History and Development of IEEE Standards for Downhole Cable

Marcus O. Durham, *Fellow, IEEE*, Robert A. Durham, *Senior Member, IEEE*,
and Richard H. Hulett, *Fellow, IEEE*

***Abstract*—Three IEEE standards that address submersible cable testing and specification were the first standards sponsored by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society. The latest editions of these standards have been completely rewritten to reflect newer technology. This paper will cover the history of the standards as well as an overview of the technical aspects. Surprisingly, the latest revision of these three standards was the most difficult to gain approval. Because of issues that arose during balloting, the IEEE has changed its policy so that standards can now have dual metric/English units.**

***Index Terms*—Cable, downhole, electric submersible pump (ESP), harsh environments, history, standards, units.**

I. INTRODUCTION

WHAT WERE the first IEEE standards developed that were sponsored by the Petroleum and Chemical Industry Committee (PCIC) of the IEEE Industry Applications Society? Are they still around? What has been their impact on other IEEE standards?

Three IEEE standards that address downhole electric submersible pump (ESP) cable were the first standards sponsored by the PCIC. This is the 25th anniversary of these standards' initial development. The documents are IEEE RP 1017, 1018, and 1019 [1]–[3].

These three ESP cable standards originated from a paper presented at the Hotel Del Coronado, San Diego, CA, in 1979 [4]. ESP installations require application of medium-voltage specialty power cables in a very harsh environment. The 1979 paper discussed the state-of-the-art in ESP cable and contained several areas of original research into the performance of the cable.

In 1979, less than five vendors manufactured all of the submersible cable in the world. Each manufacturer used proprietary guidelines, construction, and performance requirements. The typical life of a cable was significantly less than one year. The original paper addressed acceptance and maintenance test procedures for these cables and suggested changes that could be made to improve the life of the cable.

A very spirited question session followed. A representative of one of the manufacturers began a lengthy discussion about the lack of need for changes in cable design and construction. This was followed by a discussion between users about the need for changes.

Substantial debate continued into the Production Subcommittee meeting on Tuesday afternoon. At the Subcommittee meeting, a vote was taken to recommend development of standards. The ballot was immediately taken across the hall to the Standards Subcommittee. There, it was summarily approved and sponsored by the PCIC. The young authors were swept along in the rush of events that they had stimulated.

The result of the implementation of these standards has been a marked improvement in the quality of ESP cables and a coincident extension of the expected life of cables.

How that paper and the authors came together is a story in itself. At the 25th anniversary conference, a first-time attendee asked if there was any technical information about submersible pump cable performance. Since it was a common problem, a long time activist and subcommittee chairman offered to find authors for such a paper. A service company was called and asked to contribute a technical paper on cable performance and application. The service company agreed and called a user to join the paper team. The user was the first-time attendee, who originally requested the paper. Subsequently, these two researchers went to an independent manufacturer to contribute his perspective. This watershed paper had the optimum makeup of user, manufacturer, and service company.

The user coauthor, who originally requested the paper, ultimately became Chairman, with the other coauthors as significant members, of the Standard working group. Technical curiosity can lead to a career in topic. The lead coauthor has attended every conference in the intervening 25 years and has contributed more than 20 technical papers. The real story is that the IEEE is such an open forum that a young engineer can participate and have a significant long-term contribution.

II. YEARS OF CHANGE

The interaction necessary to develop standards can offer a very revealing historical perspective. Twenty-five years ago, at the onset of PCIC-sponsored standards, all participants in the

---

Paper PID-06-16, presented at the 2005 IEEE Petroleum and Chemical Industry Technical Conference, Denver, CO, September 12–14, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society. Manuscript submitted for review September 15, 2005 and released for publication September 29, 2006.

M. O. Durham is with THEWAY Corporation, Tulsa, OK 74153 USA, and also with the University of Tulsa, Tulsa, OK 74104 USA (e-mail: mod@superb.org).

R. A. Durham is with D^2 Tech Solutions, Inc., Tulsa, OK 470926 USA (e-mail: rdurham@d2ts.com).

R. H. Hulett is with Thermon Manufacturing, San Marcos, TX 78667 USA (e-mail: rhulett@thermon.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2006.890022

0093-9994/$25.00 © 2007 IEEE

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

development of a standard traveled to a central location for two days of meetings and discussion. The secretary dutifully recorded the events, which were taken and typed. At the next conference, the typed notes were reviewed and often corrected and retyped from the beginning to correct errors.

The latest revisions required few conferences. Notes and changes were exchanged electronically. Each working group participant could see the same original and recommend changes. Only tweaks and additions were required. Global changes were quickly incorporated. For the few conferences required, a projector was used with a laptop computer to view the draft on screen. This enables the working group to view the draft, see proposed revisions in the draft, and then form a consensus position without having to ballot.

While changes to the physical interaction between the working group participants made the revision process easier and quicker, one glitch came about because of international standardization. The effects of these modified expectations and the subsequent changes to the IEEE SA requirements that came about as a part of the approval process for the latest edition of these three standards are discussed in detail in the subsequent sections.

III. IEEE STANDARD PROCESS

What is the standard process, and how do standards get initiated? Many regular attendees at conferences are not aware of these procedures and as such are not able to participate in the process. In order to expand the participation of engineers in the standards process, a brief look at the process of getting a standard initiated, the development of the standards process then and now, submitting the standards, the balloting process, and the approval process is included.

Work on a standard is initiated with a Project Authorization Request (PAR). This document provides the title, scope, and purpose of the proposed standard. When the first downhole cable standards were started, the PAR was a hard copy form that was forwarded to IEEE Standards by U.S. mail. Now, the form is in electronic format, and when completed, it is forwarded to IEEE Standards by a single mouse click. When the PAR is approved, the Working Group is authorized to begin work on the project.

After the Working Group has completed a final draft, the balloting process begins. For PCIC, balloting is usually done with a Sponsor Balloting Group. IEEE requires that at least 75% of the balloters respond with a vote. When this was done by postal mail, the process was slow, and sometimes the criterion of 75% return would not be met. The reason for this would be lack of interest on the standard by some of the balloting pool members and change of postal address with no return. Today, these problems have been alleviated by a process of invitation to ballot. The invitation to ballot is send out electronically to the balloting group. Those with an interest in balloting the standard indicate with an electronic return. The 75% return criterion for ballots is no longer an issue since ballots are sent only to those that express an interest. Of those ballots that are returned, 75% must be affirmative. The Working Group must make an effort to resolve any negative comments.

When the negative comments have been resolved, and there are no technical changes needed to resolve a negative ballot, the draft is ready to be sent to the IEEE Review Committee (RevCom). If technical changes were required in order to resolve a negative ballot, a recirculation ballot is required. The recirculation ballot is sent to the Balloting Group with any revisions and a description of all unresolved negative comments. If there are no *new* negative ballots, this balloted draft is now ready to be sent to the IEEE RevCom.

RevCom reviews the standards process and addresses issues such as: “Is the draft consistent with the PAR?,” “Was the balloting process properly conducted?,” “What was the effort to resolve negative ballots?,” “Have the comments by SCC 10 (Editorial) and SCC 14 (Units and dimensions) been addressed?”. If all is in order, RevCom will recommend that the Standards Board approve the standard, recommended practice, or guide.

If there have been inconsistencies in the process, the draft is sent back to the Working Group for further resolution and another recirculation ballot. In recent years, the balloting and resolution process has been greatly accelerated by electronic correspondence. Beginning in January 2005, all balloting will be done only in electronic format. It is easy to see that much has changed during the life of these standards with the advent of electronic communication. It is also apparent that while standards are not personal whims, it is a straightforward process to develop a new standard that has a base of support.

IV. DUAL UNITS

The three standards discussed herein were initially developed over a two-year period with active participation by users, manufacturers, and service companies. Subsequently, the documents were approved by the IEEE. As part of the normal process of maintaining current standards documents, a five-year review is required.

This process has been repeated several times over the 25-year history of the standards. The newest editions of these standards have been completely rewritten to reflect newer technology in the electric submersible cable that has been developed.

Surprisingly, the latest revisions were the most difficult to get through the approval process. Nine drafts were required, primarily because of various issues revolving around IEEE standard unit designations.

The earlier published versions used English units. During the latest five-year revision process, the IEEE 2000 policy for units required that units in IEEE standards be metric units only. During the review process, the draft standards were changed to reflect this requirement. However, during the balloting process, users objected to the metrification because it is not compatible with standards from other organizations. The resulting negative ballots prevented the documents from passing. The IEEE Standards Board listened to a presentation on the case for dual units for certain Standards, where the users of the standard were primarily familiar with English units, and the other associated standards have requirements in English units. Upon further consideration, the IEEE metric policy was changed to allow dual units where appropriate.

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

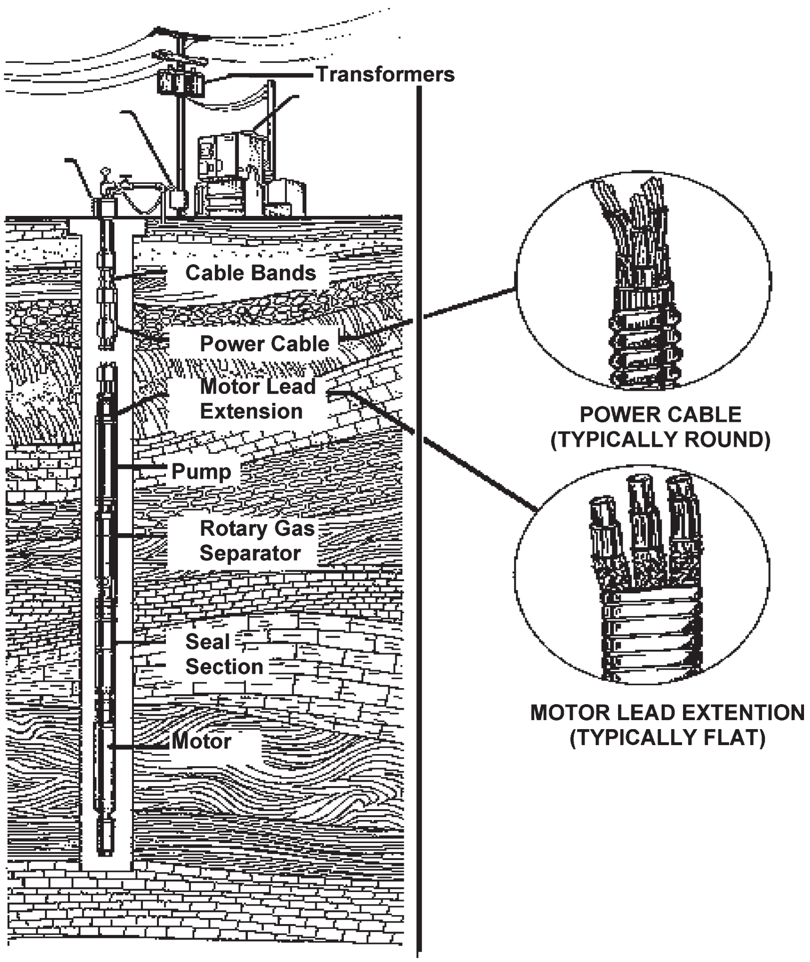

Fig. 1. Installation configuration.

These objections were numerous enough to prevent the revised standards from passing the ballot. When it appeared that other organizations would develop English unit standards, IEEE changed its policy.

As a result of the issues encountered with ESP cable standards, IEEE Standards can now have dual (metric/English) units. This policy change, while welcome by the standards working group, required yet another draft and number conversion with its inherent risks. The new policy of dual units is both reasonable and pragmatic.

V. CONFIGURATION

The ESP systems are the most effective equipment for moving large quantities of fluid from downhole applications. In harsh environments, the submersible pump is often the only apparatus that will survive the rigors of volume, depth, and temperature. Fig. 1 illustrates a typical installation [1].

The ESP cable is typically over 1 mi long and is used in an environment subject to temperatures exceeding 200 °F and pressures exceeding 2500 $\mathrm{lb/in^2}$. The cable is strapped to the fluid pipe; as a result, the cable is both suspended while being regularly compressed inside the casing. The cable is then submerged in saltwater with oil and gases and exposed to contaminants such as hydrogen sulfide and carbon dioxide. Other than the conditions described above, the ESP cable operates in a normal benign medium-voltage 100-A electrical environment.

As shown in Fig. 1, there are three types of cable that are used in an installation. These are the surface cable, power cable, and motor extension. In the simplest installations, the surface and power cables have the same design, which is typically a round construction. Round cable is a more robust design than flat cable and mitigates unbalance because of coupling between the phase wires. Round is used from the surface to near the top of the pump. In this area, the space between the inside of the casing and the tubing is generally adequate for the larger configuration cable.

In most applications, the largest pump that will fit inside the casing is installed so the pump can move higher volumes of fluid. As a result, the space between the casing and the pump is very limited. This lack of space necessitates that the motor lead cable use a flat design. A flat construction maximizes the conductor size while minimizing the physical diameter.

Finally, the flat cable is molded into an environmentally impervious connector that plugs into the motor. The flat design and the necessity to connect to the motor under high-pressure fluid have a very substantial impact on the design of the cable system.

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

VI. TRADITIONAL INSTALLATION

A major issue to arise during the development of the revisions was how to handle "traditional" installations. Since the cable operates in a classified (hazardous) area covered by National Electric Code (NEC) Article 500, substantial design, code, and safety issues are involved [5].

The traditional installation has the cable on the surface. It passes through a sealed transition. The same cable is then installed in the well. This practice has been used since the origin of the submersible pump. The safety record for the wellhead transition is admirable.

One company was involved in developing an alternative cable feed-through process. By focusing on a limited view of the NEC, this design was then promoted as the only safe method of connecting the surface cable to the well. In addition to the simple mechanical transition, other manufacturer's designs use a threaded connector approved by a nationally recognized testing laboratory.

Classification of the surface installation equipment is determined by the likelihood of an electrical failure occurring at the same time that 1) an ignitable vapor is present and 2) the electrical failure will be the source of ignition. Based on the relatively low likelihood of the above combination, the area around the wellhead is classified as Division 2.

The cable makes the transition from ground surface into a deep well by a simple mechanical seal. There are no connections that are made or broken under load. There are no contacts or switches associated with the installation at this point. There is, therefore, little risk of ignition. This meets all the requirements of Division 2 criteria.

The *Code* recognizes industry experience and makes provisions for this *de facto* standard to be used as a guide for interpreting the installation.

"FPN No. 1: It is important that the authority having jurisdiction be familiar with recorded industrial experience as well as with the standards of the National Fire Protection Association (NFPA), the American Petroleum Institute (API), and the Instrumentation, Systems, and Automation Society (ISA) that may be of use in the classification of various locations, the determination of adequate ventilation, and the protection against static electricity and lightning hazards. NEC 500.4 [5]."

Had this alternative feed-through concept been accepted and incorporated into the standards revisions, more than 2000 installations would have been invalidated. This could have dealt a devastating blow on the cable manufacturing and the petroleum production industry, particularly for wells with smaller production. In order to meet the concerns about wellhead transitions, an acceptable installation procedure that recognizes the proper installation practices that have been historically used is described in the cable testing standard IEEE RP 1017.

Several vendors have an alternative design for cable transition that is approved by nationally recognized testing laboratories. These newer designs clearly meet the requirements for classified areas. In conjunction with the traditional installation, safe economically acceptable designs are available for every condition.

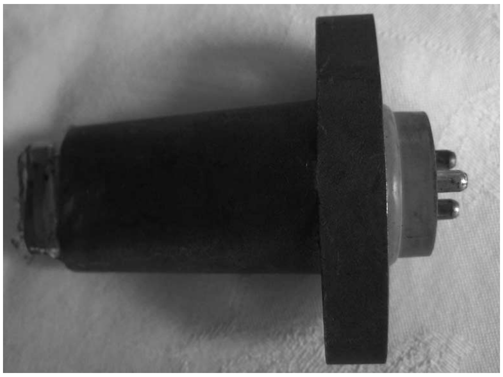

Fig. 2. Flat cable connector.

The issue of installation continued to cause a negative ballot from one of the balloters.

VII. SHIELDED

The 2005 version of the NEC has added a requirement for shielded cable in most medium-voltage applications. Article 210.6 requires that "... insulated conductors operated above 2000 volts...shall be shielded." For direct burial cables, Article 210.7 makes a more stringent requirement stating that cables *rated* above 2000 V shall be shielded [5]. ESP cables are exempted from these requirements as long as the cables are designed and constructed to a recognized standard, such as the three standards discussed in this paper.

Notwithstanding the exemption, there are several reasons that shielding is not used. First, voltage stress on the insulation is a major consideration in the design. This stress is managed through the physical design and construction of the cable. The compounding of insulation materials, in particular, makes shielding redundant [6].

Second, significant industrial experience by the users, with monitoring by the manufactures, has shown that the failure of the cable is from other factors that shielding would not mitigate. Treeing is not a significant method of failure.

Third, time in use is relatively short. Conventional industrial and commercial installations are designed for the life of the project, which often exceeds 30 years. Because of equipment operations, the submersible cable is often removed from service several times in its life. The cable is high potential tester (hi-pot) tested before reinstallation. Therefore, the state of the cable is relatively well known at the time of its reuse. Since an installation of cable, pumping equipment, and service costs can well exceed \$100 000 for each failure, it is imperative that only good quality cable is reused.

Finally, space constraints are a tremendous problem. As discussed earlier, the motor lead cable is necessarily small, and the connector spacing is restricted, as shown in Fig. 2. This design renders shielding of the cable virtually impossible.

VIII. AMPACITY VS VD

Two criteria are used when determining the appropriate ampacity of a conductor. The NEC has tables that are based

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

on current ratings [5]. This is primarily a heat consideration based on work by Neher and McGrath [7]. The application of Neher–McGrath to electrical submersible design is discussed in [8].

The NEC tables are the recommended *minimum* wire size for a particular current load. Although this is usually adequate for runs from a motor control center to a motor, this method of conductor sizing has serious shortcomings when distances between transformer and motor are extended.

As mentioned earlier, submersible cable runs from the transformer to the motor are often in excess of 5000 ft. With these long distances, voltage drop, rather than ampacity, becomes the constraining factor. The NEC recognizes this issue in Article 310.15(A)(1) FPN1 [5].

Cable ampacity ratings are limited by five factors, namely: 1) ambient temperature; 2) liquid/gas environments; 3) heat rise due to resistance heating; 4) heat distortion properties of insulation; and 5) ability to dissipate heat.

The economics of decreasing losses in the cable will provide incentive to increase the size of the 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 is equal to the incremental cost of the next larger wire size.

According to API RP 11S4 [9], a maximum of 5% voltage drop over the entire length of the cable will provide reasonable operating efficiency. In addition, the use of larger conductors improves cable life by reducing internal heating from I^2R losses.

IX. IEEE RP 1017

IEEE 1017 is the *Recommended Practice for Field Testing ESP Cable*. The following abstract gives an overview of the document.

“Abstract: Procedures and test voltage values for acceptance and maintenance testing of ESP cable systems are presented. This recommended practice applies to cable systems rated 3 kV and 5 kV (phase to phase) and is intended only for this special-purpose cable. The intent is to provide uniform test procedures and guidelines for evaluation of the test results.”

A background section is included in the standard and serves to further elucidate the purpose. “Guidance for the field and maintenance testing of conventional power cable is available in IEEE Std 400; however, that document is not an applicable guide in assessing the condition of ESP cable [10]. By adopting some of the principles set forth in IEEE Std 400 and applying others developed from field experience, this recommended practice for submersible cable testing will assist those with the responsibility for determining the dielectric condition of this type of cable.”

RP 1017 presents procedures and test voltage values for acceptance and maintenance testing of ESP cable systems. Several methods of testing and evaluating are discussed. The relative merits of each instrument are delineated.

DC hi-pot is the preferred technique for determining the quality of the cable. DC tests are selected because of the inherent advantages that dc has over ac testing. These advantages include smaller test equipment and minimization of damage, which aids in fault examination. A dc hi-pot test applies controlled overpotential to the cables. Leakage current is then measured. Through the judicious interpretation of these data, the condition of the cable can be determined without physical damage to the cable.

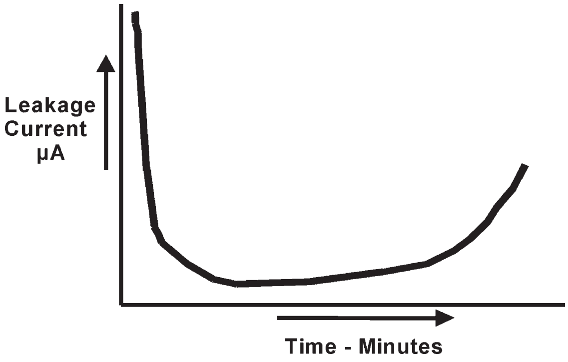

Fig. 3. Leakage of deteriorated cable.

Insulation Resistance Meters by themselves are not recommended for testing the reliability of ESP cable. The output voltage is insufficient to establish a conductive path across insulation defects and will only indicate gross defects.

Fault-locating devices are used to determine the location of a problem, if one exists.

Time-Domain Reflectometers (TDRs) use high-frequency pulses to detect anomalies in the cable. A TDR sends a pulse down the cable, and the reflective signal is measured. This measurement indicates where the fault should be located. The TDR requires interpretation from an experienced operator.

Thumpers apply a high-voltage capacitive discharge into the test cable. This test is sometimes used to break down conductor insulation to locate a fault. However, this approach creates extreme stress on the cable insulation. If improperly used, it can actually create faults in otherwise good cable.

Bridge Type Fault Locators use a balancing bridge in conjunction with high dc voltage to measure conductor impedance (distance) to a fault. This is one of the least destructive types of fault-locating equipment, and it is relatively effective. However, if a high-resistance fault is present, this device may not be effective.

DC Burn uses a dc voltage (5–10 kV) applied to a faulted cable. The voltage is allowed to remain until the fault location becomes obvious.

X. IEEE RP 1017 TESTS

In the test process, a dc voltage is imposed on the cable to be evaluated. The leakage current is measured and plotted over the duration of the test. Interpretation of the data gives an indication of the quality of the cable based on an IEEE paper [11]. A typical diagram showing the leakage current of a deteriorated cable at fixed voltage is shown in Fig. 3.

The level of the test voltage is adjusted based on the condition of the cable. The objective is to evaluate, not damage, the

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

TABLE I
TEST VOLTAGE

Cable rating ac kV	Factory test dc kV	Acceptance test dc kV	Maintenance test dc kV
3	27	22	11
5	35	28	14

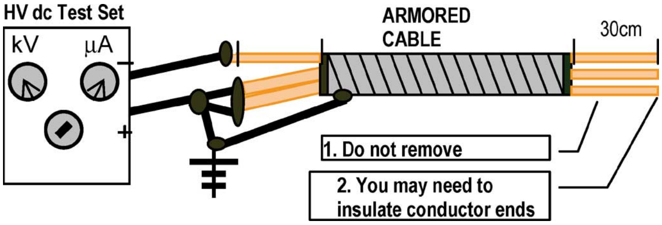

Fig. 4. Test setup.

insulation. Cable that is previously used, then, is tested at a level lower than new cable.

Factory test: This test is completed by manufacture at the 100% level, as indicated in Table I. For a 3-kV cable, this is 900% of the rated voltage. For a 5-kV cable, 700% is sufficient. This voltage test is conducted phase to ground.

Acceptance test: Acceptance testing is intended to detect damage prior to the initial installation of new cable. These tests are normally performed by the user or his designated representative using dc voltage at 80% of the factory test voltage.

Maintenance test: This test is made after removing the cable from a well and is normally performed by the user or his designated representative using dc voltage at 40% of the factory test voltage. It is intended to detect the deterioration of the cable insulation and to determine suitability for reuse. Maintenance testing is sometimes referred to as proof testing.

Safety procedures and environmental considerations are key components to a successful evaluation. The connections for the tests are shown in Fig. 4 [1].

XI. IEEE RP 1018

IEEE 1018 is the *Recommended Practice for Specifying ESP Cable: Ethylene–Propylene Rubber Insulation*. The following abstract of IEEE 1018 gives an overview of the document.

"Abstract: Minimum requirements for the construction, manufacturing, purchasing, and application of 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."

The properties and characteristics of the materials are identified in Tables II–VII.

A replication of the table developed in IEEE 1017 is the *Test Voltages for ESP Cable* and is shown in that section.

TABLE II
CONDUCTOR CHARACTERISTICS (METRIC UNITS)

Size *	Area m*	Wt. kg/km	Sol. Dia.	Stra. Dia. 7 wire	Com. Dia. 7 wire	Res. Ω/km Plain Cu
10 m	10.0	88.5	3.57	-	-	1.87
6 A	13.3	118.0	4.11	-	-	1.32
16 m	16.0	140.0	4.48	-	-	1.17
4 A	21.1	188.0	5.19	-	-	0.830
4 A	21.1	188.0	-	5.89	5.41	0.846
25 m	25.0	222.0	5.64	-	-	0.742
2 A	33.6	306.0	6.54	-	-	0.522
2 A	33.6	306.0	-	7.42	6.81	0.531
1 A	42.4	386.0	7.35	-	-	0.413
1 A	42.4	386.0	-	8.33	7.57	0.423
1/0 A	53.5	475	-	9.35	8.56	0.335
2/0 A	67.4	599	-	10.80	-	0.266

- m = mm^2
- A = AWG
- Dia = mm

TABLE III
ETHYLENE–PROPYLENE PROPERTIES

Physical Requirements - Unaged	6.2
Tensile strength, minimum, MPa	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

TABLE IV
NITRILE PROPERTIES

Physical Requirements – Unaged	12.4
Tensile strength, minimum, MPa	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 V
EPDM JACKET PROPERTIES

Physical Requirements – Unaged	6.9
Tensile strength, minimum, MPa	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

In addition, descriptions of the construction of the ESP cable further illustrate its properties and characteristics.

Round Cable: The three insulated conductors should be cabled around a centrally located filler that provides blockage.

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

TABLE VI
PHYSICAL 75 mils/3 kV

Values for 1.91 mm (75 mil) insulation
3kV EPDM

Conductor Size	Conductor dia. mm (inch)	Insul. min. point mm	Calc. Insul. dia. mm	IR value 1 km MΩ	dc leakage 1 km 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

TABLE VII
PHYSICAL 90 mils/5 kV

Values for 2.29 mm (90mil) insulation
5kV EPDM

Conductor Size	Conductor dia. Mm (inch)	Insul. min. point mm	Calc. insul. dia. mm	IR value 1 km MΩ	Dc leakage 1 km μA/kV
$10mm^2$	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
$16mm^2$	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
$25mm^2$	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

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 the 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 thickness. Splines are provided for grip of the overlying armor. The jacket should separate cleanly from the underlying components.

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, as shown in Fig. 5.

Fig. 5. Round cable.

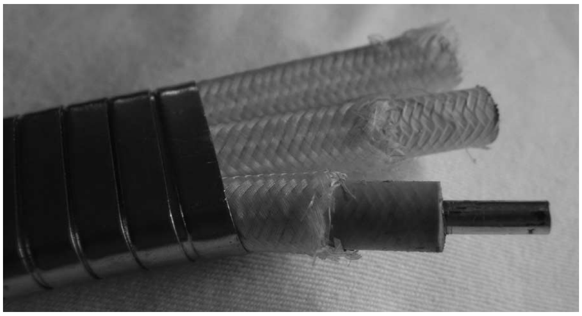

Fig. 6. Flat cable.

Flat Cable Nonleaded: Each insulated conductor should 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).

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, as shown in Fig. 6. 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.

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

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.

minimum wall thickness at any point should be no less than 0.8 mm (0.032 in).

XII. IEEE 1019

IEEE 1019 is the *Recommended Practice for Specifying ESP Cable—Polypropylene Insulation*. The following abstract of IEEE 1019 gives an overview of the document.

"Abstract: Minimum requirements for the construction, manufacturing, purchasing, and application of 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."

The document is very similar to IEEE 1018. The significant difference is the material used for the insulation and jacket. All the table values are changed, but the same basic design is used. Therefore, a detailed discussion is foregone in deference to reading the standard.

XIII. CONCLUSION

ESP cable is a special purpose design for harsh installations at elevated temperature and pressure under saltwater with hydrocarbons and other chemicals. It is of medium voltage operating at about 100 A. Three related IEEE standards began life 25 years ago. These are IEEE Standards 1017, 1018, and 1019. During the recent five-year review, the standards were significantly updated to reflect newer technology. As a result of this review, there was an analysis of the IEEE requirement for total metrification. The result is the IEEE Standards Board changing their policy to permit both metric and English units.

REFERENCES

[1] *IEEE Recommended Practice for Field Testing Electric Submersible Pump Cable*, IEEE Std 1017-2004.

[2] *IEEE Recommended Practice for Specifying Electric Submersible Pump Cable*, IEEE Std 1018-2004.

[3] *IEEE Recommended Practice for Specifying Electric Submersible Pump Cable—Polypropylene Insulation*, IEEE Std 1019-2004.

[4] M. O. Durham, L. Boyer, and R. Beer, "Field requirements of submersible cable," in *Proc. PCIC Conf.*, San Diego, CA, Sep. 1979, pp. 113–118.

[5] NFPA 70, *National Electrical Code*, Quincy, MA: National Fire Protection Association, 2002.

[6] M. O. Durham, D. H. Neuroth, K. Ashenayi, and T. Wallace, "Field test technology relationships to cable quality," *IEEE Trans. Ind. Appl.*, vol. 31, no. 6, pp. 1381–1389, Nov./Dec. 1995.

[7] J. H. Neher and M. H. McGrath, "The calculation of the temperature rise and load capability of cable systems," presented at the AIEE General Meeting, Montreal, QC, Canada, Jun. 1956, Paper IEEE 57-660.

[8] G. Baker and M. O. Durham, "Correlations of submersible cable performance," *IEEE Trans. Ind. Appl.*, vol. 28, no. 2, pp. 282–286, Mar. 1992.

[9] *Recommended Practice for Electric Submersible Pump Installation*, API RP 11S4.

[10] *IEEE Guide for Making High-Direct-Voltage Tests on Power Cable Systems in the Field,* IEEE Std 400-2001.

[11] M. O. Durham, R. A. Durham, D. Anderson, "What are standardized equations for acceptance of hi-pot tests and for voltage drop?" in *Proc. PCIC Conf.*, Indianapolis, IN, Sep. 1998, pp. 281–287.

Marcus O. Durham (S'64–M'76–SM'82–F'93) received the B.S. degree in electrical engineering from Louisiana Tech University, Ruston, the M.E. degree in engineering systems from the University of Tulsa, Tulsa, OK, and the Ph.D. degree in electrical engineering from Oklahoma State University, Stillwater.

He is a Principal Engineer with THEWAY Corporation, Tulsa. He is also a Professor with the University of Tulsa. He has published seven books used in university-level classes.

Dr. Durham is a Fellow of the American College of Forensic Examiners (ACFE), Certified in Homeland Security by the ACFE, a member of the Society of Petroleum Engineers, a member of the National Fire Protection Association, and task group member of the American Petroleum Institute. He is also a member of Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu. He is a Registered Professional Engineer in Louisiana, Oklahoma, and Arkansas, a state-licensed electrical contractor, an FCC-licensed radiotelephone engineer, an extra-class amateur radio operator, and a commercial pilot. He has been awarded the IEEE Richard Harold Kaufmann Medal "for development of theory and practice in the application of power systems in hostile environments." He was recognized with three IEEE awards for his standards development work. He has been awarded numerous times for the over 117 technical papers he has authored. He is acclaimed in *Who's Who of American Teachers, National Registry of Who's Who, Who's Who of the Petroleum and Chemical Industry of the IEEE, Who's Who in Executives and Professionals, Who's Who Registry of Business Leaders*, has been named Congressional Businessman of the Year, and received the Presidential Committee Medal of Honor.

Robert A. Durham (S'90–M'92–SM'06) received the B.S. degree in electrical engineering and the M.E. degree in technology management from the University of Tulsa, Tulsa, OK, and the Ph.D. degree in engineering management from Kennedy Western University, Agoura Hills, CA.

He is a Principal Engineer with D^2 Tech Solutions, Inc., Tulsa, an engineering and technology-related firm concentrating on mechanical and electrical systems and conversions. He is also a Chief Engineer with THEWAY Corporation, Tulsa, an engineering, management, and operations group that conducts training, develops computer systems, and provides design and failure analysis of facilities and electrical installations. He also serves as President of Pedocs Inc., a natural resources developer. He specializes in power systems, utility competition, controls, and technology integration. His work experience is broad and encompasses all areas of the power industry. His technical emphasis has been on all aspects of power systems from electric generating stations, to EHV transmission systems, to large-scale distribution systems and power applications for industrial locations. His extensive client list includes the development of a broad spectrum of forensic, electrical, and facilities projects for many companies. He is also involved with the audit of market participants in competitive utility markets to ensure that these facilities are adhering to the rules of the market. He is a nationally recognized author, having received several awards from technical and professional organizations such as the IEEE, and has published magazine articles on multiple occasions.

Dr. Durham is registered as a Professional Engineer in five states.

Richard H. Hulett (M'76–SM'90–F'03) received the B.S.M.E. degree in 1964 and M.S.M.E. degree from Stanford University, Stanford, CA.

He was previously with Raychem for 20 years. He is currently the Senior Vice-President of electrical products with Thermon Manufacturing, San Marcos, TX, where he has been employed for 11 years. He has authored numerous papers and has received honorable mention for two papers presented at the IEEE PCIC Conference.

Mr. Hulett has been a member of the IEEE/IAS/PCIC for the past 26 years. He is currently a member of the IEEE Standards Board and also is serving on NESCOM. As a member of PCIC, he is a member of the Standards Subcommittee (where he is currently Chair). He has been a member of the IEEE 515 Working Group since 1979 (where he has served as Chair and Co-Chair since 1985). He is also a member of the Codes and Regulations Working Group and the Chemical Subcommittee. He has also been a member of the American Society of Mechanical Engineers since 1964. He received the David C. Azbill Award and the IEEE Standard Medallion.

Authorized licensed use limited to: IEEE Xplore. Downloaded on September 27,2024 at 01:22:31 UTC from IEEE Xplore. Restrictions apply.