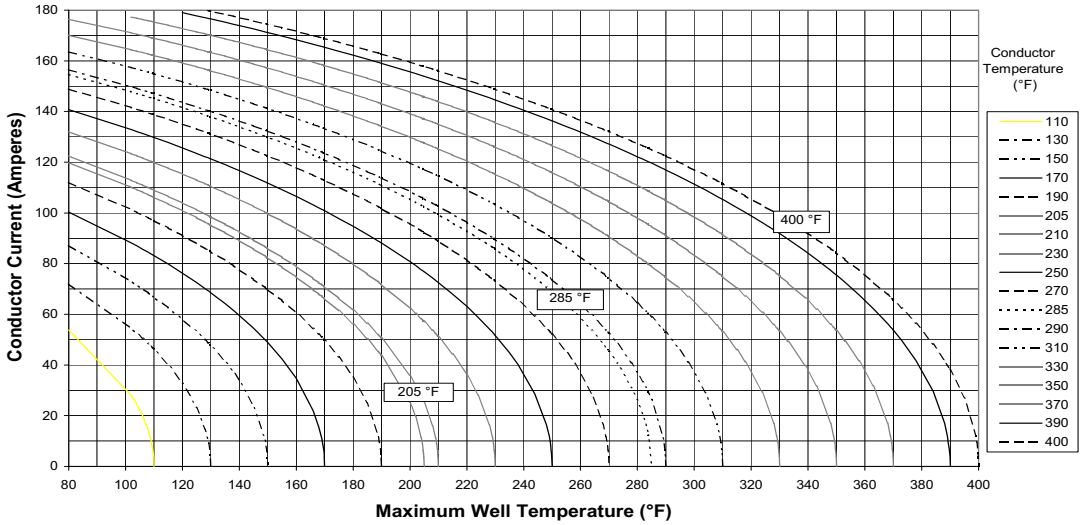


Figure 12—#2 Awg stranded flat pump cable conductor temperature chart

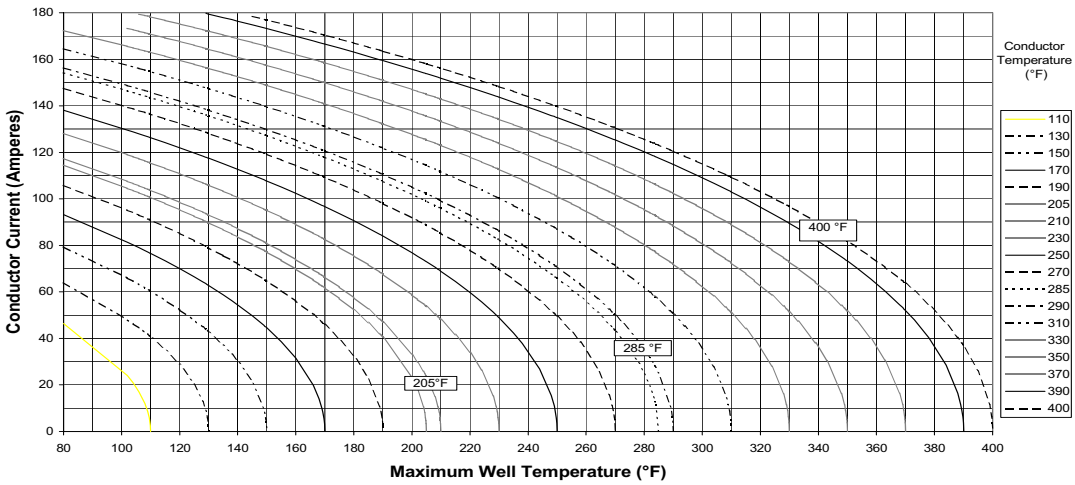


Figure 13—#1 Awg stranded round pump cable conductor temperature chart

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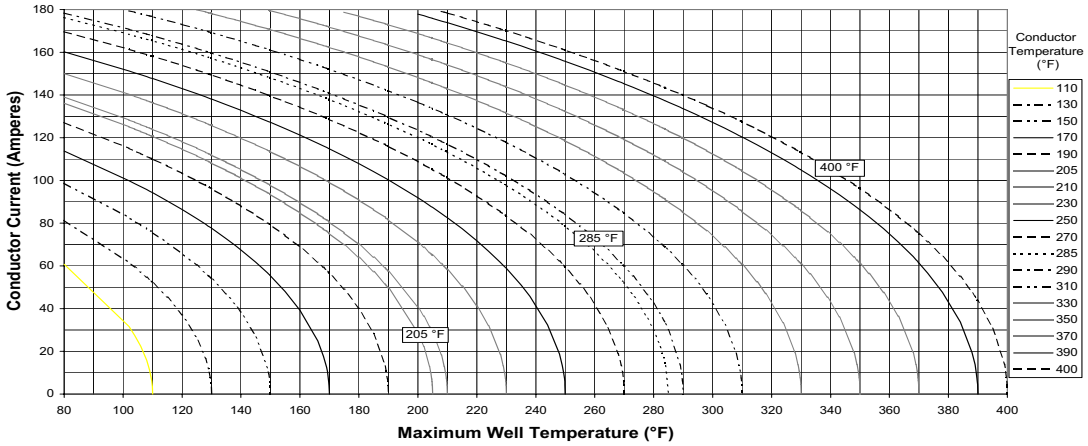


Figure 14—#1 Awg stranded flat pump cable conductor temperature chart

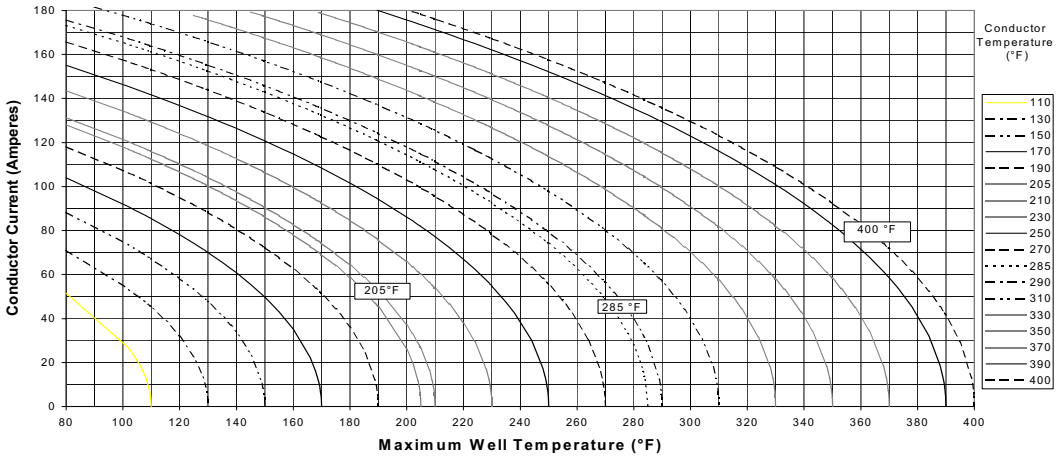


Figure 15—#1/0 Awg stranded round pump cable conductor temperature chart

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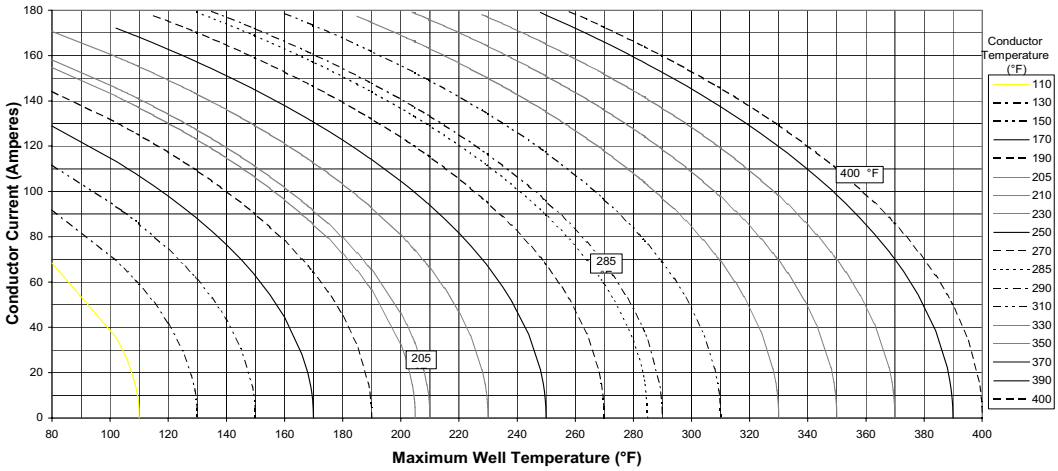


Figure 16—#1/0 Awg stranded flat pump cable conductor temperature chart

B.2 Polypropylene cables

Figure 17—Round cable normally used in wells with operating temperatures less than 80 ºC (176 ºF)

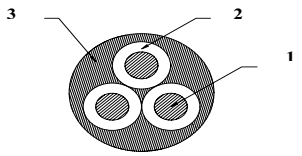
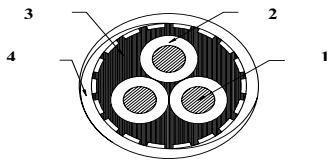


Figure 18—Round cable normally used in wells with operating temperatures less than 96 ºC (205 ºF)



Item	Description	Item	Description
1	Conductor, Copper	1	Conductor, Copper
2	Insulation, Polypropylene	2	Insulation, Polypropylene
3	Jacket, Polyethylene	3	Jacket, Nitrile
		4	Armor

All round cables have a physical filler to fill interstice.

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Figure 19—Flat cable normally used in wells with operating temperatures less than 96 ºC (205 ºF)

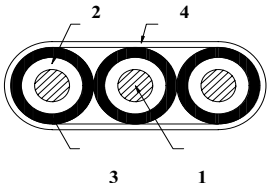
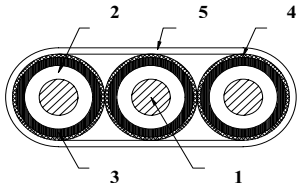


Figure 20—Flat cable normally used in wells with operating temperatures less than 96 ºC (205 ºF)



Item	Description	Item	Description
1	Conductor, Copper	1	Conductor, Copper
2	Insulation, Polypropylene	2	Insulation, Polypropylene
3	Jacket, Nitrile	3	Jacket, Nitrile
4	Armor	4	Barrier Layer
		5	Armor

B.3 EPDM cables

Figure 21—Round cable normally used in wells with operating temperatures less than 140 ºC (284 ºF)

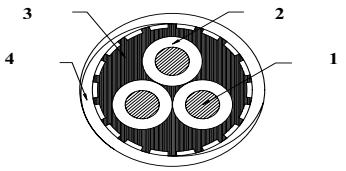
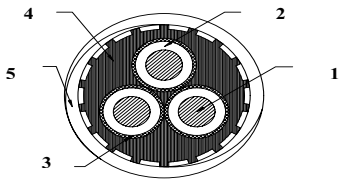


Figure 22—Round cable normally used in wells with operating temperatures less than 204ºC (400 ºF)



Item	Description	Item	Description
1	Conductor, Copper	1	Conductor, Copper
2	Insulation, EPDM	2	Insulation, EPDM
3	Jacket, Nitrile or EPDM	3	Barrier Layer
4	Armor	4	Jacket, Nitrile or EPDM
		5	Armor

All round cables have a physical filler to fill center interstice.

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Figure 23—Flat cable normally used in wells with operating temperatures less than 140 ºC (284 ºF)

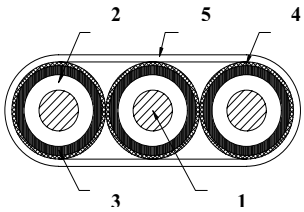
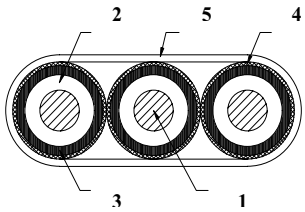


Figure 24—Flat cable lead sheath for harsh environments and temperatures less than 204 ºC (400 ºF)



Item	Description	Item	Description
1	Conductor, Copper	1	Conductor, Copper
2	Insulation, EPDM	2	Insulation, EPDM
3	Jacket, Nitrile or EPDM	3	Lead Sheath
4	Barrier Layer	4	Bedding Layer
5	Armor	5	Armor

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