CABLE TESTING TECHNOLOGY HELPS MANAGE ESP CABLE LIFE

George Rocha, Mobil Exploration and Producing U.S.
Robert Lannom and John Green, ESP Inc.

Introduction

ESP cable is an integral part of the submersible pumping system. Operating cost considerations have moved the industry towards re-use of equipment. Testing of submersible pumps, motors, seal sections and gas separators is currently being conducted by all major manufacturers of ESP equipment. A normal progression would require that ESP Cables follow the same suit. Many users currently rely on a 1000 Volt megohmmeter or a DC Hi-Pot test to determine if a cable is suitable for re-use. These instruments if used at a single voltage point may not give a true picture of the cable insulation reliability. This paper describes environmental aspects which must be considered along with a jointly developed testing procedure for determining the re-use of ESP cable. The ultimate goal of the testing procedure is to gather data and optimize the life of ESP cables under specific applications. The procedure was jointly developed by Mobil and ESP Inc. Use of the procedure was initiated at Salt Creek field in January 1992, and to date over 167 cable strings have been tested.

Factors affecting ESP Cable Life

ESP Cable failures are defined as a breakdown of the dielectric strength of the cable insulation where an electrical short occurs between phases or to ground. This includes breakdowns in cable splices (old and new splices) which are also part of the cable insulation. Several factors including the different types of stresses - mechanical, electrical, thermal and chemical - have a direct relationship on insulation life. These factors are discussed individually as follows:

Mechanical stresses

Mechanical damage is the most common reason cable failures occur at Salt Creek. Most of these types of failures can be prevented by utilizing proper handling and operating procedures. Some of the types of damage seen include;

* Rig slips setting on the cable.
* High compressive forces on cable armor due to improperly set pneumatic banders.
* Uneven spooling of the cable (cable suspended in a catenary).
* Sharp bending of the cable during installation.
* Armor damage due to wear against casing or BOP's while tripping in or out of the hole.

Mechanical damage caused by cable decompression is very difficult to prevent or predict. It can be caused by drawdown of the well or pulling of the downhole equipment. The problem is caused by migration of wellbore fluids and gasses into the jacketed materials. On initial installation, a pressure differential exists between internal pressure of the jacketed materials and wellbore fluids. Factors affecting the permeation rate are the partial pressures of the gas or the concentration factor of the fluid and the solubility of the permeant (Migrating gas or fluid). Once the internal components of the cable have reached the same pressure as the well through diffusion and physical compression, the cable has reached equilibrium.

When the fluid is drawn down or the well is pulled, a pressure differential is created with the higher pressure existing in the cable insulation and jacket. The problem arises (Gas Blown cable) when the polymers are not given sufficient time to de-gas and the resulting differential exceeding the hoop strength of the cable materials. The hoop strength of the jacket and insulation varies significantly with temperature and material type. Typically, the cable armor provides most of the hoop strength in the string (i.e. The only thing that keeps the cable from gas blowing).

Electrical stresses

Electrical damage is usually caused by lightning or switching transients. A commonly accepted mathematical model for electrical stresses vs. cable life is the Kiersztyn equation (1).

$$\ln(L) = -n^*(\ln E) + C'$$

Where L = Expected Life
E = Applied electrical stress
n = constant (8 to 12 typical)
C' = Constant

The above equation shows a relationship indicating that cable life decreases as the operating voltage is increased. This especially applies to transients where the insulation can see a large increase in the electrical stress even though it is for a short period of time. It should also be noted that the equation requires precise information on constants which can only be determined experimentally for a specific set of operating conditions. ESP cable operating in an oilfield environment will rarely see a specific set of conditions for any given amount of time.

It is also interesting to note that cable life is reduced because of electrical stresses applied during acceptance and maintenance tests according to the equation. Salt Creek has not experienced shorter cable run life since the inception of the testing program (See cable related failures). This loss is thought to be insignificant because of the harsh operating environment cable sees during its useful operating life (Which is significantly shorter than its theoretical maximum).

Thermal stresses

The importance of these stresses can be estimated by the Arrhenius relationship which can be expressed as:

$$L = A \exp (B/T)$$

Where L = Life
T = Temperature
A,B = Constants

The constants here once again depend on the material in question and the operating conditions. The temperature rise in the cable itself is due to both the ambient temperature in the well and the heat generation in the cable due to current loading. Other sources of heat can include an ESP which cycles or pumps off. The nature of the above equation shows that an increase in temperature will result in a decrease of insulation life.

Chemical stresses

Chemical attack of the cable can affect both the insulation material and the cable armor. Cable armor in most wells is composed of galvanized steel and is very susceptible to corrosion attack in a wellbore environment. Under deposit corrosion in the cable armor (bacterial corrosion) is very common in wells at Salt Creek. A drop in pH due to the initiation of CO_2 injection is also expected to increase the corrosion rates of the cable armor. The rate of the attack is dependent on a number of factors but again will primarily be determined by the partial pressures of the gas.

Chemical attack can also occur on the jacket and insulation material. Well fluids, gases and downhole treating chemicals can attack the polymeric materials in ESP cable. As in thermal stresses, the rate of attack is proportional to the operating temperature of the cable. In a CO_2 environment, CO_2 causes a phenomenon known as environmental stress cracking in Polypropylene (PPE) insulation. This basically results in small cracks occurring in the cable insulation which ultimately result in failure (2).

The above discussions are intended to show that a mathematical model for determining cable life is not practical. All factors effecting cable life are interrelated with the operating conditions being the primary drivers. The environment in which the cable was being used and the proposed operating environment for the cable should be the biggest concern in determining cable suitability. Minimum acceptance criteria for one field may not directly apply to another. Best estimate criteria must initially be set up for the field and adjusted as more data is obtained through time.

PROCEDURE FOR ACCEPTANCE OF NEW AND USED SUBMERSIBLE ELECTRIC CABLE

The following is a description of the testing procedure currently being used in testing ESP cable at Salt Creek. The acceptance criteria is specific for the field and should not be considered suitable for all cable applications. Figure 1 is an example of a report which can be generated from the information obtained by using the proposed testing procedure.

1) A certified factory test report is to be received with the delivery of each new reel of submersible electric cable. A copy of this report should be forwarded to the Field Operations Engineer.

2) Each new cable reel shall be tested according to the criteria set up for new cable. Test results will be reported to the Field Operations Engineer. Any test failures or unusual cable problems/conditions will be reported immediately.

3) The Cable is tested as follows:

A) The cable will be measured and visually inspected. The cable must be of continuous length with no splices (new cable). Used cable will have no more than two splices (excluding MLE-Motor Lead Extension- and upper pigtail splice) and the jacket or conductor insulator should not be visible through the armor. All testing of used cable will be done after the MLE is cut off unless specified by the field engineer.

B) The three conductors will be megged individually with a 1000 VDC megger. This will be done by connecting the positive lead of the megger to each phase and the negative lead to the armor. Conductors not being tested will be grounded. This test only serves as a verification to continue with the Hi-Pot test with the primary emphasis being on achieving balanced readings between phases.

Acceptance - New cable - 5000 MOhms/1000'(PPE), 3000 MOhms/1000' (EPDM)
Maintenance - Used cable - 2500 MOhms/1000'(PPE), 1500 MOhms/1000' (EPDM)

C) The continuity of each conductor shall be checked with a digital ohm meter. The resistance values for each phase should be well-balanced and should not exceed the following values by 3%.

Conductor size	ohms/1000'@ 77 F
#1 AWG	.134
#2 AWG	.169
#4 AWG	.261
#6 AWG	.410

Temperature correction factors as per ICEA/NEMA will be used.

D) The Cable will be hypotted to a maximum of 28.0 KVDC for 5 KVAC cable and 22.0 KVDC for 3 KVAC cable (Use 14.0 KVDC maximum for 5 KVAC used cable 11.0 KVDC maximum for 3 KVAC used cable). Each phase to ground will be tested as described in the report testing requirements.

Hi-Pot test readings will not exceed the stated leakage readings at maximum voltage (Phase to Ground). The phase-ground results should be plotted on a linear graph with voltage on the X-axis and current leakage/1000' on the Y-axis. A minimum of five incremental voltage readings will be taken at 1 minute intervals. The increments should be evenly divided up to the maximum voltage for the given cable.

KV	Leakage	Cable type
28	.050 uA/KV/1000'	5KV Acceptance Test, PPE (Polypropylene)
28	.100 uA/KV/1000'	5KV Acceptance Test, EPDM
22	.050 uA/KV/1000'	3KV Acceptance Test, PPE (Polypropylene)
22	.100 uA/KV/1000'	3KV Acceptance Test, EPDM
14	.100 uA/KV/1000'	5KV Maintenance Test, PPE (Polypropylene)
14	.200 uA/KV/1000'	5KV Maintenance Test, EPDM
11	.100 uA/KV/1000'	3KV Maintenance Test, PPE (Polypropylene)
11	.200 uA/KV/1000'	3KV Maintenance Test, EPDM

See Table 1 for additional information which is required in the test procedure.

Discussion

Theoretically, cable resistance or leakage can be calculated by determining the K factor for the insulation material. Insulation resistance varies as a function of the K factor, wire diameter, and insulation diameter. The K factor will vary for different polymeric blends (i.e. PPE vs EPDM - Ethylene Propylene Diene Terpolymer) thereby changing the insulation resistance. Each cable manufacturer produces or purchases its polymers from different sources so a K factor for EPDM or PPE may not be accurate for all manufacturers. The ICEA (Insulated Cable Engineers Association) has established K factors of thermoplastic and thermoset-EPDM which can be used to set acceptance standards but may not be very accurate for a particular type insulation.

Experience at Salt Creek during the past two years has shown that the above stated acceptance criteria are adequate for cable used at Salt Creek. This assumption is based on cable related failures and cable rejection rates.

The multi-step voltage readings better indicate the cable's condition by providing a trend in the resistance as the electrical stress is increased-as opposed to merely providing one data point. As an individual cable string ages, the slope of the leakage on subsequent tests increases. The slopes of all three phases should also be very close and almost plot one atop the other. A potential indicator of a problem could be if the slope of one phase is significantly different from the others or, if the slope/slopes of the phase/phases begin to exponentially increase at the higher voltages.

Figure 2 shows two plots of current leakage vs voltage. Line 1 is a plot of what proper leakage should look like if the insulation is in relatively good shape (Equal increments of voltage giving equal increments of current). Line 2 is a plot showing insulation degradation. The point at which the leakage starts increasing at a more rapid rate is referred to as the "Knee" (Point A). If the test is carried out much past this point, a complete breakdown of the insulation will occur (Destructive testing)(3).

The graphical presentation of leakage vs voltage in Figure 1 clearly shows a "knee" on the B phase. This Salt Creek cable was tested using the proposed procedure and was rejected for use in this field.

Testing Equipment Specifications

The ESP Computerized Test system is suitable for cable shop use and an office environment with the addition of an optional host computer/printer system. The test system includes a computer, monitor, high voltage power supply, high voltage measurement section, data acquisition hardware, cables, and a rack mount cabinet. The host system includes a computer, monitor, printer and networking system for connecting to the test unit. The physical dimensions and performance specifications are as follows:

Physical:

Rack mount cabinet: 67"H x 22"W x 35"D
Weight: Approximately 800 lbs
Temperature Range: 0 C to +55 C
Humidity Range: 0 - 99%
Test lead length: 30 feet

Electrical

Requirements: 110 VAC +/-10%, 60 HZ, 750 VA
Test Voltage Range: 0-28 KV
Voltage Resolution: 100 Volts
Voltage Accuracy: 0.5% Full Scale
Voltage Drift vs Time: 0.01%/hr
Voltage Drift vs Temp.: 0.005% per C
Maximum Voltage Ramp Rate: 50 Volts/sec
Current Limit: 0.75 uA
Leakage Current Range: 0 - 180 uA
Current Resolution: 0.01 uA
Current Accuracy: 0.25% Full Scale
Current Drift vs Time: 0.01% / hr
Current Drift vs Temp: 0.01% per C

The computerized testing procedure is based on IEEE and draft API standards. The entire testing procedure is computer driven which reduces the chance of human error. Maximum test voltage and acceptance limits can easily be adjusted which simplify the go/no go interpretation based on the graphical printout and interpertaion (See figure 1). The test data is stored in a standard d-base format for convenient analysis which also assists in tracking cable inventory. Cable condition and history may be tracked for an individual cable string with the use of the d-base program.

Cable failure rates at Salt Creek

The cable testing procedure was initiated at Salt Creek in January of 1992. The cable related failures are listed as a percentage of the overall field failure rate. There are currently 144 submersible pump installations on this Unit.

Year	ESP Failure rate Failures/Well/Year	Total ESP failures	Cable failures	% of ESP failures
1991	.84	112	20	18
1992	.50	70	10	14
1993	.52	73	8	9

The cable failures listed above do not include MLE or mandrel/pigtail failures since the testing procedure does not address these items. An overall reduction in failure rates is easily seen as a % of total failures.

This trend would be expected to continue if the operating conditions would stay relatively constant. Unfortunately, the initiation of CO_2 injection will change the operating environment of the cable. It is very difficult to predict how the CO_2 will effect cable life. It can only be expected that mechanical damage and corrosion will increase; however, the magnitude of this increase is not known at this time.

Conclusions and Observations

1. The testing program has resulted in a reduction of cable related failures at Salt Creek.

2. The loss of cable life due to the testing procedure is insignificant.

3. Acceptance criteria set up for Salt Creek may not necessarily be applicable to other fields. Best guess estimates should be set up for the field initially then be adjusted as more data is received (i.e. Salt Creek initially set its leakage criteria at 0.3 uA/1000/KV for used cable - Testing showed that 0.1 uA/1000/KV was more appropriate.).

4. Cable failing the Salt Creek acceptance test may still be suitable for other applications. All factors known to effect the cable life along with historical testing data need to be considered prior to re-running cable.
(i.e. The cable which failed the acceptance test in Figure 1 may still be utilized in a shallow, low voltage, low corrosion application.

5. Cable test results can be significantly affected by temperature, humidity and cable preparation procedures-which were not covered in this paper. These items should be recorded in any testing procedure and should be compared any time a problem is identified. Consistency is the most important factor in electrically testing cable.

6. The testing procedure can be conducted using a stop watch and Hi-Pot tester. The readings can be recorded on the above form and later plotted. Computerized test methods can better control uniformity and repeatability of testing procedures.

7. The testing procedure requires that the cable be visually inspected. This is just as important as the electrical tests conducted on the cable.

8. During 1993, the testing procedure resulted in approximately 24,000 feet of cable being rejected (four Salt Creek reels) out of 83 cable reels tested.

References

(1) Kiersztn, Stanley E., "Formal Theoretical Foundation of Electrical Aging of Dielectrics", IEEE Transaction of Power Apparatus and Systems, Volume PAS-100, No. 11, November 1981.

(2) MacKenzie, B., Montgomery, P., "Interaction Between CO2 Flood Conditions and Poly-Nitrile Type Cable" , SPE 1988 ESP Workshop.

(3) Miller, H.N.,"DC Hypot Testing of Cables, Transformers, and Rotating Machinery", Associated Research Inc., 1965.

Table 1

Date Received ____________, Date Tested ______________
Ambient Temperature _______ Deg F,
Humidity ______________
New cable ____
Used cable ____ Well Number ____________
Manufacturer ______________
Cable serial # ______________
Armor Type : Galvanized _____ , S.S. ______
Cable size : __________
Cable KV : __________
# of Splices, __________
Splice locations ______________________
# of Armor Repairs __________
Repair locations ______________________

Comments: ____
____
____

A) Meg test w/ 1000 VDC Megger:
A Phase ___________ Megohms/1000'
B Phase ___________ Megohms/1000'
C Phase ___________ Megohms/1000'

Acceptance - New cable - 5000 MOhms/1000'(PPE), 3000 MOhms/1000' (EPDM)
Maintenance - Used cable - 2500 MOhms/1000'(PPE), 1500 MOhms/1000' (EPDM)

B) Continuity Tests:

A Phase ________ Ohms/1000'
B Phase ________ Ohms/1000'
C Phase ________ Ohms/1000'

Minimum acceptance values:

Conductor size	ohms/1000'@ 25 C, 77 F
#1 AWG	.134
#2 AWG	.169
#4 AWG	.261
#6 AWG	.410

Temperature correction factors as per ICEA/NEMA will be used.

C) Hi-Pot tests:

New Cable - 5 KVAC Microamp readings
Phase - Ground

DC Voltage	A	B	C	Time increment
5.0 KV				1 Min
10.0 KV				1 Min
15.0 KV				1 Min
20.0 KV				1 Min
25.0 KV				1 Min
28.0 KV				1 Min

New Cable - 3 KVAC Microamp readings
Phase - Ground

DC Voltage	A	B	C	Time increment
5.0 KV				1 Min
10.0 KV				1 Min
15.0 KV				1 Min
20.0 KV				1 Min
22.0 KV				1 Min

Used Cable - 5 KVAC Microamp readings
Phase - Ground

DC Voltage	A	B	C	Time increment
2.0 KV				1 Min
5.0 KV				1 Min
8.0 KV				1 Min
12.0 KV				1 Min
14.0 KV				1 Min

Used Cable - 3 KVAC Microamp readings
Phase - Ground

DC Voltage	A	B	C	Time increment
2.0 KV				1 Min
5.0 KV				1 Min
8.0 KV				1 Min
10.0 KV				1 Min
11.0 KV				1 Min

C A B L E   T E S T   R E P O R T

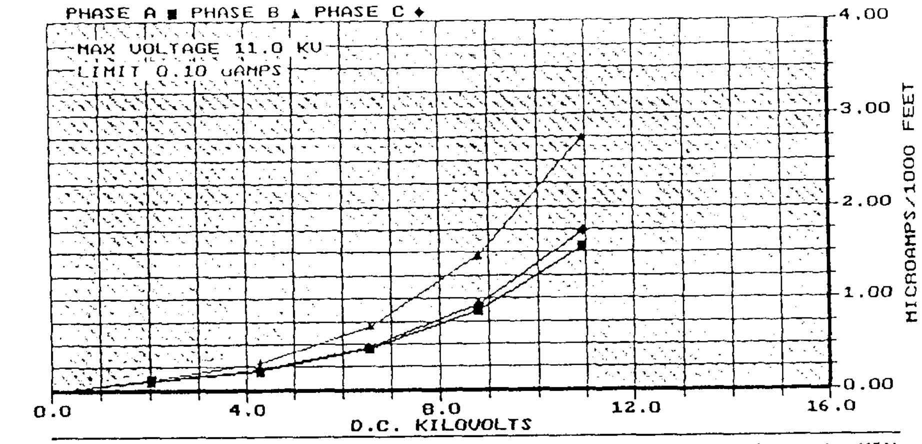
TEST DATE: 02/26/1993 TEST TIME: 17:58

RESISTANCE TEST:

	PHASE A	PHASE B	PHASE C	IDEAL
OHMS/1000 FEET @ 77F	0.161	0.163	0.163	0.169
OHMS/TOTAL FEET @ 77F	0.954	0.964	0.964	1.002

MAX DEVIATION FROM IDEAL: -4.75% MAX IMBALANCE PHASE TO PHASE: 1.08%

DC HIGH POTENTIAL TEST:



TEST TEMP: 60 F TEST HUMIDITY: 0% TEST INTERVAL: 1 MIN

KVOLTS			MICROAMPS/LENGTH			MICROAMPS/1000'			MICROAMPS/1000'/KV		
A	B	C	A	B	C	A	B	C	A	B	C
2.1	2.0	2.0	0.57	0.69	0.55	0.10	0.12	0.09	0.047	0.057	0.045
4.3	4.3	4.3	1.15	1.72	1.26	0.19	0.29	0.21	0.045	0.067	0.050
6.6	6.6	6.5	2.61	4.10	2.77	0.44	0.69	0.47	0.067	0.105	0.071
8.8	8.8	8.8	5.13	8.70	5.51	0.87	1.47	0.93	0.098	0.167	0.106
10.9	10.9	10.9	9.28	16.29	10.27	1.57	2.75	1.73	0.143	0.252	0.159

COMMENTS:
SPLICE AT 3185

CUSTOMER:

NAME: MOBIL
LOCATION: SNYDER
LEASE: SALT CREEK
LAST WELL: K-51
NEXT WELL: STOCK
DAYS RUN:

CABLE:

BUILT BY: REDA
SERIAL NO: NA
TYPE: REDALENE
KV RATING: 3
WIRE GAUGE: 2
LENGTH FT: 5927
CONFIG: FLAT
CONDITION: USED

CABLE TESTED AS PER IEEE 1017-1985 MAINTENANCE TEST FOR USED CABLE

Figure 1

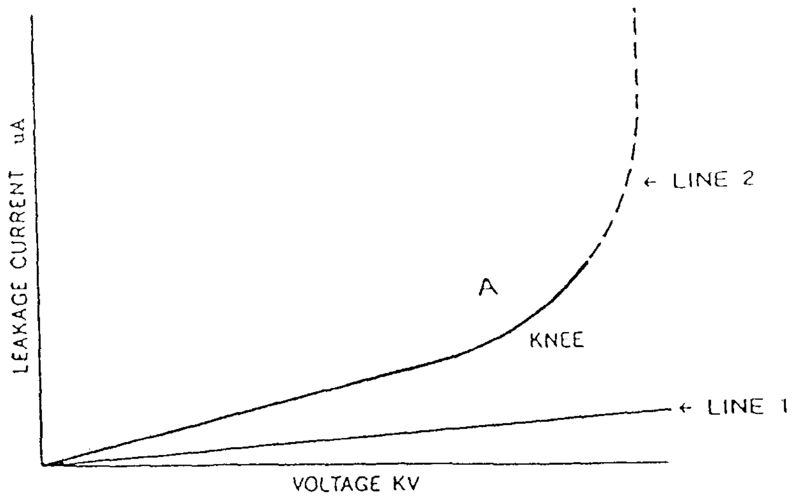


Figure 2 - Leakage vs. voltage