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DRAFT IEEE Recommended Practice for Specifying Electric Submersible Pump Cable— Polypropylene Insulation

Sponsor

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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 polypropylene rubber insulation, nitrile jacket, and armor. The recommendations apply to cables rated for voltages not exceeding 3 kV or 5 kV (phase to phase)and for ambient temperatures not exceeding 96 °C (205 °F) or below -10 °C (14 °F) Conductors, insulation, assembly, jacket, armor, requirements for testing by the manufacturer and cable ampacity ratings are covered. **Keywords:** cable testing, submersible pump cable, field testing, cable construction, assembly, testing, ampacity ratings.

Foreword

(This foreword is not a part of DRAFT IEEE 1019, IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Polypropylene Insulation.)

This recommended practice, under the jurisdiction of the IEEE Industry Applications Society, Petroleum and Chemical Industry Committee, 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 polypropylene insulation, nitrile jacket, 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 or 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 these specifications. Furthermore, the committee hereby expressly disclaims any liability or responsibility for loss or damage resulting this standard's use and for violation of any federal, state, or municipal regulation with which it may conflict, or for the infringement of any patent resulting from its use.

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IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Polypropylene Insulation

1. Scope

This recommended practice establishes requirements for three-conductor round and flat-type oil well cable used in supplying three-phase ac electric power to submersible pump motors. The major cable components are: copper conductors, polypropylene insulation, polymeric jacket, and galvanized armor. Cables meeting requirements of the recommended practice should be rated for voltages not exceeding 3 kV or 5 kV (phase to phase).

Conductor operating temperatures for cables should not exceed 96 °C (205 °F). Use of cable above rated temperature can cause premature deterioration of the insulation. Low temperature handling below –10 °C (14 °F) may cause cracking of the insulation or jacket.

Cable purchased under the recommendation of this document, unless otherwise specified herein, should meet the requirements of ASTM B3 [6][1], ASTM A90 [5], ASTM B8 [7], ASTM B33 [8], ASTM B189 [9], ASTM D412 [10], ASTM B496 [11], ICEA S-19 [12], and ICEA S-61-402 [13], 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 that shortens cable life. ICEA S-61-402 [12] 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] Numbers in brackets correspond to those of the references listed in Section 2.

2. References

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

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

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

[6] ASTM B3, Standard Specification for Soft Annealed Copper Wire.[2]

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

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

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

[10] ASTM D412, Standard Test Methods for Rubber Properties in Tension.

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

[12] ICEA S-19-81, Rubber-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy (NEMA WC 3).[4]

[13] ICEA S-61-402, Thermoplastic-Insulated Wire and Cable for the Transmission and Distribution of Electrical Energy. (NEMA WC 5)

[14] IEEE Standard 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 Lanes, P.O. Box 1331, Piscataway, NJ 08855-1331 USA.

3. Conductors

3.1 Material. Conductors should be annealed and coated 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 1a or 1b. Concentric-stranded conductors should conform to ASTM B8 [7], or when compact round conductors, are used, should conform to ASTM B496 [11], 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 ºF) , 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 a thermoplastic polypropylene meeting the properties shown in Table 2 when tested in accordance with ICEA S-61-402, [13], Section 6, except that pull rate should be 5.08 cm/min (2.0 in/min). The polypropylene should be copper stabilized.

Table 2 Polypropylene Properties

Physical Requirements – Unaged	
Tensile strength, minimum, MPa	20.7 (3000psi)
Elongation at rupture, minimum, percent	250
Physical Requirements - Aged in Air	
Oven at 121°C (250°F) for 72 hours	
Tensile strength, minimum, percent of unaged value	75
Elongation at rupture, minimum, percent retention	75

4.2 Construction. The insulation should be extruded on the conductor. For 3 kV rated cable, average wall thickness should be 1.9 mm (0.075 in) or more, with a minimum wall thickness of 1.7 mm (0.068 in) at any point. For 5 kV rated cable, average wall thickness should be 2.3 mm (0.090 in) or more, with a minimum wall thickness of 2.1 mm (0.081 in) at any point.

4.3 Gas Blockage. A 30 cm (12 in) specimen of insulated conductor removed from finished cable should be subjected to a 35 kPa (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 (0.25 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.

5. Assembly and Jacket

5.1 Material. The typical jacket is an oil-resistant thermosetting nitrile rubber meeting the properties shown in Table 3 when tested in accordance with ASTM D412 [10].

An alternate jacket material used in high water cut, low temperature applications is polyethylene. Cables using thermoplastic polyethylene have an upper conductor temperature limit of 80 °C (176 °F).

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°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

5.2 Construction

5.2.1 Round Design. 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.

A jacket should be extruded over a cable core consisting of three insulating conductors and a 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).

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

5.2.2 Flat Design. Each insulated conductor should be individually jacketed, with no splines required on the jacket material. An alternate design may have the three conductors laid parallel within a common encapsulated jacket. All interstices are filled with jacketing material. The jacket of either design should separate cleanly from the underlying surfaces.

Additional constraining covering of the extruded, wrapped, and/or woven type may be applied over either the insulation or the jacket. 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 cable without additional constraining coverings, the average jacket wall thickness should be 1.5 mm (0.060 in). The minimum thickness at any point should be no less than 1.2 mm (0.048 in).

6.0 Armor

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

6.1.1 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 (0.50 in) and should be no more than 19.1 mm (0.75 in) before forming.

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

6.1.3 Tensile Strength and Elongation. The zinc-coated strip should have a tensile strength of not less than 275 MPa (40,000 psi) and an elongation of not less than 10% in 25 cm (10 in). All tests should be performed in accordance with ICEA S-68-402 [13] prior to application of the strip to the cable.

6.1.4 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/ m^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.

6.1.5 Adherence of Coating. The zinc coating should remain adherent without flaking or spalling when tested in accordance with ICEA S-68-402 [13].

6.1.6 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.

6.2 Construction

6.2.1 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 be able to withstand a seven times overall diameter bend radius without separation of adjacent turns.

6.2.2 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 be capable of withstanding 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.

7.0 Manufacturer Electrical Requirements

7.1 Conductor Tests. Before application of any covering, all conductors should be tested to meet the physical requirements of Section 3.

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

7.2.1 Electrical Test Methods. Electrical tests should be performed per ICEA S-61-402, [13], Section 3.6.2.

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

7.2.3 Resistance: On completed cable, the conductor resistance test should be performed and should comply with Table.

7.2.4 DC Withstand Test. Finished armored cable should be tested in air by dc withstand test according to the values shown in Table 4. 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.

7.2.5 Conductance Leakage Readings: All power cables should be tested and meet the minimum test requirements for factory testing of conductance leakage at rated voltage listed in Table 4. The values are based on the bulk resistivity factor of 15240 megohms-km (50,000 megohms-kft). Refer to API 11S6 [3] for calculation method. See Table 5a and 5b for minimum conductance leakage readings.

Table 4 - 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.

7.2.6 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 time to ensure that there is no residual charge.

7.2.7 Field Testing: See IEEE standard 1017 [14] for related information on testing submersible cable. Some interpretation guidelines are also included in that document.

Table 5a (Metric units)

Values for 1.91 mm (75 mil) insulation 3kV polypropylene					
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	4,492	0.22
6 AWG	4.11 (0.162)	1.73	7.57	4,034	0.25
$16mm^2$	4.52 (0.178)	1.73	8.01	3,757	0.27
4 AWG	5.18 (0.204)	1.73	8.66	3,368	0.30
$25mm^2$	6.55 (0.258)	1.73	10.01	2,802	0.36
2 AWG	7.42 (0.292)	1.73	10.87	2,531	0.40
1 AWG	8.43 (0.332)	1.73	11.89	2,272	0.44
1/0 AWG	9.35 (0.368)	1.73	12.80	2,079	0.48
2/0 AWG	10.52 (0.414)	1.73	14.00	1,880	0.53
Values for 2.29 mm (90mil) insulation 5kV polypropylene					
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)	2.06	7.01	5,088	0.20
6 AWG	4.11 (0.162)	2.06	7.57	4,587	0.22
$16mm^2$	4.52 (0.178)	2.06	8.01	4,283	0.23
4 AWG	5.18 (0.204)	2.06	8.66	3,854	0.26
$25mm^2$	6.55 (0.258)	2.06	10.01	3,225	0.31
2 AWG	7.42 (0.292)	2.06	10.87	2,921	0.34
1 AWG	8.43 (0.332)	2.06	11.89	2,630	0.38
1/0 AWG	9.35 (0.368)	2.06	12.80	2,412	0.41
2/0 AWG	10.52 (0.414)	2.06	14.00	2,186	0.46

Table 5b (Inch-pound units)

Values for 1.91 mm (75 mil) insulation 3kV polypropylene					
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
10mm^2	3.56 (0.140)	0.068	0.276	14,739	0.07
6 AWG	4.11 (0.162)	0.068	0.298	13,235	0.08
16mm^2	4.52 (0.178)	0.068	0.314	12,325	0.08
4 AWG	5.18 (0.204)	0.068	0.341	11,050	0.09
25mm^2	6.55 (0.258)	0.068	0.398	9,194	0.11
2 AWG	7.42 (0.292)	0.068	0.428	8,303	0.12
1 AWG	8.43 (0.332)	0.068	0.468	7,455	0.13
1/0 AWG	9.35 (0.368)	0.068	0.504	6,823	0.15
2/0 AWG	10.52 (0.414)	0.068	0.550	6,168	0.16
Values for 2.29 mm (90mil) insulation 5kV polypropylene					
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
10mm^2	3.56 (0.140)	0.081	0.302	16,694	0.06
6 AWG	4.11 (0.162)	0.081	0.324	15,051	0.07
16mm^2	4.52 (0.178)	0.081	0.340	14,053	0.07
4 AWG	5.18 (0.204)	0.081	0.367	12,646	0.08
25mm^2	6.55 (0.258)	0.081	0.420	10,581	0.09
2 AWG	7.42 (0.292)	0.081	0.454	9,584	0.10
1 AWG	8.43 (0.332)	0.081	0.494	8,629	0.12
1/0 AWG	9.35 (0.368)	0.081	0.530	7,794	0.13
2/0 AWG	10.52 (0.414)	0.081	0.576	7,171	0.14

8. Cable Ampacity

8.1 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 polypropylene
(5) Ability to dissipate heat

8.2 Temperature. Conductor operating temperature as a function of well temperature and current flow are shown in Figures 1 to 16. These figures are based on Neher-McGrath calculations in an air environment. It is recommended that 96 °C (205 °F) be used as the maximum conductor operating temperature for polypropylene insulation with a nitrile jacket.

8.3 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.

8.4 Conductor Size: The conductor size depends on the length of the cable (D, in meters), the current (I), the conductor resistivity ( ), the ambient well temperature in degrees C (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.

$$\rho = \frac{0.017241x1.02x(234.5+T)}{254.5}$$ METRIC UNITS

$$\rho = \frac{10.371x1.02x(234.5+T)}{254.5}$$ 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 (176 8F),

Distance = 1524 meters (5000 feet),

Current = 60 Amps,

Voltage = 2400V phase to phase,

Voltage Drop = 5% = 120V

$$p = \frac{0.017241x1.02x(234.5+80}{254.5} = 0.0217$$ METRIC UNITS

$$A = \frac{(0.0217x1.732x1524x60)}{120} = 28.64mm^2$$ METRIC UNITS

$$p = \frac{10.371x1.02x(234.5+80}{254.5} = 13.07$$ INCH-POUND UNITS

$$A = \frac{(13.07x1.732x5000x60)}{120} = 56593cmils$$ 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.

8.5 **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 9.2.5.)

9. Tutorial Information

9.1 Definitions

hoop strength. 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 tangentially. The hoop strength resists this tendency and can be aided by additional wraps applied over the round components.

toughness factor. 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. Shunt admittance has the units “mho.” As used in this discussion, shunt admittance is a measure of leakage conductance to ground through the cable insulation.

polypropylene. A polymer of propylene. The homopolymer (one unit) of polypropylene is not used for wire and cable since it is brittle at temperatures above the freezing point. Copolymers must, then, be used for wire and cable applications. The copolymer consists of propylene and a polymerizable monomer such as ethylene.

stabilization. Polypropylene must be stabilized against certain metals because the polypropylene component of the plastic has a tendency to degrade in the presence of certain metal ions, e.g., copper and iron. Therefore, antioxidant stabilizers are used to inhibit material changes.

copper coating. Metal coatings such as lead or tin alloys are used on copper wires for multiple reasons. These include annealing the copper during manufacture, preventing sulfur cured compounds from bonding to the copper, mitigating copper corrosion from sulfur (H_2S) compounds, and inhibiting propylene from decomposition.

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 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:

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

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 = $\frac{\text{(phase to phase voltage)}}{1.732}$

Di = diameter over the insulation, mm (inches)

dc = diameter over the conductor, mm (inches)

r = radial distance from the center of the conductor at which it is desired to calculate the electrical stress, mm (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	= 5.18 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

9.2 Application Considerations

9.2.1 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.

9.2.2 Pull Rates. Gas has a very detrimental effect on cable systems. Polypropylene insulation is normally permeated to some extent by gas. This results in the insulation being softened by methane and other lower hydrocarbons, while carbon dioxide will initiate crazes leading to cracks and cable failure. In general, polypropylene will have a significantly shorter life expectancy in a CO_2 environment than do other cable materials. The nitrile jacket readily absorbs gas.

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 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 of them 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 meters 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.

9.2.3 Chemical Treatments. Most corrosion inhibitors have adverse affects on the nitrile jackets protecting the cable insulation. They include such things as the softening or hardening of the nitrile jacket. This is reflected in changes in the jacket compound’s modulus. Also, acid wash will cause the nitrile jacket quickly to become brittle. 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.

9.2.4 Balancing Flat Cable Phase Currents. Flat electric-motor cable has unbalanced series impedance, which causes current unbalance in (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 read essentially the same resistance to ground.

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 thus produce minimum unbalance in motor currents.

9.2.5 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.

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

where

I = Economic current

$ per km (kft) 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 API RP 11S4 [2], 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)

Typical cable designs and components covered in IEEE 1018 and 1019

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

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 25 Mil 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 0.56 mm 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 20 Mil Galvanized Steel

A.5 Round Cable normally used in wells where operating temperatures less than 140 °C (284 °F) - Figure 21

1. Copper Conductor
2. Insulation - EPDM
3. Jacket - Oil Resistant Nitrile Rubber
4. Armor - Standard 25 Mil Galvanized Steel

A.6 Round Cable normally used in wells where operating temperatures less than 140 °C (284 °F) - 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 25 Mil Galvanized Steel

A.7 Flat Cable normally used in wells where operating temperatures less than 140 °C (284 °F) - Figure 23

1. Copper Conductor
2. Insulation – EPDM
3. Jacket - Oil Resistant Nitrile Rubber
4. Barrier Layer, Normally Tape and Braid
5. Armor - Standard 20 Mil Galvanized Steel

A.8 Round Cable normally used in wells where operating temperatures less than 204 °C (400 °F) - Figure 21

1. Copper Conductor
2. Insulation - EPDM
3. Jacket - EPDM Rubber
4. Armor - Standard 25 Mil Galvanized Steel

A.9 Round Cable normally used in wells where operating temperatures less than 204 °C (400 °F) - 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 25 Mil Galvanized Steel

A.10 Flat Cable normally used in wells where operating temperatures less than 204 °C (400 °F) - Figure 23

1. Copper Conductor
2. Insulation – EPDM
3. Jacket - EPDM Rubber
4. Barrier Layer, Normally Tape and Braid
5. Armor - Standard 20 Mil Galvanized Steel

A.11 Flat Cable Lead Sheath, for harsh environments and temperatures less than 204 °C (400 °F) For temperature over 204°C call 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 20 Mil Galvanized Steel