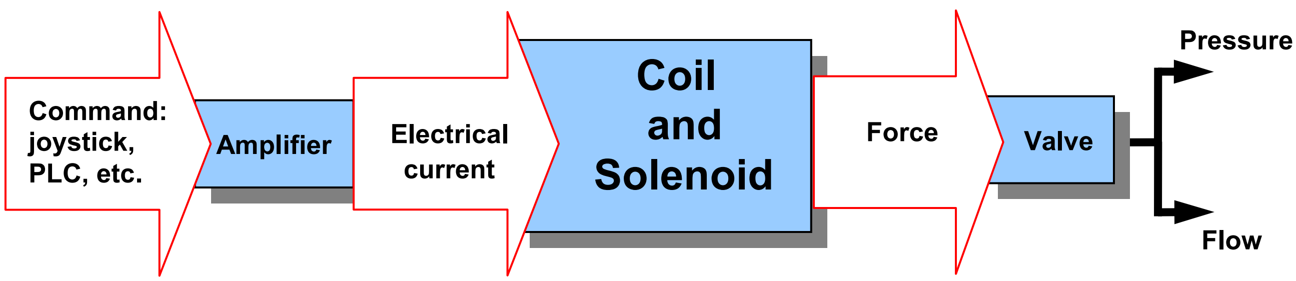
Solenoid Coils for Switching and Proportional Valves

Overview

Solenoids and coils are used to convert electrical energy to the mechanical force used to shift valve components to control flow or pressure. In Sun Hydraulics' terminology, the coil and solenoid are separate components. The solenoid is the tube that contains the armature and pole piece. The coil fits the solenoid and contains multiple wraps of copper magnet wire. With switching solenoid valves, the coil is either energized or de-energized. With electro-proportional solenoid valves, the power to the coil is controlled with a current control device, a proportional amplifier. The same coil can be used for both switching solenoids and proportional solenoids. The flow chart and valve cross-section in Figure 1 shows in a general form how an analog signal controls the power to a coil on a proportional valve. The resulting output is either pressure or flow. The same flow chart can be used to show how electric power is applied to a solenoid coil on a switching solenoid valve. However, a switching solenoid valve, the only input would be the electrical current as shown in the middle of the flow chart.

Sun Hydraulics offers two different coil power ratings, 22 Watts and 12 Watts. Coils are wound for voltages that range from 12 VDC to 220 VDC and 24, 115, 230 VAC.



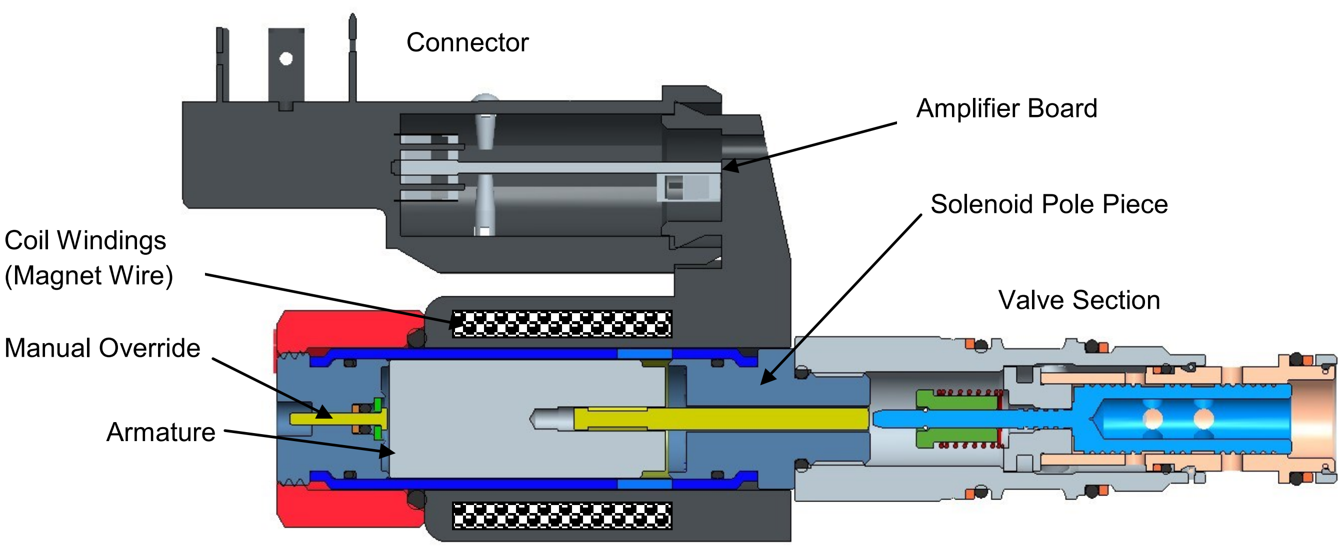


Figure 1: Cross-section of Proportional Valve

Figure 2: Coils in Increasing States of Assembly

Solenoid coils are constructed by winding magnet wire on a bobbin. After terminals and if any electronics are installed, the coil is over molded, and has a flux cage (can) installed. Figure 2 show coils in varying stages of assembly.

Temperature Ratings

In developing the temperature ratings for coils, the materials of construction and power consumption must be considered. Power consumption and temperature rise are directly related.

All materials used in Sun coils have material specifications that far exceed the usage of the coil within the published ratings. This includes the magnet wire, the bobbin material, and the material used to over mold the coils.

All coils are wound with Class N (200ºC rated) magnet wire. Classification of magnet wire is based on the magnet wire insulation. This classification is defined as 20,000 continuous hours (approximately 2.25 years) at 200ºC, the rated temperature. The melt temperature listed for the magnet wire in Table 1 is the temperature at which thermoplastic flow of the insulation occurs. Class N magnet wire is used because it has the highest temperature rating for magnet wire that is readily available that can be easily wound around the bobbin.

Table 1. Materials of Construction with Melt Temperatures

Part	770 and 790 Coil Family		760 Coil Family	
	Material	**Melt Temperature**	**Material**	**Melt Temperature**
Magnet wire Class N (200°C rated)	Polyamide Coated Copper	390°C	Polyamide Coated Copper	390°C
Bobbin	PA66-GF33, 33% Glass Fiber Reinforced Polyamide 66 (black) [DuPont Zytel]	285-305°C	PA66-GF33, 33% Glass fiber reinforced polyamide 66 (natural)	285-305°C
Over Mold	PA66-GF33, 33% Glass Fiber Reinforced Polyamide 66 (black) [DuPont Zytel]	285-305°C	Polyester Thermoset Bulk Molding Compound, 10% Glass Reinforced	Not Applicable
Terminals	Tinned Brass	900-940°C	Tinned Brass	900-940°C

Glass filled nylon (DuPont Zytel® 70G33L BK031) is the material used for coil bobbins and overmolding the coils in the 770 and 790 family of coils. This material is used because its properties remain stable throughout a wide range of temperature. Zytel® is used instead of other commonly used thermoplastics used with solenoid coils because it is less brittle and the increased flexibility of Zytel® contributes to the coils passing the thermal shock test discussed in section 6, summary of environmental test specifications.

Polyester thermoset bulk molding compound is used to encapsulate the 760 coil family. Thermoset over molding is an older process used on the older design 760 coil. It is not used on the 770 coils because it is a slower, more expensive process. Thermoset polymers do not replasticize with temperature; therefore, it does not have a melt temperature.

The choice of the materials of construction is crucial for the long life of the coil. From the table of materials of construction and the explanation of the insulation rating, it is apparent that this is the limiting design factor for the coils.

In order to understand the power consumption of coils an understanding the temperature rise and the effects of temperature on the resistance of the copper magnet wire is required. As current flows through the copper winding, the temperature increases. As the temperature of copper rises, the resistance increases.

The temperature rise and change in copper resistance can be described mathematically with Equations 1-4. The results of these equations are shown graphically in Figure 3 for a 24 VDC coil (770-224). The initial resistance of 26.2 Ω is the resistance of the coil at the nominal temperature of 20°C.

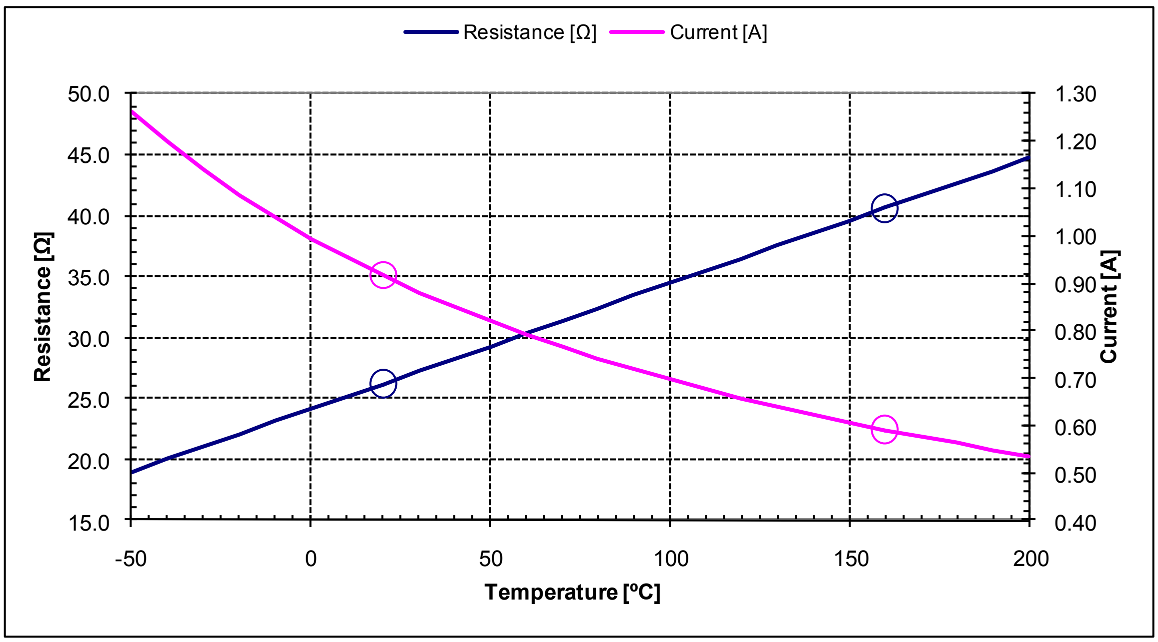


Figure 3: Effects of Temperature on Copper Resistance

$$\frac{234.5+t_2}{234.5+t_1}=\frac{R_2}{R_1} \quad [1] \qquad \text{Rearranging} \qquad t_2=\frac{R_2}{R_1}(234.5+t_1)-234.5 \quad [2] \qquad \theta = t_2 - t_1 \pm \Delta T \quad [3]$$

$$\text{or} \quad \theta = \left(\frac{R_2}{R_1}-1\right)(234.5+t_1)\pm \Delta T \quad [4]$$

R1= resistance before coil is energized [Ω]
R2= resistance after the coil is energized [Ω]
T1= temperature before coil is energized [ºC]
T2= temperature after coil is energized [ºC]
ΔT= change in ambient temperature (add if ambient temperature rises, subtract if drops)
Θ= the rise in copper temperature [ºC]

Key points circled on the graph in Figure 3 are the nominal resistance of 26.2 Ω at 20°C and the current flow at that resistance with the rated 24 VDC (0.92 A). To the right are the points highlighted that correspond to 160°C (0.59 A and 40.6 Ω). The key point of 0.59 A is important when setting up proportional amplifiers on 24 VDC coils.

Figure 4 shows the stabilized temperature of a 24 VDC coil at a 10% over voltage (26.4 VDC) in a 50°C ambient. As can be seen, the current stabilizes at approximately 0.59 A and the surface temperature stabilizes at approximately 135ºC.

Comparing this to the 160°C copper temperature shown in Figure 3, the difference demonstrates that there is approximately a 25 ºC temperature differential between the surface temperature and the copper winding temperature. The 50°C ambient and 10% over voltage are the upper limits to the ratings that Sun has placed on the 770 coils. This provides a 40°C margin of safety between the copper temperature and the rating. As this rating is based on a high ambient temperature with an over voltage condition, the margin of safety is conservative. However, the published data from the magnet wire manufacturer is at 200ºC, with an expected life of the magnet wire insulation is 2.25 years at continuous duty. There is no published data on the life of the magnet wire insulation when the temperature is below 200ºC. Therefore, in order to prevent premature coil failure, it is prudent to operate below the published ratings. ***(Operating beyond the published ratings may lead to premature coil failure.)***

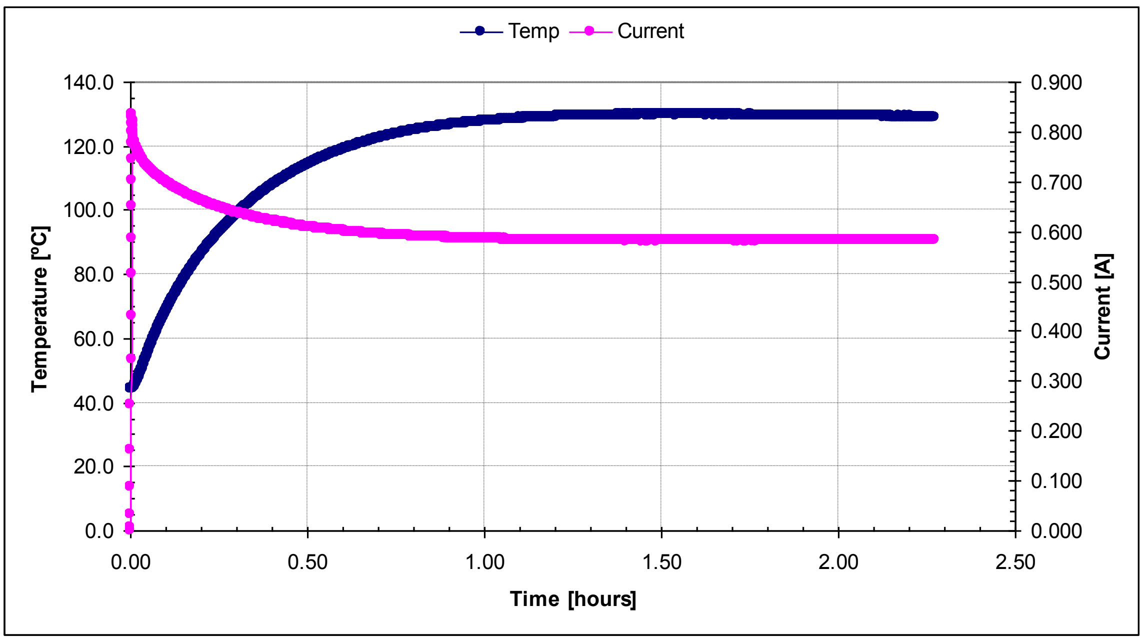
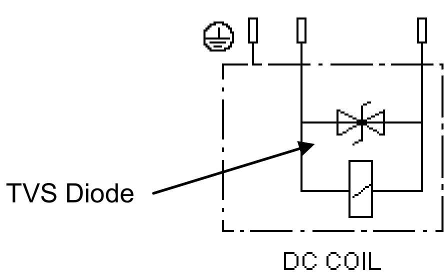


Figure 4: Stabilized Coil Surface Temperature

Overview

Surge Suppression

Sun 770 coils come standard with a Transient Voltage Suppression (TVS) diode connected across the coil for surge suppression.



Without surge suppression, when the coil is rapidly de-energized, the collapsing magnetic field creates a large voltage spike. In Figure 5, the spike is greater than 400 v from de-energizing a 24v coil including switch noise. Spikes can be positive, negative, or both. Figure 6 shows that a TVS diode clips the voltage spike. In this case the spike is limited to -68v, just above the breakdown voltage of the TVS diode installed in the 24v coil.

The voltage spikes can cause damage to electrical and electronic systems in machinery. The break-down voltage of the TVS diode is listed on individual coil product pages. The TVS break-down voltage was selected based upon peak-to-peak AC voltage calculated from the equation below. The breakdown voltage is defined as the point when the diode will close or conduct current across its leads. A safety factor was added to the V_{max} value to prevent nuisance tripping of the TVS diode and would allow for an industry standard value. V_{RMS} is the root mean square value of the sinusoidal voltage. Keep in mind that the peak-to-peak value is double the voltage.

$$V_{\max} = V_{RMS}\sqrt{2} \qquad [5]$$

If the break-down voltage of the

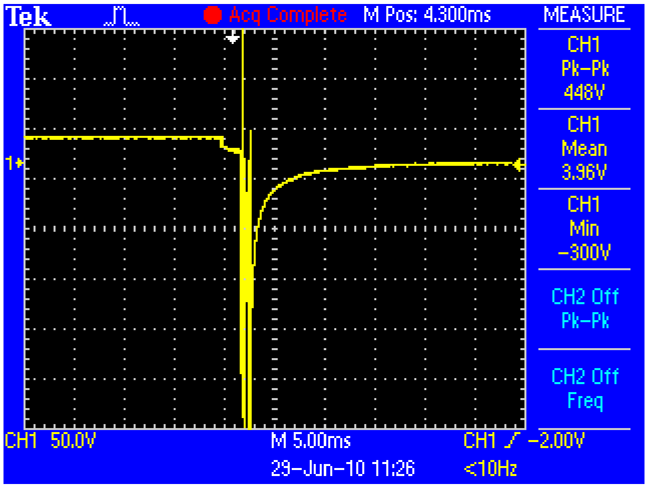


Figure 5: Voltage Spike without TVS Diode

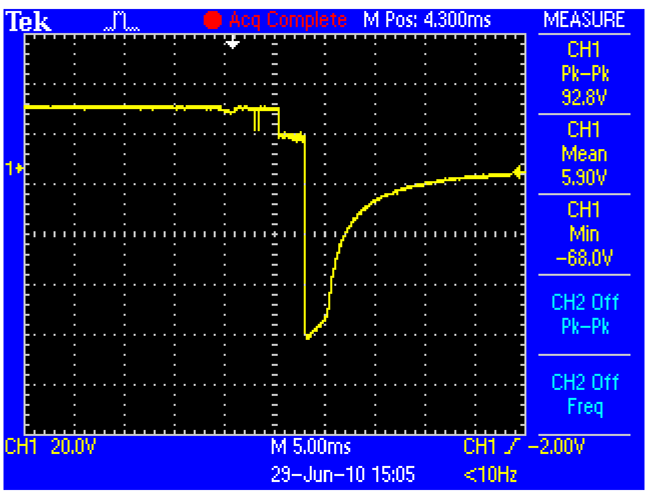


Figure 6: Clipped Voltage Spike from TVS Diode

TVS diode that is built into the coil is too high, then the user must install a lower value TVS diode across the coil terminals.

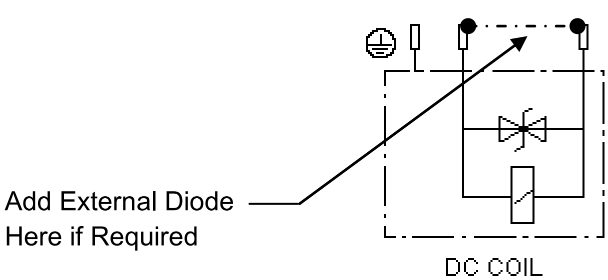


Figure 7: Alternative Surge Suppression Connection

Generally speaking, TVS diodes fail closed, shorting the coil and rendering it useless. Excessive surges, spikes, and over voltage will cause the TVS diode to fail. Great care has been taken to size the TVS diode to prevent nuisance failures.

Sun 760 coils come standard with a Metal Oxide Varistor (MOV) molded within the coil. MOVs are sized differently from TVS diodes. The specifications for MOVs state the maximum V_{DC} and V_{RMS}.

Generally speaking, MOVs fail open leaving the coil without the surge suppression. The values selected for use in Sun coils were again selected with great care to prevent nuisance failure. Equipment manufacturers should understand the potential mode of failure for MOVs and, if necessary, add secondary protection for surge suppression.

AC coil installations are typically in industrial environments. These environments notoriously have poor power quality. Surges, spikes, and brownouts are often common. While Sun has added a TVS diode or MOV to help protect the bridge rectifier used within AC coils (they are actually DC coils), failures may occur. If multiple coil failures persist, consider having the facility's power quality evaluated by qualified personnel.

Table 2 summarizes Sun's standard voltage suppression options.

Table 2. Surge Suppression Semiconductor Values

Voltage	770 Coil Family TVS Breakdown Voltage	760 Coil Family MOV Maximum Continuous Voltage
6 VDC	—	45
12 VDC	68	45
14 VDC	68	—
24 VDC	68	45
28 VDC	68	—
36 VDC	68	65
48 VDC	100	65
127 VDC	250	—
220 VDC	400	—
24 VAC	68	—
115 VAC	250	130
230 VAC	400	250

Coil Polarity and Orientation

On simple solenoid coils (no embedded electronics), there is no polarity. Positive and negative power for DC coils can be connected to either of the power terminals. Similarly for AC coils, the hot and neutral can be connected to either power terminal. For safety, the ground terminal, terminal 3 on DIN plugs, should be properly connected to earth ground.

Coils may be installed on the solenoid in any orientation. There is not a top or bottom to the coil.

Caution: *It is the responsibility of the user to adhere to all applicable electrical codes.*

In Rush Current

All Sun solenoids manufactured for operation with DC voltage. All Sun coils are wound as DC voltage including the AC coils. These have an internal full wave bridge rectifier. Therefore, there is no appreciable in rush current when a coil is energized. Figure 8 shows the typical energization of a 12 VDC coil. As can be seen, with 12 v supply applied (yellow trace), current increases smoothly over a period of just over 50 ms (blue trace). No spikes or surges in either current or voltage are observed.

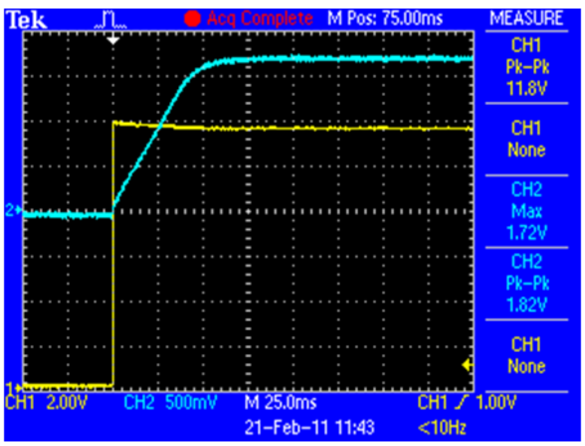


Figure 8: Energizing a 12 VDC Coil

Mating Connectors

Sun offers a number of integral connectors and flying lead wire options. The preferred connectors are shown below. Conduct a simple internet search to find sources to purchase from.

Deutsch
www.deutsch.net

- Embedded electronics connector DT 04-6P
- Solenoid coils , Sun Hydraulics models 770-9** and 770-7**-99 DT 04-2P
- Plugs, cable boots, terminal sockets, and locking wedges are ordered separately

Metri-Pack and Weather Pack
Delphi www.delphi.com

- Solenoid coils, Sun Hydraulics models 77*-78** Metri-Pack 150 series (sealed) male connector (2 cavities) and male terminals
- Solenoid coils, Sun Hydraulics Models 770-7**-19 Weather Pack 2M connector
- Plugs, wire seals, terminal sockets, terminal position assurance clips, and connector position assurance wedges are ordered separately.

AMP Junior Timer
AMP/Tyco Electronics www.tycoelectronics.com

- Solenoid coils, Sun Hydraulics Models 77*-6** AMP Jr. Timer (2 pole male connector)
- Connector plugs, terminal sockets, clips, and cable boots are ordered separately
- Keep in mind that with some mating connectors, a specific crimp tool is required to install the mating terminal socket to the end of the wire.
- With some makes of mating connectors, a connector boot option is available but is usually ordered separately

Embedded Amplifiers

Table 3. Embedded Amplifier DIN Plug Pin Out

Terminal	Function
1	-V supply (common)
2	+V supply
3	Command Input
4	**Option B**– command common **Option C**- +5V reference **Option D**- enable

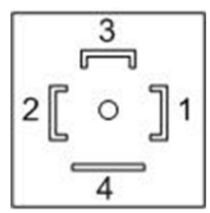


Figure 9: Embedded DIN Plug Face

Table 4. Embedded Amplifier Deutsch Plug Pin Out

Terminal	Function
1	+V supply
2	Command input
3	-V supply (common)
4	+5V reference
5	Command common
6	Enable

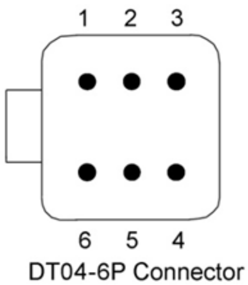
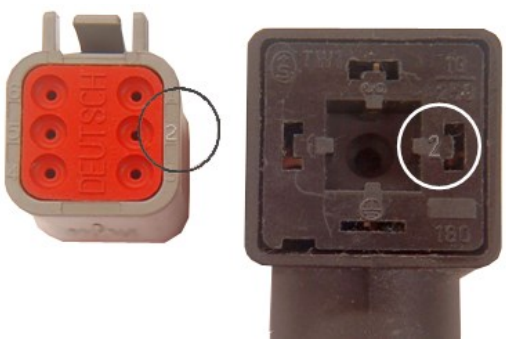


Figure 10: Embedded Deutsch Connector Face

If in doubt, check the mating connector. Nearly all manufacturers mold the terminal numbers adjacent to the terminal.



Summary of Sun Hydraulics' Environmental Test Specifications

Sun Hydraulics engineering standard S-367, Environmental test specification for electrical and electronic components describes fourteen tests used to test the environmental integrity of solenoid coils and electronic components. A course of standardized test that determine pass fail are described in the acceptance test. These tests include the following:

- Acceptance tests
- Water jet tests (IP tests)
- Extended thermal shock immersion test
- Storage temperature test
- Chemical resistance test
- Free fall test
- Humidity test
- Extended operation test
- Vibration test
- Operation shock test
- Corrosion test
- Maximum load cycling
- Circuit protection
- Lead wire pull strength

These tests were designed to assure the field reliability in the wide variety of environmental conditions experienced in both industrial and mobile applications.

Additional details of these tests can be found by reviewing the test specification. It can be found in the technical information section of the Sun Hydraulics web site.

IP Ratings

Intrusion protection (IP) rates the electrical connector against the ingress of dust and water. Standardized tests are conducted in sequence and are described by international standards (IEC 60529 and DIN 40 050). The test parameters are summarized in the table below. It is important to understand that the tests are designed to be conducted in increasing order of severity. Therefore, by default a high IP rating on a connector means that with "backward compatibility", the lower IP ratings are also passed. In other words, a connector with an IP rating of IP69K has also passed the tests for IP 68, 67, 66 65, and so on.

Sun offers coils with a variety of different connectors with different IP ratings. Selection and installation of the proper high-quality mating connector is necessary to achieve the minimum IP ratings published for the coils. For example, most manufacturers of DIN mating connectors publish IP65 as the rating. High quality manufacturers publish IP67.

Figure 5: IP Rating Test Requirements

IP	Test	Water Flow	Duration	Sun Coil Connector Highest Rating
65	6.3 mm nozzle, 2.5 -3 m distance	12.5 L/min	3 minutes min.	DIN Spade* Amp Jr. Timer* Leads
66	12.5 mm nozzle, 2.5-3 m distance	100 L/min	3 minutes min.	
67	1 m immersion	—	30 minutes	DIN* Amp Jr. Timer*
68	Immersion depth by agreement, 1 m is common for industry	—	By agreement, 120 hours common (Sun uses 360 hours)	
69 K	80-100 bar (1160-1450 psi) at 80° C (176° F) 100-150 mm distance	15 L/min	2 minutes	Deutsch Metripack

*Selection of the mating connector can affect the IP rating.

Troubleshooting

With the design and recommended limits of operation of Sun solenoid coils, failures should not be experienced. However, if a failure is considered to have happened, some basic trouble shooting information will help determine if the coil has failed and in what manner.

Basic trouble shooting includes:

- Is the coil energized when it should be?
    - ◊ A quick check can be made without a volt meter by simply trying to remove the coil from the solenoid. If there is magnetic resistance to removing the coil, it is energized.
- Is the coil warm after being energized?
    - ◊ If not, then there is likely an issue.
- Has the coil become excessively hot?
    - ◊ Melted plastic would indicate this and this is likely caused by an internal short circuit.

Advanced trouble shooting includes using a digital volt meter (DVM) to measure the supply voltage and coil resistance. Supply voltage should match the coil voltage within ±10%. Coil resistance measurements can be made with the ohm meter function of the DVM. The measured value should be compared to the published value keeping in mind that the coil temperature directly affects the coil resistance. If short is measured in a DC voltage coil, the likely cause is that the TVS diode has failed (in the coils that have the TVS diode).

Note that it is not possible to measure the coil resistance of an AC voltage coil. The output voltage of a DVM is not high enough to open the diodes in the bridge rectifier. Therefore, the coil resistance can not be measure directly.