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

Sponsor

Petroleum and Chemical Industry Committee
of the
IEEE Industry Applications Society

Abstract: Minimum requirements for the construction, manufacturing, purchasing, and application of electric submersible pump (ESP) cable are presented. The cable is round or flat, with ethylene-propylene rubber insulation, nitrile jacket, 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 °C (284 °F) for nitrile or a maximum of 204 °C (400 °F) 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:** cable testing, submersible pump cable, field testing, cable construction, assembly, ampacity ratings.

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Foreword

(This foreword is not a part of Draft IEEE Std 1018, 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 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. 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 rated temperature can cause premature hardening of the jacket therefore reducing 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 document, unless otherwise specified herein, should meet the requirements of ASTM B3 [6][1], ASTM B8 [7], ASTM B33 [8], ASTM B189 [9], ASTM B496 [10], and ICEA S-68-516 [11], where applicable.

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 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 [11] 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.

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[1]Numbers in brackets correspond to those of the references listed in Section 2.

2. References

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

[2] API RP 11S4, Recommended Practice for Sizing and Selection of Electric Submersible Pump Installations, [2]

[3] API RP 11S5, Recommended Practice for Application of Electric Submersible Cable Systems, [2]

[4] API RP 11S6, Recommended Practice for Testing of Electric Submersible Pump Cable Systems, [2]

[5] ASTM A90, Standard Test Method for Weight of Coating on Zinc-Coated (Galvanized) Iron or Steel Articles. [3]

[6] ASTM B3, Standard Specification for Soft or Annealed Copper Wire.[3]

[7] ASTM B8, Standard Specification for Concentric-Lay—Stranded Copper Conductors, Hard, Medium-Hard, or Soft. [3]

[8] ASTM B33, Standard Specification for Tinned Soft or Annealed Copper Wire for Electrical Purpose. [3]

[9] ASTM B189, Standard Specification for Lead-Coated and Lead-Alloy-Coated Soft Copper Wire for Electrical Purposes. [3]

[10] ASTM B496, Standard Specification for Compact Round Concentric-Lay-Stranded Copper Conductors. [3]

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

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

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[2]API publications are available from the Publications Section, American Petroleum Institute, 1200 L Street NW, Washington, DC 20005, USA.

[3]ASTM publications are available from the Customer Service Department, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103, USA.

[4]ICEA publications are available from ICEA, P.O. Box 411, South Yarmouth, MA 02664, USA.

[5]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 00885-1331, USA.

3. Conductors

3.1 Material. Conductors should be annealed, coated or uncoated, copper in accordance with ASTM B3 [6] for uncoated conductors, in accordance with ASTM B33 [8] for tin-coated conductors; or in accordance with ASTM B189 [9] for lead or lead-alloy coated conductors.

3.2 Construction. Conductors should be solid or concentric-stranded as shown in Table 1. Concentric-stranded conductors should conform to ASTM B8 [7], or when compact round conductors, are used, should conform to ASTM B496 [10], with diameters nominally 92% of corresponding non-compact conductors. When stranded products are used the interstices should be filled for gas blockage.

3.3 Conductivity. Conductors should have a direct current resistance at 25 °C (77 °F), not to exceed the values listed in Tables 1a or 1b.

Table 1a, Conductor Characteristics (Metric units)

Conductor Size	Conductor Area	Nominal Weight	Nominal Diameter of Conductor (mm)			Conductor Resistance (ohms/km @ 25°C)	
	(mm^2)	(kg/km)	Solid	Stranded 7 wire	Compact 7 wire	Plain Copper	Tinned Copper
$10mm^2$	10.0	88.5	3.57	-	-	1.87	1.88
6 AWG	13.3	118.0	4.11	-	-	1.32	1.36
$16mm^2$	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
$25mm^2$	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	-	9.35	8.56	0.335	0.348

| 2/0 AWG | 67.4 | 599 | - | 10.80 | - | 0.266 | 0.276 |

Table 1b, Conductor Characteristics (Inch-pound units)

Conductor Size	Conductor Area	Nominal Weight	Nominal Diameter of Conductor (inches)			Conductor Resistance (ohms/kft @ 77°F)	
	(cmil)	(lb/kft)	Solid	Stranded 7 wire	Compact 7 wire	Plain Copper	Tinned Copper
10mm^2	19644	59.7	0.140	-	-	0.569	0.572
6 AWG	26240	79.4	0.162	-	-	0.403	0.414
16mm^2	31109	95.6	0.178	-	-	0.357	0.360
4 AWG	41740	126.0	0.204	-	-	0.253	0.261
4 AWG	41740	126.0	-	0.232	0.213	0.258	0.263
25mm^2	49305	149.2	0.222	-	-	0.226	0.228
2 AWG	66360	206.0	0.258	-	-	0.159	0.169
2 AWG	66360	206.0	-	0.292	0.268	0.162	0.174
1 AWG	83690	260.0	0.289	-	-	0.126	0.130
1 AWG	83690	260.0	-	0.328	0.298	0.129	0.134
1/0 AWG	105600	319.2	-	0.368	0.337	0.102	0.106
2/0 AWG	133100	402.7	-	0.414	-	0.081	0.084

4. Insulation

4.1 Material. Insulation should be constructed of ethylene-propylene rubber that meets the properties shown in Table 2 when tested in accordance with ICEA S-68-516 [11].

4.2 Gas Blockage. A 30 cm (12 in) specimen of insulated conductor removed from finished cable should be subjected to a 35kPa (5 psi) differential air pressure for a period of 1 hour @ 25 °C (77 °F). 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 <u>should</u> be tightened with minimum torque to prevent leakage. The opposite end of the sample <u>should</u> be left submerged in water. No air bubbles <u>should</u> be detected at the submerged end of the cable during the test period.

Table 2   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

4.3 Construction. The insulation should be extruded on the conductor.

4.3.1 Non-lead Sheath Product. For 3 kV rated cable, average insulation wall thickness <u>should</u> be 1.9 mm (0.75 in) or more, the insulation minimum wall thickness <u>should</u> not be less than 1.7 mm (0.068 in) at any point. For 5 kV rated cable, the insulation average wall thickness <u>should</u> be 2.3 mm (0.090 in) or more. The insulation minimum wall thickness <u>should</u> 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 <u>should</u> be 1.9 mm (0.075 in) or more. The insulation minimum wall thickness <u>should</u> 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 <u>should</u> 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 cable jacket. The first type is a oil-resistant thermosetting nitrile rubber. The nitrile rubber should meet the properties shown in Table 3 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 <u>should</u> meet the properties shown in Table 4. EPDM rubber is used in higher temperature wells and may be rated up to temperatures of 204 °C (400 ºF) .

Both of these compounds must be tested in accordance with ICEA S-68-516 [11], Section 6.

Table 3

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 °C) 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 4

EPDM Jacket Properties

Physical Requirements – Unaged	6.9 (1000 psi)
Tensile strength, minimum, MPa	
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

6.2 Construction

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

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

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

6.2.2 Flat Cable Non-leaded. Each insulated conductor <u>should</u> be individually jacketed. Splines are not required on the jacket. An alternate 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, prior to 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, prior to 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 [11] prior to application of the strip to the cable.

7.1.4 Weight of Zinc Coating. The weight of zinc coating should be determined prior to 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 [5]. 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 <u>should</u> remain adherent without flaking or spalling when tested in accordance with ICEA S-68-516 [11].

7.1.6 Armor For Harsh Environments. Thicker steel strip can be provided. Heavier Type II galvanizing may be used as per ASTM-A90 [5]. For extremely corrosive environments stainless steel (316L) or Monel armor is available.

7.2 Construction

7.2.1 Round Cable. The armor strip <u>should</u> 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 <u>should</u> be able to withstand a seven times overall diameter bend radius without separation of adjacent turns.

7.2.2 Flat Cable. The construction <u>should</u> consist of the three-phase conductors laid in parallel. The armor strip <u>should</u> 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 <u>should</u> be capable of withstanding a bend that is seven times the major axis of the cable. The armor overlap <u>should</u> not open up between adjacent turns. The direction of bend <u>should</u> be in the normal direction of cable spooling.

8. Manufacturer's Electrical Test Requirements

8.1 Conductor Testing. Before application of any covering, conductors should be tested to meet the physical requirements of Section 3.

8.2 Electrical Test. The manufacturer, in accordance with this section, to determine compliance with these standards <u>should</u> electrically test all submersible pump cables. Tests <u>should</u> be conducted on single insulated conductors and on finished cable.

8.2.1 Electrical Test Methods. Unless otherwise noted electrical tests <u>should</u> be performed per ICEA S-68-516 [11], Section 6.

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 5. The duration of both tests should be 5 minutes.

8.2.3 Resistance. On completed cable the conductor resistance test <u>should</u> be performed and should comply with Table 1a or 1b.

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 5. 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.

**Table 5
Test Voltages for ESP Cable***

Cable Rating (kV rms.) (Phase-to-Phase)	Factory Test Voltage (kV)	Acceptance† Test Voltage (kV)	Maintenance‡ Test Voltage (kV)
3	27	22	11
5	35	28	14

*All tests are dc, conductor to ground for 5 minutes
†Acceptance test is 80% of factory test.
‡Maintenance test is 40% of factory test.

8.2.5 Conductance Leakage Readings: All power cables <u>should</u> be tested and meet the minimum test requirements for factory testing of conductance leakage readings per Table 6 at the prescribed voltage level in Table 5. The leakage values are based on bulk resistivity factor of 6100 megohms-km. (20,000 megohms-kft) Refer to 11S6 [4] for 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 [12] for related information on testing submersible cable. Some interpretation guidelines are also included in that document.

Table 6a (Metric units)

Values for 1.91 mm (75 mil) insulation 3kV EPDM					
Conductor	Conductor dia.	Insulation min. point	Calculated Insul. dia.	IR value, 1 km	dc leakage, 1 km
Size	mm (inches)	mm	mm	MΩ	µA/kV
10mm^2	3.56 (0.140)	1.73	7.01	1,797	0.56
6 AWG	4.11 (0.162)	1.73	7.57	1,614	0.62
16mm^2	4.52 (0.178)	1.73	8.01	1,503	0.67
4 AWG	5.18 (0.204)	1.73	8.66	1,347	0.74
25mm^2	6.55 (0.258)	1.73	10.01	1,121	0.89
2 AWG	7.42 (0.292)	1.73	10.87	1,012	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 (90mil) insulation 5kV EPDM					
Conductor	Conductor dia.	Insulation min. point	Calculated insul. dia.	IR value, 1 km	Dc leakage, 1 km
Size	Mm (inches)	mm	mm	MΩ	µA/kV

10mm²	3.56 (0.140)	2.06	7.01	2,035	0.49
6 AWG	4.11 (0.162)	2.06	7.57	1,835	0.54
16mm²	4.52 (0.178)	2.06	8.01	1,713	0.58
4 AWG	5.18 (0.204)	2.06	8.66	1,542	0.65
25mm²	6.55 (0.258)	2.06	10.01	1,290	0.78
2 AWG	7.42 (0.292)	2.06	10.87	1,168	0.86
1 AWG	8.43 (0.332)	2.06	11.89	1,052	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

Table 6b (Inch-pound units)

Values for 1.91 mm (75 mil) insulation 3kV EPDM					
Conductor	Conductor dia.	Insulation min. point	Calculated Insul. dia.	IR value, 1 kft	dc leakage, 1 kft
Size	mm (inches)	Inches	inches	MΩ	μA/kV
10mm²	3.56 (0.140)	0.068	0.276	5,896	0.17
6 AWG	4.11 (0.162)	0.068	0.298	5,294	0.19
16mm²	4.52 (0.178)	0.068	0.314	4,930	0.20
4 AWG	5.18 (0.204)	0.068	0.341	4,420	0.23
25mm²	6.55 (0.258)	0.068	0.398	3,678	0.27
2 AWG	7.42 (0.292)	0.068	0.428	3,321	0.30
1 a AWG	8.43 (0.332)	0.068	0.468	2,982	0.34
1/0 AWG	9.35 (0.368)	0.068	0.504	2,732	0.37
2/0 AWG	10.52 (0.414)	0.068	0.550	2,467	0.41
Values for 2.29 mm (90mil) insulation 5kV EPDM					
Conductor	Conductor dia.	Insulation min. point	Calculated insul. dia.	IR value, 1 kft	Dc leakage, 1 kft
Size	mm (inches)	inches	inches	MΩ	μA/kV
10mm²	3.56 (0.140)	0.081	0.302	6,678	0.15
6 AWG	4.11 (0.162)	0.081	0.324	6,021	0.17
16mm²	4.52 (0.178)	0.081	0.340	5,621	0.18
4 AWG	5.18 (0.204)	0.081	0.367	5,058	0.20
25mm²	6.55 (0.258)	0.081	0.420	4,233	0.24
2 AWG	7.42 (0.292)	0.081	0.454	3,833	0.26
1 AWG	8.43 (0.332)	0.081	0.494	3,452	0.29
1/0 AWG	9.35 (0.368)	0.081	0.530	3,169	0.32
2/0 AWG	10.52 (0.414)	0.081	0.576	2,868	0.35

9. Cable Ampacity

9.1 Ampacity. Cable ampacity ratings are limited by these factors:

(1) Ambient temperature
(2) Liquid/gas environments
(3) Heat rise due to resistance heating
(4) Heat distortion properties of insulation
(5) Ability to dissipate heat

9.2 Temperature. Conductor operating temperature as a function of well temperature and current flow is shown in Figs 1 to 16. 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, meters or feet, the current (I), the conductor resistivity (ρ), the ambient well temperature (T), and the voltage drop (VD). 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-mm^2/m (Ohm-cmils/ft). The basic value for bare copper resistivity is 0.017241 (10.371), and 0.017965 (10.810) for tinned copper.

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

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

The conductor area (A) is calculated from the formula given below. The wire size is read from Table 1a or Table 1b

$$A = \frac{(\rho x 1.732 x D x I)}{VD}$$

EXAMPLE:

Ambient Temperature = 80°C (1768F),

Distance = 1524 meters (5000 feet),

Current = 60 Amps,

Voltage = 2400V phase to phase,

Voltage Drop = 5% = 120V

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

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

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

$$A = \frac{(13.07 x 1.732 x 5000 x 60)}{120} = 56593 cmils \quad \text{INCH-POUND UNITS}$$

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

Use this wire size to check the cable temperature with the Conductor Temperature Charts (Figure 1 - 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 Section 10.2.5

10. Tutorial Information

10.1 Definitions

hoop strength. Is a measure of the tangential resistance to elongation. Since 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.

toughness factor. 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, while a more gummy material will have less tensile strength and more elongation.

compounds modulus. A relative measure of the force achieved at a given elongation of the material. It is normally recorded as a stress (MPa or psi) at the given percent elongation. A lower modulus material has more of a tendency to give prior to breaking, that is, less resistance to expansion.

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

ultimate elongation. The percent change in length at rupture.

tensile stress. The force exerted per unit area.

tensile strength. The stress (MPa or psi) required to break the item.

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

EPDM (ethylene-propylene diene monomer). Terpolymer of ethylene, propylene, and a diene with the residual unsaturated portion of the diene in the side chain.

EPM (ethylene-propylene monomer). Comprised of copolymers of ethylene and propylene.

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

voltage stress. Voltage stress may be thought of in terms 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/mil (or volts/mm) required to puncture a sample of known thickness. For conventional cables the voltage stress is normally maintained at less than 2165 volts per mm (55 volts per mil).

With electrical stress, the further away (outward) from the conductor one moves, the lower the stress becomes. there are formulas used to calculate the electrical stress levels. These 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 may be calculated by the following formula:

$$S = E \div [2.303 * r * \log(D_i \div d_c)]$$

where S = Stress in the insulation at radius r, volts/mil (1 mil = 0.001" = 0.0254mm)

E = phase to ground voltage, volts
   = for three phase systems = (phase to phase voltage)
                                   1.732

Di = diameter over the insulation, (inches)

dc = diameter over the conductor, (inches)

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

The **maximum stress** (S_{max}) on the insulation is at the conductor surface. In this case *r* would be equal to _ * d_c.

$$s_{max} = E \div [2.303 * (d_c \div 2) * \log(D_i \div d_c)](V \div mm) \quad \text{METRIC UNITS}$$

$$s_{\max} = E \div [2.303 * (d_c \div 2) * \log(D_i \div d_c)](V \div mils) \quad \text{INCH-POUND UNITS}$$

The **minimum stress** (S_{min}) on the insulation is at the surface of the insulation. In this case r would be equal to _ * D_i.

$$S_{\min} = E \div [2.303 * (D_i \div 2) * \log(D_i \div d_c)](V \div mm) \quad \text{METRIC UNITS}$$

$$S_{\min} = E \div [2.303 * (D_i \div 2) * \log(D_i \div d_c)](V \div mils) \quad \text{INCH-POUND UNITS}$$

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

Example: 3/C #4 solid copper

Example: 3/C #4 solid copper
    Copper Tensile breaking strength   = 344.7 MPa (41916 PSI)
    Conductor diameter   = 5.182 mm (0.204 in)
    Conductor area   = 0.211 cm^2 (0.0327 in^2)
    Cable weight   = 1.265 kg per meter (0.85 pounds/foot)

Calculate the maximum force a single conductor can support: Metric (US)

Maximum force = 344.7 MPa * 0.211 = 727.5 kg per conductor

(Maximum force = 41916 PSI * 0.327 = 1371 lbs per conductor)

Assume the tension is equal on all three legs of the cable. The maximum pulling force, which can be applied on the cable would be 3 times that of the single conductor.

Maximum force = 727.5 kg per conductor * 3 = 2182.5 kg per cable

METRIC UNITS

(Maximum force = 1371 lbs per conductor * 3 = 4113 lbs per cable)

INCH-POUND UNITS

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

Maximum length = 2182.5 / 1.265 = 1725 meters METRIC UNITS

(Maximum length = 4113 / 0.85 = 4838 feet)   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 inches) unit being the generally recommended size (see API RP 11S3 [1]). 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, potentially causing 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.

While the above 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 give consideration to reducing cable pulling rates. Typical rates vary from 305 to 1200 meters (1000 to 4000 Feet) per hour. However, the "proper rate" is whatever works for your 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. This is reflected in changes in the jacket compounds 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 prior to 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.

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, causing 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, thereby minimizing 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.

Since 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 below. The 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.

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

where

I $= $ Economic current

$ per km change in wire cost   = Cost difference between two cables using different conductor sizes

Resistive difference   = Difference in resistance between two conductor sizes at the well's bottom-hole temperature.

$/kWh   = Electrical power cost

#ph   = Number of phases (normally there are three)

PO Years   = Number of years to see payout using larger conductor

According to API RP 11S4 [3], 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.

Annex A
(informative)

Cable Designs and Components
  A.1   Round Cable normally used in wells where operating temperatures less than 80 °C (176 °F) - Figure 17
    1. Copper Conductor
    2. Insulation - Polypropylene
    3. Jacket - Polyethylene- Excellent Abrasion Resistance

  A.2   Round Cable normally used in wells where operating temperatures less than 96 °C (205 °F) - 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 where operating temperatures less than 96 °C (205 °F)– 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 where operating temperatures less than 96 °C (205 °F) - 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

A.5 Round Cable normally used in wells where operating temperatures less than 140 °C (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 where operating temperatures less than 140 °C (284 ºF) - Figure 22
A) Copper Conductor
B) Insulation - EPDM
C) Optional, Tape, Braid, Tape and Braid or Extruded Barrier
D) Jacket - Oil Resistant Nitrile Rubber
E) Armor - Standard 0.64 mm (0.025 in) Galvanized Steel

A.7 Flat Cable normally used in wells where operating temperatures less than 140 °C (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 where operating temperatures less than 204 °C (400 ºF) - Figure #21 and 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 where operating temperatures less than 204 °C (400 ºF) - Figure #21 and 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

A.10 Flat Cable normally used in wells where operating temperatures less than 204 °C (400 ºF) - Figure 23
A) Copper Conductor
B) Insulation - EPDM
C) Jacket - EPDM Rubber

    D) Barrier Layer, Normally Tape and Braid
    E) Armor - Standard 0.51 mm (0.020 in) Galvanized Steel

A.11 Flat Cable Lead Sheath, for harsh environments and temperatures less than 204 °C (400 ºF), for temperature over 204 °C (400 ºF) call the manufacturer - Figure 24
    A) Copper Conductor
    B) Insulation - EPDM
    C) Jacket - Lead Sheath
    D) Bedding Layer, Can be Braid or Bedding Tape
    E) Armor - Standard 0.51 mm (0.020 in) Galvanized Steel