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Compendium of Electrical Submersible Pump Systems Testing Criteria

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Abstract: The maturing electrical submersible pump industry has numerous recommended practices and procedures addressing various facets of the operation. Ascertaining the appropriate technique is tedious for experienced engineers as well as novices. Seldom are all the documents available at one location. This synopsis of all the industry practices provides a ready reference for testing, design, and application of electrical submersible pumping systems. An extensive bibliography identifies significant documents for further reference.

INTRODUCTION

Electrical submersible pumps are a complex, sophisticated electrical and mechanical system. The maturing industry has developed numerous recommended practices and procedures to identify various facets of the operation. Experienced engineers have difficulty in tracking all these details. Newcomers can be overwhelmed by the proliferation of information. Furthermore, seldom are all these documents available in the field when they are needed. This synopsis will provide a ready reference of the current and pending documents addressing submersible systems. In addition many of the operations are illustrated by figures.

The American Petroleum Institute (API) supports most of the operations and mechanical references. The Institute of Electrical and Electronic Engineers (IEEE) publishes most of the electrical references. Other agencies and technical papers have references that are the basis of some of the discussions. Each of these will be investigated in order. Between them, the authors have been Chairman or members of most of the committees that have developed submersible recommended practices. This compendium is prepared from their experiences.

The documents represent the state of technology and generally accepted procedures. Nevertheless, each installation has unique considerations. Therefore, engineering judgment must be considered for each situation.

OPERATION, MAINTENANCE, AND TROUBLESHOOTING

API Recommended Practice 11S [1] relates field considerations rather than specification or testing. Table 1 illustrates data critical to a successful installation and operation. Once this data is gathered, appropriate adjustments can be made to the installation. Comparison with operating conditions indicates trends and possible problem areas.

Ammeter chart analysis points to operating problems. Figure 1 depicts an inappropriate curve. Anything other than a smooth line reveals questionable areas. Comparison of amp charts with past charts directs attention to changes that will enhance performance of the installation.

Increasing current represents a possible power overload. The pump should not be restarted without checking the electrical readings. Decreasing current represents a reduction in horsepower, leading to a pump-off. Generally, the pump can be restarted after a reasonable time delay to allow fluid build-up.

Table 1
Installation Data

Motor Data	Installed:

Horsepower:	Voltage:	Nameplate Amp:
Pump Data	Installed:	
Type:	Stages:	Intake type:
B/D capacity:		
Cable Data		
Type:	Length:	Size:
Transformer		
Tap Setting:	Sec Voltage:	
Voltage Data		
No load:	Full load:	
Comments:		

Current relays provide protection for the electrical and mechanical equipment. The over-load relay should be set at 105 - 110% of the rated motor current. Any higher setting will allow the motor to burn. The underload should be set at 80% or more of the motor rated current. The idle current may be only slightly below this 80%. Therefore it may be difficult to ascertain that a system is pumped off if a motor is lightly loaded.

TEARDOWN REPORT

API Recommended Practice 11S1 [2] is a detailed checklist for inspection of equipment during teardown. The document is being revised, but the content will be consistent. Several articles have been written that describe teardown procedures for all equipment [3,4].

RP 11S1 provides a description and four-digit codes for each failure mechanism. The unique codes are designed for computer correlation of problem areas. The field data, material, and well condition sections include items critical to describing the operation and performance. Comment sections allow personal observations.

Although the form incorporates many items, it is organized to allow selection of only those applicable to the problem at hand. It should be used as a guide and record for any inspection or analysis of submersible equipment. A commercial software package is available that implements this form into a computer search system [5].

PUMP TESTING

API Recommended Practice 11S2 [6] recounts techniques for performance testing of the pump. Product consistency results during manufacturing. The same test conducted on previously used equipment determines changes in performance and acceptability for reuse of the unit.

Because of load variations and motor slip, each pump will spin at a different speed. Performance is normalized by adjusting parameters to a common reference. Since the induction motors have a slip near 3%, the nominal speed is 3500 RPM. Approximations of performance are related by commonly called affinity laws.

$$\begin{aligned} \text{Flow}_{\text{adjusted}} &= (\text{rated RPM / Test RPM})^1 * \text{Flow}_{\text{test}} \\ \text{Head}_{\text{adjusted}} &= (\text{rated RPM / Test RPM})^2 * \text{Head}_{\text{test}} \\ \text{BHP}_{\text{adjusted}} &= (\text{rated RPM / Test RPM})^3 * \text{BHP}_{\text{test}} \end{aligned}$$

Another reference point is pump efficiency. The ratio of power out to power input includes all the performance measures.

$$\text{efficiency} = (\text{head} * \text{flow rate}) / (\text{Conversion factor} * \text{BHP})$$

For rate in barrels per day (BPD), head in feet (FT), power in horsepower (HP), and a specific gravity of 1.0, the conversion factor is 136,000 BBL FT / HP DAY.

API RP 11S2 recounts techniques for performance curves based on fresh water at 60F. Correct the factors for alternate test fluids.

$$\begin{aligned} \text{Head}_{\text{water}} &= \text{Head}_{\text{test}} * \text{H}_{\text{viscosity}} \\ \text{Flow}_{\text{water}} &= \text{Flow}_{\text{test}} * \text{Q}_{\text{viscosity}} \\ \text{BHP}_{\text{water}} &= \text{BHP}_{\text{test}} / \text{SpGr} * \text{BHP}_{\text{viscosity}} \end{aligned}$$

Engineered centrifugal pumps have a limited number of stages. Each of these can be custom trimmed to meet precise performance specifications. Multi-stage manufactured pumps have variations in each stage, so the tolerances necessarily are somewhat broad. All the comparisons over the recommended operating range employ flow rate as the abscissa. Acceptable limits are arrayed in Table 2.

Table 2
Pump Test Performance

Head	± 5% over range
Flow	± 5% over range
BHP	± 8% over range
Eff	90% at rated flow

INSTALLATIONS

API Recommended Practice 11S3 [7] identifies wiring methods for surface equipment. *API Recommended Practice 500* [8] and *National Electrical Code Article 500* [9] specify environmental situations that restrict installation options. Figure 2 is presently under review. Nevertheless, it provides guidance for the equipment.

The supply from the transformer to the control panel and from the control panel to the junction box are installed as conduit and wire. An acceptable alternative is appropriately rated direct burial cable. Numerous agencies, such as Canadian Standards Association (CSA) and Factory Mutual (FM), evaluate performance of cable for use in the US. A safety bonding conductor is connected between the panel, vent box, and the wellhead.

The vent box allows depressurization of the cable before it enters the motor control panel. It should be no closer than 15 feet to the well head or the control panel. A seal is installed on the conductors entering the vent box from the control panel.

Area classification is based primarily on the probability of having a fuel source that will be ignited by the electrical equipment. Division 1 anticipates this under normal conditions. Division 2 locations are likely to have the vapors or gases only under abnormal conditions. Otherwise, the location is unclassified. A Division 2 area is defined for five feet around the wellhead and around the vent, as shown in Figure 3. Neither the vent or the well head are expected to release hydrocarbons under normal conditions.

The vent box makes the transition from the well to the surface wiring. Downhole cable is installed directly to the well. The cable should be protected from mechanical damage by a fence or running in a pipe or trough. Armored submersible cable is bonded to the vent box and wellhead.

During installation and removal of the equipment from the well, safety is paramount. Back-up tongs are used to prevent the tubing from turning. A cable spooler controls the reeling rate of the cable. A guide wheel greater than 54 inch diameter prevents damage as the cable feeds to the well.

SIZING AND SELECTION

API Recommended Practice 11S4 [10] incorporates numerous considerations for sizing a pumping system. The article is being rewritten, but the following principles will be maintained.

The well parameters determine the quantity of fluid available and the producing pressure required.

Gradient (psi/ft) = Net SpGr * water gradient (0.433 psi/ft)

Fluid over pump (ft) = Pump intake pressure (psi) * gradient

Vertical head, H_D (ft) = Vertical depth (ft) - fluid over pump

Tubing friction, H_F (ft) = Loss per 1000 ft * Length (ft)

Producing head, H_T (ft) = Pressure (psi) / gradient (psi/ft)

Total Dynamic Head, TDH (ft) = $H_D + H_F + H_T$

A pump type is selected from the flow rate. With multiple possibilities, select one operating on the right side of the flow curve. From the flow-vs-head curve in Figure 4, read the head per stage at the projected flow rate.

Calculate the number of stages.

stages = TDH / Head per stage

From the flow vs. horsepower curve, select the maximum horsepower for the stage type. Calculate the pump horsepower required.

Pump HP = # stages * Hp per stage * composite SpGr

Add seal chamber power and gas separator power to obtain the motor power. From available equipment, pick a motor with greater horsepower capabilities. From our experience, in general employ a motor with a nominal 1200 volt rating, if appropriate cable can be selected. Higher voltage motors are more prone to problems from transients.

The pump conditions are influenced by well conditions including gas production, viscosity, emulsion breaking, and temperature. To obtain optimum performance, correct for these variations.

The following additional information and correlating data is provided to assist in appropriate decision making besides that in the *RP 11S4*.

The *National Electrical Code* [9] suggests a maximum 5% voltage drop in cable for reasonable efficiency. If this value is used, there will seldom be starting problems. Starting inrush current for induction motors is about 600%. With a 5% voltage drop in the cable, the resulting drop in voltage to the motor terminal will be approximately 30%. This is well within the range of most motors.

Select cable materials based on the operating temperature. Later *Recommended Practices* for cable will be individually addressed [11, 12, 13]. The documents on cable application and specification lists the primary material constraints based on temperature .

Cable voltage drop (V_D) in volts/kft determines the cable size. Correct the motor voltage (V_M) for the drop (5%) in the cable to determine transformer supply voltage (V_T).

$$V_T = V_M * 1.05$$

$$V_D = V_T * 0.05 / \text{length (kft)}$$

Use performance curves from *IEEE RP 1018 and 1019* [12, 13] to correct for the operating temperature. With the voltage drop and the current rating of the motor, a cable size is established.

The surface electrical equipment has been previously described [14]. Transformer size depends on the surface voltage, the motor current, and a three-phase electrical factor. The capacity can be obtained from one three-phase transformer. Standard values are 75, 100, 150, 225, 300, and 500 KVA. Alternately three single-phase transformers can be combined. Standard sizes are 15, 25, 37.5, 50, 75, 100, 125 and 167.5 KVA.

$$KVA = V_T * \text{Motor amps} * 1.732$$

The control panel has a voltage rating greater than the transformer voltage and a current rating greater than the motor. The panel size is based on current.

Table 3
Control Panel

Size	Amp
2	45
3	90
4	135
5	270

APPLICATION OF CABLE SYSTEMS

API Recommended Practice 11S5 [11] defines materials and construction of the power cable system. The document is broken into sections describing individual conditions or materials. The format of each section is description, applications, and limitations. A broad range of materials are prescribed for cable components. Table 4 lists the nomenclature for the possible constituents.

Table 4
Cable Component Legend

1	Conductor
2	Strand Gas Block
3	Conductor/Insulation Gas Block
4	Auxiliary Insulation, type
5	Basic Insulation, type
6	Physical Filler
7	Jacket, type
8	Barrier Layer
9	Braid
10	Lead Sheath
11	Bedding Layer
12	Struts
13	Armor

The most prevalent insulation materials are polypropylene (poly) and ethylene propylene diene monomer (EPDM) rubber. The usual jackets are nitrile or EPDM rubber. Additional materials satisfy operating constraints. The conductor is generally copper in sizes of AWG # 1, 2, 4, and occasionally 6. Non-corrosive environments permit galvanized steel armor while corrosive wells dictate stainless steel or monel. One of the most common designs is shown in Figure 5. A flat profile may be required in wells with close tolerance between the tubing and the casing diameters.

Table 5 is a summary of appropriate materials based on conductor temperature. The conductor temperature includes ambient conditions as well as heat rise due to current flow in the wire.

Table 5
Cable Material

oF	Insulation	Jacket
<200F	Polypropylene	
<250F	Cross link	nitrile
<280F	EP rubber	nitrile
>280F	EP rubber	Ep rubber & barrier

Seldom is a single cable available from the vent box to the motor. A splice makes the transition between two cables while a connector makes the transition to a packer or motor. Figure 6 is a representative splice. The successful application of a splice relies on the art and skill of the craftsman as much as the design.

The following discussion is derived from experience in addition to publications. Long flat cables are subject to impedance unbalance between the phases. The result can be a difference in voltage drop between the legs. The imbalance results in negative sequence heating of the cable and motor.

A small voltage imbalance results in a much larger current imbalance. The ratio of these effects is the square of the voltage. The maximum allowable voltage unbalance should be 5%. This results in a current unbalance of approximately 25% and the horsepower rating should be reduced by 25%.

Unbalance can often be accomplished by rotating all three of the phase wires. Rotating only two will cause the motor to turn in the opposite direction.

The direction of motor rotation can be ascertained by using color codes and marks to keep the phases in proper sequence. An alternate method is use of a rotation meter. Connect the instrument leads to the de-energized motor. Turning the motor shaft will indicate postive, ABC, rotation or negative, ACB, sequence.

TESTING OF CABLE SYSTEMS

API Recommended Practice 11S6 [15] describes available techniques for field testing cables. Factory testing assures performance of finished products. Factory tests are discussed in *IEEE Std 1017, 1018, 1019* [16, 12, 13].

The basis of testing in the next paragraphs has been thoroughly discussed in a technical paper [17]. In general, voltage is applied and current is measured during a test. The current may be read directly as leakage current (I_L). Conductance (G) represents the leakage current divided by the applied voltage. Alternately, the ratio of applied voltage to leakage current is displayed as insulation resistance (IR). For a consistent electrical field stress on the insulation (KV/inch), more voltage is applied for thicker insulation.

Insulation properties and resulting electrical characteristics change with materials. Polypropylene is more homogeneous and has a resistance factor value 2.5 times greater than EPDM. Therefore, it will have much less leakage current.

Size, shape, material, and configuration influence the insulation resistance. Regardless, an approximate conductance for new materials can be determined from the bulk properties.

Polypropylene	0.10 *u*a/kV/kft
EPDM rubber	0.25 *u*a/kV/kft

The conductance value will increase with exposure to moisture, well fluids, pressure, mechanical stress, and temperature. Example 1 illustrates the impact of voltage, current and temperature on the conductance.

Example 1

Conductance reading	0.5 *u*a/kV
Cable temperature	100^{o}F
Correction factor	3.26
Temperature corrected	0.5 *u*a/kV/3.26
	0.153 *u*a/kV
Length	5000 ft
Corrected conductance	0.153 *u*a/kV/5kft
	0.031 *u*a/kV/5kft

Caution: Since many instruments operate at several thousand volts, safety must be premier when conducting all tests. Isolate energized lines and ground all unused metal surfaces. The applied voltage may leave a residual charge after removal. Therefore, discharge the conductor by grounding the terminals for up to four times the period that the line was energized.

Before beginning tests, visually inspect the armor and connecting devices for damage. If injured, further inspect the jacket, insulation coverings, insulation, and conductors. Isolate or repair any impairment before continuing with the test.

The cable ends, connectors, penetrators, and potheads should be prepared so there is no leak-over or arcing during test. Before testing, allow the system to de-gas and reach room temperature. A continuity check of each conductor assures no open circuits.

Potheads are generally tested to 30 psi differential pressure and may also be vacuum tested. Isolate connections by immersing in clean, electrical grade oil or using sleeves as shown in Figure 7.

Isolate cable ends by separation. At least 8 inches of insulation material should be exposed on both ends. Ensure that the bare conductor is no closer than 6 inches to another conductor or a grounded surface.

Type of testing: Four situations influence the type of testing: acceptance, maintenance (proof) in-situ, and diagnostic (fault).

Acceptance testing is performed on unused cable at arrival or prior to installation in the well. The testing consists of insulation resistance (IR) and dc high potential tests (hi-pot).

Maintenance testing is performed on cable prior to reuse. The same tests are used as acceptance. However, lower levels are acceptable, since cable deteriorates due to environmental influences. The maximum dc test level is the acceptance value while the minimum level is the maintenance level.

In-situ testing is low energy evaluation performed during and after installation of the system in the well. The low energy will only reveal gross defects. The predominant method is insulation resistance. Occasionally time domain reflectometry (TDR), a fault location procedure, has been investigated.

Diagnostic (Fault) testing identifies location of problems after acceptance, maintenance, or in-situ testing. These procedures are destructive, so they should be performed after all other data has been gathered. The techniques are listed in order of increasing destruction: physical inspection, insulation resistance, time domain reflectometer, high voltage bridge fault locator (Murry Loop), dc high potential, and capacitive discharge (thumper). The last three are performed only after all equipment has been disconnected from the cable. Other more elegant tests are usually available from a laboratory.

Methods of testing: Four methods are described: insulation resistance, dc high potential, ac high potential, and fault location.

Insulation resistance is the first tier of test methods. Since the value changes with the environment, the compensation procedures described in Example 1 are employed. Test signals are 1000 or 5000 volts. The correlation between the two values is tedious. The lower value is often inadequate to find anything but the gross defects. However, it is the most common. Perform the test between all the phases and between each phase and ground. Since IR readings are temperature dependent, resistance drops as the cable is lowered. A sudden drop may indicate system problems. However, the system may operate with readings as low as 1 megohm.

Dc high potential is the predominant method of ascertaining problems. There are some indications that the process may prestress the cable causing later failure. Present industry accepted values are shown in Table 6. The table is extracted from *IEEE RP 1017* [16] which provides detailed procedures for step testing. A go-no go test is conducted by steadily raising the voltage to the level. Maintain the voltage for at least five minutes before reducing to zero. If the current remains constant or decreases, the insulation is good. Conduct the test between each conductor and ground.

Table 6
Cable dc Test Levels, kV

Cable rating, ac	Factory	Accept	Maintenance
3	27	22	11
5	35	28	14

Because of reduced spacing and insulation levels, connectors should be tested at slightly reduced upper limits.

Table 7
Connector dc Test Levels, kV

Cable rating, ac	Accept	Maintenance
3	18	11
5	24	14

Ac high potential testing is not performed in the field. The method does not polarize the insulation like dc. However, the equipment is larger with additional safety risks. Extended periods of high voltage may weaken polypropylene insulation. If a failure occurs, it will cause arcing resulting in damage to the cable. The standard values are listed in Table 8.

Table 8
ac Test Levels

Cable rating	Factory
3000	9,000
4000	11,500
5000	13,000

The predominant first fault location method is the Murry loop. The technique requires a carbon path. It will not work with an open conductor, direct short, or multiple faults. One end of the conductor is connected to the top, while the other end of the conductor is connected to the bottom. The armor is connected to the common. While a high voltage is applied, the bridge is adjusted to give a percentage length.

Capacitive discharge is a destructive method. A high energy charge is applied to one conductor. Ground all other conductors and the armor. The fault is located by sight and sound when arcing occurs. At discharge, remove the energy immediately.

Time Domain Reflectometers have promise, but are seldom used. A low energy pulse is applied to one conductor. The reflected signal is recorded on an oscilloscope. The technique identifies large changes in insulation impedance. The losses in the submersible cable are so high that the signal is distorted. In addition, the technique requires comparison with known conditions, which are rarely available.

A series of papers on operation problems and their soloutions shows results of using some of these procedures [18].

APPLICATION AND TESTING OF SEAL CHAMBER

API Recommended Practice 11S7 [19] lists considerations and techniques for testing the seal chamber section between the motor and the pump. The seal chamber provides 5 major functions: oil expansion volume, pressure equalization, exclusion of well fluids, thrust compensation, and torque transmittal. These features define the procedures necessary for evaluation of the device.

The chamber section is designed to operate at near-zero differential pressure between the well pressure and the pressure in the motor. Therefore, the walls can be comparatively thin and little fluid movement should exist between the well and the internal part of the seal section.

The well fluid contains gas, oil, water, brine, and well treatment chemicals. These fluids attack the wetted surfaces of the section. The housing is often carbon steel or high chrome alloys. The shafts are high nickel materials such as monel, inconel or stainless. Rubbing metal surfaces are typically bronze. Metals should be selected and mated to prevent galvanic corrosion. The mechanical seals are usually carbon on ceramic. Where abrasive fluids exist, seal faces are silicon carbide or tungsten carbide.

The elastomers deserve special consideration. Well treatment chemicals in particular may attack elastomers. The material is also influenced by temperature limits shown in Table 9.

Table 9
Material Temperature

Nitrile	250F
Highly saturated nitrile, HSN	275F
Fluoroelastomers	325F
Tetrafluoroethylene/propylene, TFE/P	350F

Since motor oil viscosity decreases with increasing temperature, appropriate oil type should be considered. Oil will be drained if the seal chamber is other than vertical. Wells with any section deviated more than 30 degrees should have bladder type seals to prevent loss of oil.

The section provides isolation and expansion by labyrinth (manometer) sections or elastomer bladders. Multiple sections improve the life expectancy. Where two thrust bearings are in tandem sections, the upper will carry the pump load unless spacing adjustments are incorporated.

The seal chamber section makes the transition from the motor to the pump. Interchangeability of equipment from different manufacturers depends on seal section characteristics. These include flange alignment, shaft size and strength, thrust requirements, and compatibility of oil in the motor and seal.

The temperature rise and fluid expansion in the seal chamber is determined by outside functions. Variable frequency drives, voltage unbalance, and low voltage conditions cause increased motor temperature. Restricted fluid flow and specific heat of the well fluid restrict transfer of heat from the housing.

Testing of the seal involves acceptance during manufacturing, analysis before re-use, and teardown analysis after use. Since teardown includes most of the other features, it will be used as a guideline. A successful analysis requires gathering operating and well condition information, accurate assembly of pull & run records, and prompt completion of a teardown report such as *API RP 11S1* [2].

1. When the unit is pulled and prior to laying down, check for well fluids. Emulsion indicates running problems, while free water may indicate ingress at or after the problem.

The remaining checks are performed during dismantle.

2. Inspect the outside of the unit for corrosion, pits, and scale. Observe dents, scratches, or bending from the pull or run.

3. With the protective end caps in place, pressurize the unit for 10 to 20 psi. Use a soap solution to look for leaks.

4. Remove the end caps and apply 3 to 4 psi on the body. Rotate the shaft slowly, then push and pull on the shaft to look for top seal leaks.

5. Measure the shaft vertical movement to determine if the extension is in range.

6. Survey the fluid in each chamber for discoloration. It may be caused by high temperature, well fluid, internal wear, or a motor burn. The specific gravity and dielectric may also be checked.

7. Peruse O-rings for cuts, cracks, softening, hardening, or leakage tracks.

8. Analyze shaft seals for proper installation and operation. Check the snap ring for retention, spring for tension, rubber bellow for adhesion, and mechanical faces for errant tracking, scoring, or leakage.

9. Check the upthrust bearing, downthrust bearing, and thrust runner. The retainer should be intact and the contact surfaces should be consistent with operating conditions.

10. Examine shaft bushings for uneven wear and the shaft for abrasion.

11. Investigate the shaft spline twist from overload or wear from vibration.

12. Scrutinize any filters or screens for plugging and foreign objects.

13. Apply 5 to 10 psi differential across the bladder to identify leaks. Probe the elastomer for hardening, softening, pinholes, cuts, cracks and leakage tracks. Assess the interior fluid.

14. Verify the relief values opens at 5 psi and closes at 3 psi or less. Scrutinize the valve for chemical attack or foreign matter.

Checks 1, 2, 3, and 5 to 12 are equally appropriate for motors.

SYSTEM VIBRATIONS

API Recommended Practice 11S8 [20] lists considerations and definitions about vibration in submersible pumping systems. Vibration is simply oscillation in a mechanical system described by a frequency and amplitude. Forced (or excited) vibrations continue in steady state conditions, while free vibrations eventually die out after the initial disturbance.

Although not defined in the RP, the following explanation is beneficial [21,22]. The vibration depends on the relationship of the forcing function to the mechanical properties of mass, spring (stiffness), and damper. The frequency is calculated from the square root of the mass times spring product. The amplitude is attenuated by the damper.

Potential sources of vibration are mass unbalance of materials, misalignment of rotating components, flow disturbance from turbulence and cavitation, bearings from rotation or oil whirl, and mechanical rubbing. Table 10 relates frequency of vibration to probable causes. The frequency is a multiple of the rotating speed. The nominal speed is 3500 RPM.

Table 10
Vibration Analysis

Parts	F x RPM	Cause
Rotor and shaft	1 or 2 x	bent shaft
All rotating	1 x	unbalance
Coupling, bearings	1 to 2 x, or 3x	misalignment
Sleeve bearings	< 1/2 x	lightly loaded
Anti-friction bearing	> 5 x	excessive friction
Mechanical rub	1/3 or 1/2 x	periodic contact
Journal bearing	1/2 x	bearing rotating
Motor	1 x	eccentric armature

Vibration can be reduced at the source during manufacturing. However, once the equipment is fabricated, there are options to reduce the impact of vibration. The first is isolation from external sources such as other pumps. Next, avoid the structures natural frequency by ± 25%.

Resonance occurs when the vibration frequency matches the natural frequency of the support system. The natural frequency can be changed by modifying the mass and stiffness. Alternately, a variable frequency drive can modify the frequency of the pump system.

Vibration potential is inherent in any mechanical equipment with a long length to diameter ratio. The modes of vibration are torsional when changing speeds, axial load on thrust bearings, and lateral (transverse) from alignment and loading. Both torsional and lateral modes have associated critical speeds which should be avoided.

Velocity measurements can be made with three types of transducers. Accelerometers measure acceleration and can be integrated to provide velocity and displacement at frequencies of 15 -10,000 Hz. Velocity probes measure directly in ranges of 10-3,000 Hz. Proximity probes measure displacement directly but are seldom used because of mounting problems. Vibration measurements should be taken at the mid-point, top radial bearing, and bottom radial bearing for each housing in the submersible system. Table 11 indicates vibration severity after ISO 2372, 1974 specifications.

MOTOR TESTING

API Recommended Practice 11S9 [25] for testing motors is being developed. Until that document is established, other procedures are necessary. *IEEE RP for Testing Insulation Resistance of Rotating Machinery* [26], *IEEE RP for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage* [27], *IEEE Test Procedure for Polyphase Induction Motors Having Liquid in the Magnetic Gap* [28], *IEEE Standard Test Procedure for Polyphase Motors and Generators* [29] and *NEMA Motors and Generators* [30] are the fundamental documents.

Table 11
Vibration Severity

Peak velocity		Severity	Peak-to-Peak @3600	
in/sec	cm/sec		mils	mm
<0.014	<0.036	extreme smooth	<0.074	<0.0019
0.028	0.071	very smooth	0.148	0.0038
0.042	0.107	smooth	0.233	0.0057
0.057	0.145	very good	0.302	0.0077
0.099	0.251	good	0.525	0.0133
0.156	0.396	fair	0.828	0.0210
0.255	0.628	slightly rough	1.353	0.0344
0.396	1.006	rough	2.101	0.0534
0.622	1.580	very rough	3.300	0.0838
>0.622	>1.580	extremely rough	>3.300	>0.0838

Although submersible systems use three-phase induction motors, they are unlike conventional equipment. First the unit is extremely long compared to the diameter. Second the air gap is filled with oil. Third, the systems are not designed to standard voltages. Finally, the heat is transferred from the motor to a hot, moving liquid rather than to ambient air. Evaluation of these differences are critical to the successful performance of the submersible motor.

A series of mechanical and electrical tests form the basis of acceptance testing following manufacture. The three types of mechanical tests are shaft tolerances, housing pressure, and coast test for friction. The shaft is checked for end play. In addition the movement in the extended length of the shaft are measured at the top and the bottom. Approximately 10 psi is applied to the housing. The joints, flanges, drains, fills, and pothead are checked for leaks. No pressure change is permissible. After assembly, the motor is installed in a test well for the coast test along with electrical checks.

Caution: All the electrical tests are conducted at elevated voltages. These can be harmful or fatal. The tests should only be conducted by qualified, skilled individuals. Extreme care must be exercised to prevent serious injury.

Winding Resistance: The size and length of wire will change the resistance of the copper in a winding. A simple check can verify the proper motor is under investigation. Use an ohmmeer to measure the resistance of the copper in one winding. Compare the value to the manufacturers specification for that motor.

Insulation Resistance: The first electrical check is insulation resistance. The phase wires must be disconnected to perform this test. The test is conducted between each pair of phase wires and between each wire and the ground. Typically a 1000 V to 5000 V source is applied. A megohm reading is taken after 1 minute. The megohm values will decrease with the moisture in the air, the terminations, contamination, temperature, and material. The same electrical safety precautions used for cable are applicable for motors.

IEEE Std 43 [26] recommends minimum insulation resistance (R) in megohm given by the relationship

$$R = kV + 1$$

where kV is the rated terminal voltage. However, for submersibles, the insulation resistance values should exceed 100 megohms.

Polarization Index: The measured insulation resistance of a winding will typically increase with duration of the applied voltage. A greater increase indicates the winding is dry and clean, while a relatively flat megohm reading points to contamination. The polarization index (PI) is the ratio of the megohms measure at 10 minutes to the value measured at one minute. The ratio should be 2 or more for good quality winding conditions.

The insulation resistance and polarization index will change dramatically as a motor is dried. A plot is shown in Figure 8 illustrates the PI.

HiPot: Dc high potential is the predominant method of ascertaining problems. A voltage of 2 times the rated voltage plus one thousand volts is recommended. Since submersibles use basically a 5000 volt insulation system, the motor should be is tested at 11,000 volts. A go-no go test is conducted by steadily raising the voltage to the level. Maintain the voltage for at least five minutes before reducing to zero. If the current remains constant or decreases, the insulation is good. Conduct the test between each conductor and ground.

A step test can be used to determine the quality of the insulation. The details are outlined under the cable section for *IEEE RP 1017* [16].

Idle power: After assembly, the motor is placed in a test well. Energize the motor at rated voltage. Measure or calculate the current, power factor, power, efficiency, speed, noise level (decibels), and temperature. The no load test reflects conditions independent of the pump and seal section. The motor should be run to establish break-in and detect infantile problems. Typically the motor is run until the oil reaches a nominal temperature of 145F before the test is completed.

Coast test: When power is removed from the idle test, the time is measured until the shaft stops rotating. The coast time indicates windage (oilage), and friction from thrust bearing, and alignment of sleeve bearings. Shorter motors and viscous oils will cause less coast time. Typically the coast time should be greater than 5 seconds.

Oil inspection: After the running test, take samples of the motor oil. Inspect the oil for contaminants and discoloration. A dielectric test may be used. With 1” diameter electrodes, 40C oil should withstand a potential greater tna 27 kV ac across a gap of 0.1” Oil that has been placed in a motor should withstand greater than 15 kV.

Re-use testing: Before a motor is considered for re-use, several tests should be conducted. These include the mechanical shaft checks, pressure checks, and coast test. The electrical tests include insulation resistance and hi-pot.

Teardown: Follow the first six items for a seal chamber. Perform and insulation resistance test and inspect the oil. If the oil is discolored or contaminated, determine the source of the material. Analyze sleeve bearings, thrust bearings, and rotor bearings for wear or improper spinning. Review all surfaces for rubbing. If the stator checks electrically, it can be dried for reuse.

FIELD TESTING

IEEE Recommended Practice Std 1017 [16] gives procedures for testing of submersible cable. The earlier section identified the fundamentals of testing and the voltages from the *IEEE RP*. As a result, this portion will only address dc high potential step testing and interpretation.

Caution: The tests involve high voltage. The preparation and cautions noted above must be followed.

After preparation, the high voltage test instrument is connected between each phase conductor and ground. The other conductors must be grounded.

If the step method of voltage increase is employed, a minimum of five steps are suggested. Duration at each step is long enough for the current to stabilize before taking a leakage current reading. One minute is suggested. The maximum test voltage should be maintained for five minutes. The current is noted at one minute and five minutes after the maximum is reached. Figure 9 represents a step test.

After completion of the test, voltage should be gradually reduced to zero. Then the phase wire must be grounded for adequate time to discharge any remaining charge in the insulation.

The most difficult portion of the test is interpretation of the leakage current level. Reasonable levels were developed in an previous paper [17, 31]. In general, if the current in each phase remains steady or decreases, the cable is acceptable. If the current starts increasing, the cable is unusable.

SPECIFYING RUBBER INSULATION

IEEE Recommended Practice Std 1018 [12] describes the performance of material used in the manufacture of cable with ethylene-propylene rubber (epr) insulation.

Table 12 lists the physical characteristics of copper conductor.

Table 12
Physical Characteristics

Awg Size	Area cmil	Weight lb/k ft	Diameter mil 1 str	7str	Bare Ω/kft	Coated Ω/kft
6	26240	79.4	162		0.419	0.431
4	41740	126.0	205	232	0.263	0.271
2	66360	206.0	258	292	0.169	0.175
1	83690	260.0	289	328	0.134	0.139

The properties of e-p rubber insulation are given in Table 13.

Table 13
EP Rubber Physical Requirements

Unaged	
tensile strength, min, psi	900
elongation at rupture, min, %	1000
Aged in air at 250F for 7 days	
tensile strength, min, % of unaged	75
elongation, min, % retention	75

The properties of nitrile rubber jacket are given in Table 14.

Table 14
Nitrile Physical Requirements

Unaged	
tensile strength, min, psi	1800
elongation at rupture, min, %	300
Aged in air at 212F for 7 days	
tensile strength, min, % of unaged	50
elongation, min, % retention	50
Aged in ASTM2 at 250F for 18 hours	
tensile strength, min, % of unaged	60
elongation, min, % retention	60

The properties of galvanized steel strip is given in Table 15.

Table 15
Galvanized steel Requirements

bare steel nominal width	<0.75 in
thickness for round	>= 22 mil
thickness for flat	>= 17 mil
tensile strength	> 40,000 psi
elongation	>10% in 10 in
weight of zinc	>0.35 oz/ft^2
zinc coated thickness	<120% of bare

Voltage ratings of cables are based on thickness of insulation. The relationships are shown in Table 16.

Table 16
Voltage Ratings

Rating	Thickness	kV Test	
kV	mil	AC	DC
3	75	9	27
5	90	13	35

Cable ampacity ratings are limited by several factors:

ambient temperature
liquid/gas environment
heat rise due to resistance
heat distortion properties of insulation
ability to dissipate heat.

The maximum copper conductor temperature for EPDM insulation with Nitrile jacket is 284F. Numerous curves are developed to correlate these properties with well temperature, current capacity, wire size, and cable shape. The method of developing these curves are described in a technical paper [32]. Figure 8 illustrates the relationship for round cable.

SPECIFYING POLYPROPYLENE INSULATION

IEEE Recommended Practice Std 1019 [13] describes the performance of material used in the manufacture of cable with polypropylene insulation.

The tables and properties for copper, nitrile, armor, and voltage rating are the same as e-p rubber. The major difference is the insulation property and the ampacity.

The properties of polypropylene insulation are given in Table 17.

Table 17
Polypropylene Physical Requirements

Unaged	
tensile strength, min, psi	3000
elongation at rupture, min, %	250
Aged in air at 250F for 7 days	
tensile strength, min, % of unaged	75
elongation, min, % retention	75

The maximum copper conductor temperature for polypropylene insulation is 205F. Numerous curves are developed to correlate these properties with well temperature, current capacity, wire size, and cable shape. Figure 9 illustrates the relationship for round cable.

SUMMARY

Numerous standards, recommended practices, procedures, and papers have addressed electric submersible pumps. Since there is so much data, it is difficult to identify all the information. This paper provides a brief synopsis of the major documents. These address installation, manufacturing, and re-use. The paper is intended as a ready reference for situations where all the documents may not be available.

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FIGURES